CAA2015

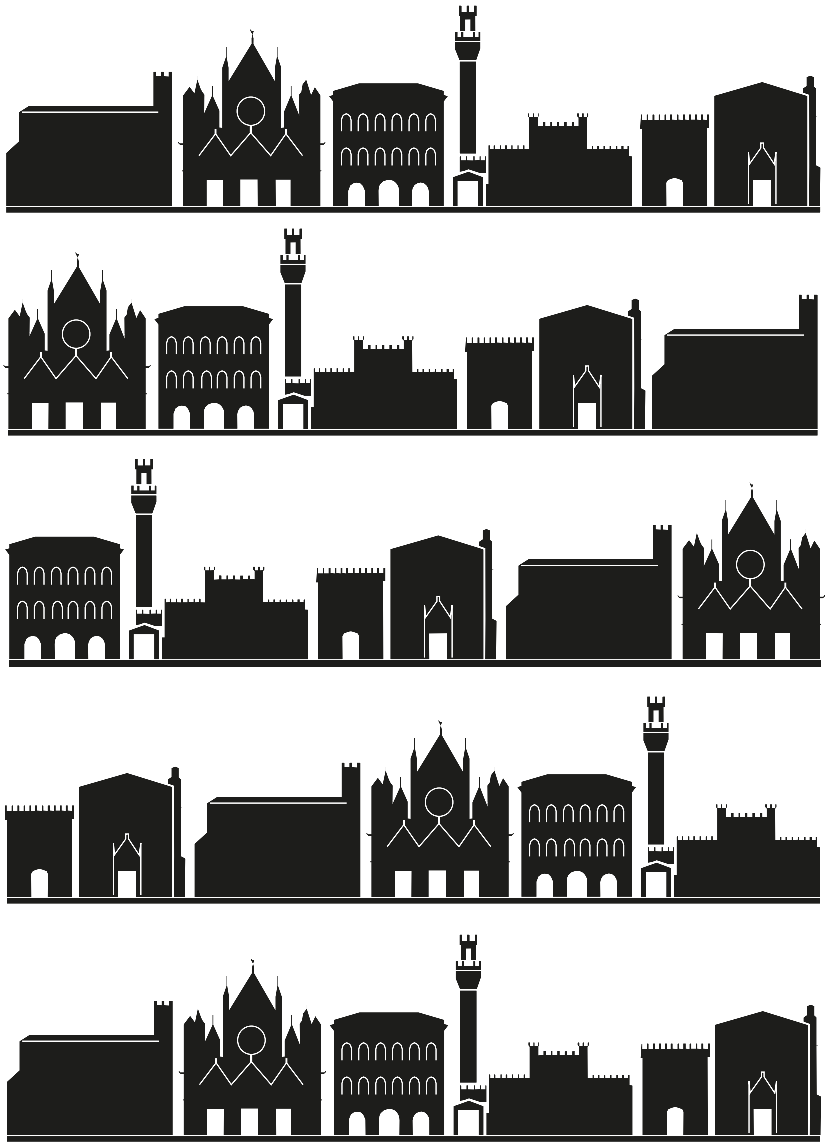
KEEP THE REVOLUTION GOING >>>

Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods In Archaeology

edited by

Stefano Campana, Roberto Scopigno, Gabriella Carpentiero and Marianna Cirillo

Volumes 1 and 2



UNIVERSITÀ DI SIENA 1240

CAA Computer Applications & Quantitative Methods in Archaeology

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Introduction

Stefano Campana

Roberto Scopigno

Chairmen of the 43rd CAA

KEEP THE REVOLUTION GOING!

This volume brings together all the successful peer-reviewed papers that have been submitted for the proceedings of the 43rd conference on Computer Applications and Quantitative Methods in Archaeology that took place in Siena (Italy) from March 31st to April 2nd 2015.

The number of people who signed on for CAA 2015 really took us by surprise: 550 delegates registered for the conference, from many more places than we would ever have anticipated. Altogether, within the four days of the conference 280 papers were presented in 48 sections divided into ten macro topics, 113 posters, 7 roundtables and 12 workshops.

That number, in itself, has prompted a thought or two. Above all it says to us that CAA is very much alive and kicking, that it is in robust good health, and that it remains a wholly relevant force in the scientific community, fully engaged with the questions of the day, and a continuing focal point for the profession. All of that speaks well for the motto of CAA 2015: KEEP THE REVOLUTION GOING!

Although the significance of our motto is obvious, we think it is worth some thoughts. Few would deny that in the past 30 years or so, digital technologies have profoundly revolutionised archaeology – in the office and laboratory, in the field and in the classroom. The progressive introduction of digital techniques in the archaeological process has of course led to a general increase in efficiency. But perhaps more importantly it has provided a spur to the discussion of methodology and through that has strongly influenced not only the way we go about things but also the outcomes that we have been able to achieve.

The pioneering phase in the application of digital techniques in archaeological research has clearly been fruitful and today computer applications such as GIS, databases, remote sensing and spatial analysis as well as virtual and cyber archaeology are deeply embedded within our universities. This is all good, of course, but we must not assume that the task has been completed. An intrinsic revolutionary instinct towards technological development has been awakened. But it will only survive by virtue of the results that it brings about. Or using the words of our Chairman Prof Gary Lock: 'Computers not only change the way we do things, but more importantly they change the way we *think* about what we do and why we do it'. The general thrust of this statement can be summed up and reinforced by recalling a quote from the philosopher Don Ihde, who has argued we should never forget that all technologies should be regarded as '*cultural instruments*', which as well as strategies and methodologies implemented in our researches are also '*non-neutral*'.

So KEEP THE REVOLUTION GOING! is a motto that lays stress on the need to maintain innovation in archaeology through technological advances. But innovation must have at its root the fostering of critical thought and the framing of new archaeological questions. So there is much work still to be done, and fresh challenges to be faced in the months, years and decades ahead.

One final thought. The date of this conference, and most of all the opening ceremony, has not come about by chance. The 30th of March, for the University of Siena and in particular for the human sciences and archaeology, represents a sad but enduring anniversary. Eight years ago on this day we lost a key figure in the Italian archaeological community of the last 50 years; a man who had an extraordinary influence on many aspects of medieval and archaeological studies. Not least we call to mind his role in the promotion and development of digital archaeology. Our thoughts and memories go therefore to our friend and mentor Professor Riccardo Francovich. He always inspired us to seek new horizons and without him we doubt that this conference would have found its way to Siena.

Introductory Speech

Professor Gabriella Piccinni
Dean of the Department of History and Cultural Heritage, University of Siena

First of all, on behalf of the Rector of the University, and as Dean of the Department of History and Cultural Heritage, I wish you all a very warm welcome to the University of Siena.

This greeting goes in the first instance to all of the distinguished speakers at this meeting but also to all who are here in our company to listen and to take part in scientific debate. A warm welcome, naturally, goes to all of the institutions represented at this table, to the Chairman of CAA International, Professor Gary Lock, to the National Research Council, our partner in the organization of this congress, and to the Ministry of Heritage, Culture and Tourism. Last but not least I extend my thanks to all who have committed their time and energy to the organisation of this meeting: the scientific secretariat, the conference office, our student volunteers, the institutions that have kindly agreed to act as patrons, and the sponsors who have so generously supported this initiative.

I confess that when Stefano Campana first told me about the opportunity for our university here in Siena to organise such a prestigious event as the international meeting of the CAA, now in its forty-third year, I was immediately excited and engaged because I strongly believe that events like this represent one of the most tangible and concrete demonstrations of how a University works, how it forms and reinforces knowledge; these kinds of events delight me as a scholar and as a teacher, as well as the director of a university department.

It is a great honour for us to host CAA International, bearing in mind the history of our university, and in particular its tradition of archaeological studies, within which it has played a pioneering and leading role in the field of Digital Archaeology. I cannot but recall how the University of Siena has, since the early nineties, played a central role both nationally and internationally in the development of computer applications in archaeology. My thoughts and deep gratitude go inevitably to our late colleague and friend, Professor Riccardo Francovich, who remains always in our work and in our hearts. His exceptional energy and his qualities as an innovator provided an extraordinary impetus in this area of studies; an impetus that lives on through the work of his students and through the many many people who were inspired by his example.

The conference numbers are frankly astonishing: roughly 550 delegates – the organizers were actually forced to close registration because the results were beyond their wildest dreams. The University’s halls are overflowing, its facilities at full stretch to host this event. The congress has representatives from more than 50 countries and from all of the most prestigious universities and institutions in Europe and beyond. In the short space of the next four days the work programme will be intense, with 46 thematic sessions, 12 workshops, 7 panel discussions, 4 key-note speeches and all sorts of informal discussions and social activities that will promote the continuing exchange of ideas.

Let me end with a simple thought. Without entering into discussions and analyses that lie outside my role (or even competence) here today, I feel that seeing so much dynamism and so many young scholars, teachers and researchers coming together here in Siena from all around the world to talk about the new opportunities offered by the application of technology within archaeological studies should prompt a few moments of reflection about the ways and means through which we deliver our higher education and training. Today more than ever, in front of this audience, we see how vibrant and strong is the demand for discussion and training in these topics. In keeping with the motto of the conference, the future is still to be built, let us show the same commitment that enabled our predecessors to overcome the first heroic phase of the 1990s and the early years of the new millennium. Always, of course, keeping alive the flame of innovation that has from the outset been the guiding light of this of CAA International initiative.

Acknowledgements

It goes without saying that the organization of an event such as CAA is a complex and demanding task that only achieves success through real teamwork. So we will start by offering heartfelt thanks to all who have helped to make this meeting possible: the University of Siena. We are particularly grateful to the Rector prof Angelo Riccaboni and the Director of the Department of History and Cultural Heritage prof Gabriella Piccinni for their constant support and valuable advice. Particular thanks are offered to the conference office Giuliana Pasquini, Roberta Corsi, Elisa Pratali and Serena Mazza and to our many students volunteers, Mirko Buono, Marta De Pari, Valery Del Segato, Cesare Felici, Ilenia Galluccio, Nadia Messina, Michele Pellegrino, Sara Linda Russo. Last but by no means least we owe a deep debt of gratitude to all who have given their time and enthusiasm to the organisation of the meeting – to the Scientific Secretariat under the leadership of Dr Marianna Cirillo.

For the same reasons, I am most grateful to the Monte dei Paschi Foundation and to Verince srl for the outstanding work in organizing the social events including the 'ice-breaker' party, visits to various monuments and cultural activities within the city of Siena, the social dinner and the field trip. In particular I would like to mention Marco Forte, Laura Tassi and Laura Manzi, who have substantially contributed towards making CAA Siena unforgettable for their delegates.

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CHAPTER 1
Teaching and Communicating Digital Archaeology

From the Excavation to the Scale Model: a Digital Approach

Hervé Tronchère
herve.tronchere@mairie-lyon.fr
Service archéologique de la Ville de Lyon;

Emma Bouvard
emma.bouvard@mairie-lyon.fr
Service archéologique de la Ville de Lyon, UMR 5138 ArAr;

Stéphane Mor
stephanemor@gmail.com
La Fabrique d'Objets Libres;

Aude Fernagu
fabmanager@fabriquedobjetslibres.fr
La Fabrique d'Objets Libres;

Jules Ramona
jules.ramona@mairie-lyon.fr
Service archéologique de la Ville de Lyon

Abstract: Lyon's archaeological department took the opportunity of a recent rescue excavation to fulfil two purposes: improving (geo)archaeological knowledge of the city of Lyon while developing a set of tools for scientific mediation. The excavated site spanned 40000 years, from the Würmian period to the 19th century. Occupation from the ancient and medieval periods was the main focus points of this excavation. A 3D diachronic reconstruction was achieved for this site using a fully digital workflow. Stratigraphic and architectural data obtained from the fieldwork, or reconstructed afterwards, were integrated into GIS and modelling software to produce 3D volumes. We could produce static high-resolution renderings, a 3D printed scale model of the stratigraphy and buildings, as well as digital interactive media. This project allowed us to explore the interest of 3D both for archaeological research, as a way to develop and validate research hypotheses, and for scientific education.

Keywords: Landscape and Archaeological reconstruction, 3D printing, Virtual reality, Scientific mediation, Lyon (France)

Introduction

Our project started with the will to collaborate with the FabLab of Lyon in order to experiment with 3D printing (Wohlers 2013) applied to archaeology. Such techniques are already used for artefacts (Fantini *et al*. 2008), but we aimed at applying them to stratigraphy. We widened this initial goal to encompass other 3D methods and tools and developed an uninterrupted digital process that finally allowed us to produce several virtual and physical restitutions of an archaeological site.

Our questions were 1/ how could we, as archaeologists, adopt these innovative techniques 2/ how could they enhance our scientific practices 3/ how could they improve our educational practices 4/ could we obtain valid results with limited resources?

An emergency excavation that started at the beginning of 2014 in Lyon (France) proved to be the ideal testing ground for this experiment (Bouvard *et al*. 2015).

Salvage archaeology must adapt to several constraints that we have to overcome if we want to understand the evolution of a territory wider than the plot we dig. Time remains the first constraint, but is not the only one: urban sites for example are characterized by their confinement, fragmented nature, and stratigraphic unevenness. Therefore we need a tool that can offer the opportunity to, first fill the stratigraphic unknowns, and then help us to understand human and landscape evolution in terms of topography and sedimentology.

Moreover, sharing the cultural heritage and transmitting the knowledge to a large audience is an important part of our mission as a public institution. This is why Lyon's archaeological department involves the local community in the care of the anthropic and landscape relics that are parts of their history. For this reason, we decided to participate in a science festival ('Fête de la Science') lasting more than a week, whereby universities, museums, and other research centres offer workshops to pupils from schools and colleges, and to anyone interested in meeting scientists and learning about various scientific topics. For this event we wanted to innovate with a new and interactive education tool, associating makers and archaeologists. The goal was to create a 3D scale model of the site we excavated. We had to be able to assemble and disassemble the main stratigraphic layers and buildings, in order to explain to the general audience both the evolution of the site and the archaeological process itself. We also wanted to explore the potential of innovative human/computer interaction for archaeology and scientific mediation with various tools: contactless interaction with 3D restitutions

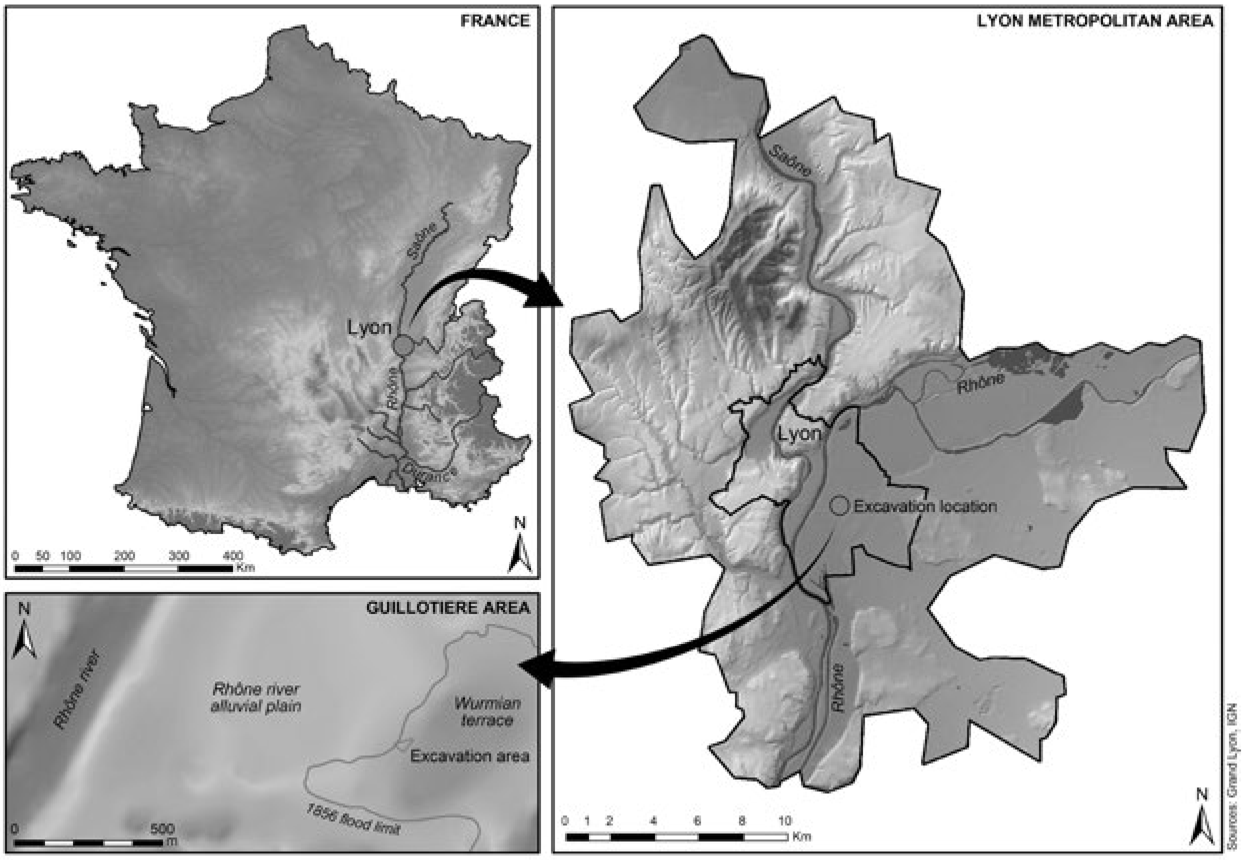

Fig. 1. Location of the archaeological site and geographical context.

of archaeological objects (using a Leap Motion controller; Spiegelmock 2013) and visit to an ancient site in virtual reality (with Oculus Rift virtual reality goggles; Knabb *et al.* 2014). These products would support a dialogue on the association between humanities and digital technologies.

One challenge of the project was the transfer of objective data from the field to a final product dedicated to education, without generating bias errors during the process. We will first present the excavation that provided the initial data. The second part of our paper will cover the end-to-end digital workflow we created to reach our objective. We will then explain the benefits we gained from the 3D restitution, from a scientific and educational point of view, and we will finally the perspectives of such an approach.

1 Archaeological context

The salvage excavation in a small plot (900m^2) took place on an *extra-muros* area around the city of *Lugdunum* (Fig. 1). We expected to find a Roman necropolis because some graves and a section of an antique road were found in the neighbourhood by archaeologists over the past twelve years (Blaizot 2010). Unfortunately this was not the case, but we did find two small settlements, one Roman and the other medieval. The site is located on the bank of the Rhône River in a district outside the Roman and the medieval town. It was a rural area in the past, but it is now an urban space. The specific topography (a moderately high terrace, a slope on the opposite side, and two large, hollow structures) allowed us to work on a stratigraphic relevant case, which seemed to be, at first, a challenge to show and to explain to non-archaeologists.

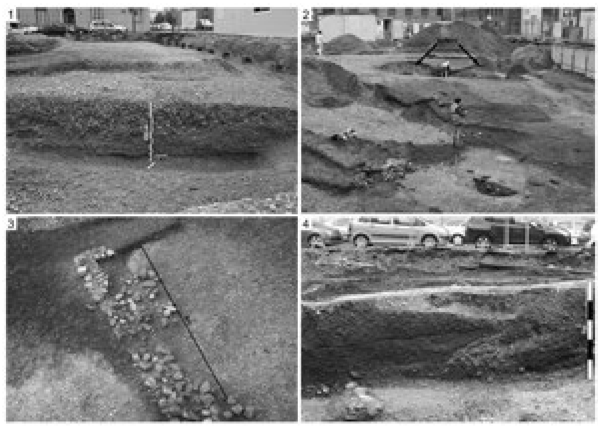

Fig. 2. Excavation: a) stratigraphic section, showing the Würmian fluvio-glacial deposits; b) gravel and pebble quarry, dug between the 1st and 3rd century AD; c) 8th-century building remains; d) late-medieval agricultural ground.

The site where the humans settled was a Würmian terrace built with fluvio-glacial deposits from the Alps, made of sands, pebbles and few silts (fig. 2a). An OSL dating, a method that proved effective in glacial contexts (Lewis *et al*. 2009) gave an age of 40,000 BP for this formation (Bouvard *et al*. 2015). It is just at the limit of the Rhône alluvial plain (Macé *et al.* 1993; Bravard *et al.* 1997), and was preserved from the floods. Indeed, one of the last big inundations in Lyon, in 1856, extended up

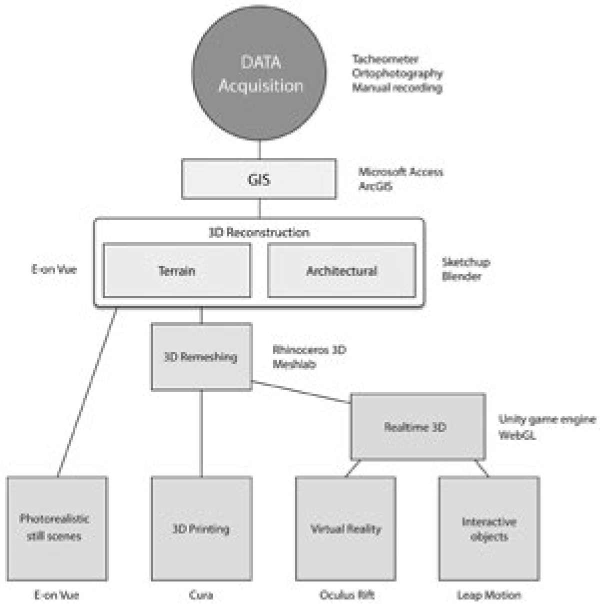

FIG. 3. FULL WORKFLOW, FROM THE FIELD DATA ACQUISITION TO THE MULTIPLE PHYSICAL OR DIGITAL OUTPUTS.

to the western limit of the plot but did not flood it (Combe 2007). The terrace was dug by human hand in two sectors of the plot (Fig. 2b). We interpreted them as two possible quarry faces made to extract building material (to make mortar, or create a road, for instance). It took place between the 1st and the 3rd century AD. Then, during the beginning of the Middle Ages, a posthole dwelling was built, quite small in scale, within the indentation made by the largest Roman quarry face (6th-7th c. AD); during the 7th or 8th century, a backfill made of funerary antique remains filled the hemispherical digging work; at the same time a second dwelling stronger than the first was built with a postament made of stones, Roman bricks and clay (fig.2c). Nothing remains from the recent periods except a thick (up to 2 m) agricultural soil made of organic earth which covers all the plot up to the 20th century ground (Fig. 2d).

2 Methods

Our initial goal was the 3D printing of each important individual stratigraphic layer and structure at one of the local FabLabs of Lyon (La Fabrique d'Objets Libres), in order to create a model that could be taken into pieces. Manipulating virtual objects and exploring the site in virtual reality were extensions of this first purpose. Unfortunately, the virtual reality application could not be ready in time for the 2014 science festival, but has been achieved since.

A complete 3D restitution of the site was needed for both purposes. This encompassed both the stratigraphic/topographic and architectural aspects, for which we used a multi-step process that we summarised in Fig. 3.

[Insert Fig. 3]

2.1 Stratigraphic reconstruction

The stratigraphic reconstruction was a complex process that could only be achieved with a combination of various pieces software and tools. Three steps can be individualized.

2.1.1 Terrain data acquisition

The first step was the acquisition of terrain data. An extensive set of control points was needed in order to create altitude isosurfaces (digital elevation models, DEM) for each stratigraphic layer. We chose not to represent each individual layer, but instead to focus on the most significant ones according to the following criteria: on the one side the periods with the greatest layers (the ancient topography and its gravel quarry, and the topography at the beginning of the modern period, which is characterized by a very thick layer of agricultural soil), and on the other side the less obvious features that had, however, significant meaning in this precise excavation (the natural landscape before the anthropic impacts, which is a state that could not be observed directly, and the medieval infill of the 8th century AD that contained ancient cremation remains).

A microtopography survey was conducted during the excavation. At every noticeable stripping phase, numerous control points were acquired, using a total station. Each point was defined both by its xyz position and by its corresponding stratigraphic layer. Since a stratigraphy is also in a way chronological information after it has been interpreted, control point attributes in fact contained 4D data (localisation + deposition period). This set of microtopography points was completed afterwards with additional control points extracted from the stratigraphic section drawings that were georeferenced in ArcGIS. Our final dataset contained about 300 control points, with a varying density according to the complexity of the terrain (the more complex the stratigraphy in an area, the more points were acquired and processed for this area).

2.1.2 Topographic restitution

The restitution of each period's topography was made with the 3D analysis module of the GIS software ArcGIS. At this step corrections had to be made several times. We had to add further control points to refine the digital elevation models. This additional data was obtained from the stratigraphic sections. We were particularly careful about the areas where the stratigraphy had not changed between two periods. For instance, the 8th century topography only differs from the ancient topography in the quarry area, whereas the remainder of the topography had to be identical. The parameters we provided to the kriging engine were thus critical in obtaining correct interpolations. The three elevation models (ancient, 8th century and late medieval/modern) that we obtained were extremely close to what we observed in the field and in the stratigraphic sections drawings.

The pre-anthropic landscape was the most difficult part of the restitution. Since it had been deeply incised by the quarry, its original shape could not be observed and measured directly. We thus had to reimagine its potential configuration. For this, we used the ancient topography dataset and removed from the interpolation all the control points that could only have been the result of direct human impact. The geomorphological expertise allowed us to discriminate features that could have been the result of natural processes (streams, erosion) from the anthropic-exclusive processes (i.e. quarry diggings). The result was an altitude surface that was the likely topography before human occupation, which was the last elevation model needed for our work (Fig. 4). Obviously this remains a hypothesis that cannot be proven with absolute certainty, but the resulting DEM

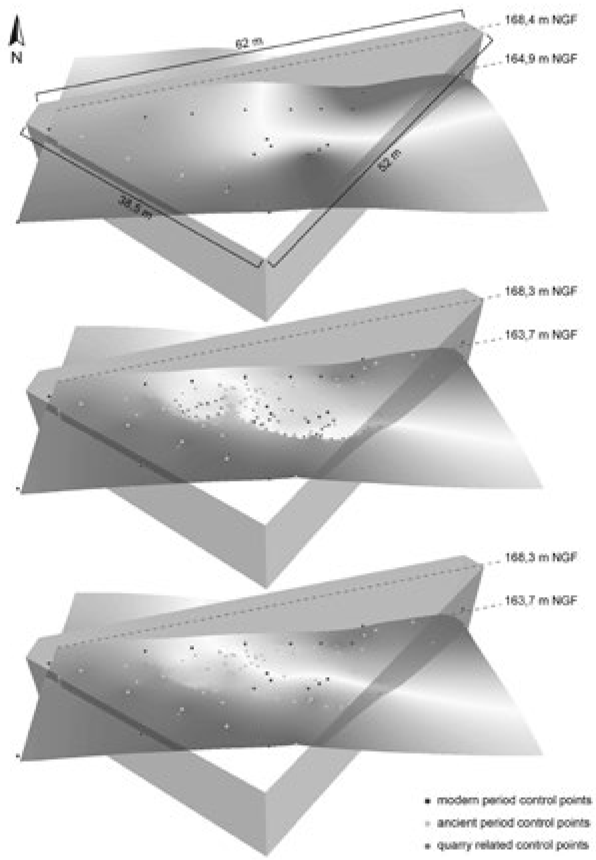

Fig. 4. GIS palaeotopographic modelling: a) topography at the beginning of the modern period; b) ancient topography; c) reconstruction of the pre-anthropic topography.

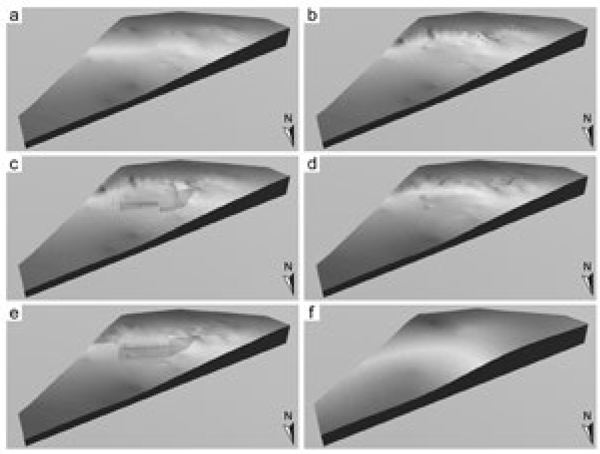

Fig. 5. Period by period volumetric restitution, incorporating the buildings: a) pre-anthropic topography; b) alteration of the landscape during the ancient period caused by quarrying (underlined in red); c) first medieval settlement (7th century); d) filling of the quarries by ancient cremation remains; e) second Middle Age settlement (8th century); f) end of Middle Age/beginning of the modern period: formation of agricultural soils.

is highly plausible. From a methodological standpoint, this process is also a shift from the restitution to the reconstruction.

2.1.3 Volumetric modelling

However, the 2.5D digital elevation models we obtained were insufficient for our purposes, which included computing the volume of gravel that had been extracted from the reconstructed natural landscape by the quarriers, as well as producing 3D prints of the stratigraphy.

The elevation models were thus imported in 3D modelling software (E-on Vue Studio), where they were used as displacement maps on special 2.5D planes ('terrains'). These terrains were converted into 3D polygonal meshes in order to create actual three-dimensional bodies (Fig. 5). The 3D software we used did not manage georeferenced data, and we therefore had to drop this spatial information. However, we preserved the size and relative positioning of objects (stratigraphical layers in our case), allowing us to keep working in a 1:1 scale environment.

Boolean operations were then conducted on the meshes to obtain a series of 3D volumes, each representing one stratigraphic unit. E-on Vue proved to be the most efficient software at our disposal to manage these computations on complex meshes. Another advantage of Vue was its 'ecopainter' and vegetation engines. This module allows the constitution of realistic ecosystems in a minimal time, an aspect we needed in order to produce a few realistic still images for the posters that would accompany the workshops. The manifoldness and 'normals' alignment of our meshes were checked and adjusted in Meshlab and Rhinoceros 3D to ensure their proper export to 3D printers.

2.2 Architectural reconstruction

The reconstruction of the two houses was closer to a regular 3D modelling process. Since several kinds of products were envisioned with different requirements in terms of resolution, file size, etc., we had to produce different models with varying degrees of details. We chose to first create high-resolution buildings, aimed at being textured in E-on Vue for photorealistic rendering. These models would then be degraded for the other applications (3D printing and real-time rendering).

2.2.1 High-resolution reconstructions

The few archaeological insights we had (some postholes for the 7th-century building, and remains of the stone base for the 8th century one) were imported as a 1:1 floor plan in Sketchup. We then built the elevations from this plan. We referred to existing literature about constructions of the early Middle Ages (Faure-Boucharlat 2001; Gentilli and Lefevre 2009), as well as remaining wood and mud traditional housing to build our houses. Several hypotheses were tested for the 7th-century building, as we were trying for the most realistic configuration: on one hand we were not certain if some postholes belonged to the house, and on the other it was clear that some other postholes had obviously not been discovered during the excavation.

Since both dwellings were extremely simple structures, advanced architectural techniques such as architectonics or material resistance were deemed not necessary. The

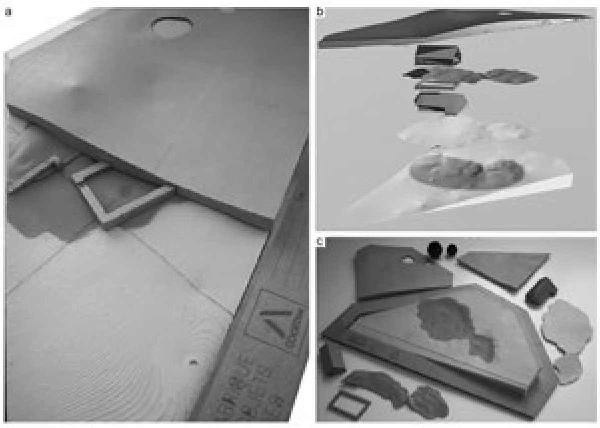

Fig. 6. 3D printed 1:100 scale model: a) assembled stratigraphic cross-section; b) digital rendering of the pieces as an exploded view; c) complete set of printed pieces.

simple Sketchup models were imported in Blender for some enhancements (for example the thatched roofs could not be modelled properly in Sketchup).

2.2.2 Low-resolution reconstructions

The file size of the high definition buildings, as well as its many small elements and complex shapes, made it difficult to render in real-time on low-to-middle end hardware. We decimated this model in Blender in order to obtain a more manageable file that could be used in WebGL applications or in game engines.

2.2.3 Creating a 'printable' file

Creating a printable file proved to be another challenge. Since we wished to print our houses at a 1:100 scale, many elements would prove too small for the printer's resolution. The walls themselves would have been only 2mm thick, resulting in a very flimsy model, a problem considering that it was supposed to be handled by the public. We had to increase slightly the thickness of the walls and roofs to get clean and sturdy prints. Also, because we could not rely on displacement or bump maps to simulate the details of the stone walls or of the roof straw, we needed to add real three-dimensional reliefs to the buildings. The details that we wanted to see on the real-life model had to be there in the mesh. Voronoï filters were applied to the basement walls of the 8th-century building to simulate the individual stones, and gaussian noise was added to the roofs. Finally, all the separated pieces of the buildings were merged into a single mesh for each house, to ease the exporting in the 3D printer software.

2.3 Realistic rendering, 3D printing and virtual simulations

Printing a scale model was the main goal, but we were confronted with a basic obstacle: the size of the model. We settled on a 1:100 scale model of the site, which was large enough for people to gather around and have a good view of the items and still allow its easy transport and storage. We had to split the larger stratigraphic layers into several blocks, since the low-cost 3D printers we had access to did not allow us to produce parts larger than a 20 cm cube. This in turn led to a further series of controls and adjustments of the meshes. This part of the work saw a close collaboration between the makers of the FabLab and the archaeologists. The cleaned objects were imported into the Cura software used to interface with the Ultimaker 3D printers. Five full days were needed for the printers to complete the production of the pieces. Some of them were then glued back together to ensure easy handling. The finished product comprised four stratigraphic layers which adjusted within each other, the few archaeological remains of the houses that we discovered, and the reconstruction of these dwellings. Each block has a distinctive colour, one for each period (fig. 6). Finishing the model also implied a few small manual interventions (sanding, paint touch-ups) and finally adding an MDF and Plexiglas base.

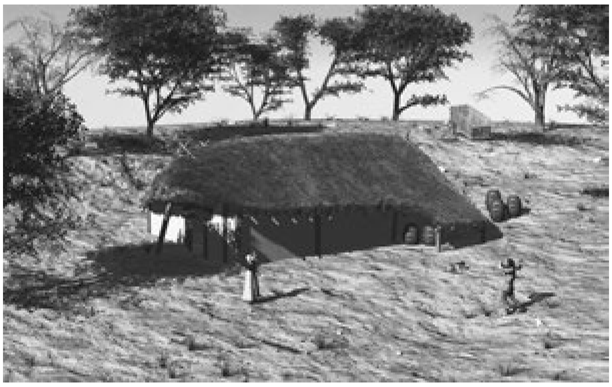

Fig. 7. Hypothetical rendering of the 7th-century dwelling and landscape.

The high definition architectural reconstructions were imported and textured in Eon-Vue. Since our objective here was realism and not real-time rendering, we used advanced procedural textures, many of them incorporating displacement maps (for example for the stone walls of the dwellings, or for the roofing, for which we used vegetation to simulate the thatched roofs). Vegetation was added using the 'ecopainter' engine of the software. We then created a few realistic still images in high resolution of the potential landscapes at the 7th and 8th centuries (fig. 7). Unfortunately, we were not able to produce quality videos because of the time needed to render a single full frame on consumer grade hardware (6 to 8 hours).

The terrains produced by E-on Vue were also imported, in combination with the low definition architectural reconstructions in the Unity Engine, in order to develop a basic virtual reality application (Fig. 8). Textures were added, this time using techniques closer to what is used in game design to ensure good real-time performances, such as normal mapping (more precisely bump mapping), so as to simulate details on the walls and roofs of the buildings. Only the largest vegetation elements (trees) were 3D objects. We used bill-boarded textures for the grass. Wind was added to enliven to the scenes and animate the moving objects (vegetation, smoke). The Oculus SDK allowed us to implement a FPS-like ('first person shooter') control scheme that would be compatible with Oculus Rift VR goggles (DK2). Our application also allows the player to switch at anytime during the simulation between the four historic periods we chose to represent to experience the site's evolution: pre-anthropic landscape, ancient quarry, 7th-century

Fig. 8. Real-time rendering of the 8th-century house in the Unity engine: a) the original landscape before human intervention; b) the landscape modified by the quarry; c) the 7th-century posthole dwelling at an early construction stage; d) the 8th-century house, built on its strong base.

settlement, 8th-century settlement. It is also possible to use the application on screen, like a regular virtual visit, without VR goggles.

Finally, the low definition architectural models, an exploded view of the scale model, as well as some 3D models of archaeological objects, like medieval cooking pots that were found on the site and reconstructed from their shards, were converted to be used in conjunction with the Three.js WebGL javascript library in a web browser. We also used the Leap.js, a library that interfaces the Leap Motion (an infrared motion sensor) with WebGL content.

3 Results

3.1 The archaeological research perspective: what does 3D bring?

One of the archaeological results relates to the quarry: thanks to GIS and the 3D volumetric meshes, we could calculate the amount of sand and pebbles extracted from the Würmian terrace during the beginning of the Roman period. Because we were manipulating real-size volumes after the reconstruction, we could find the amount of gravel (118 m^3) extracted from the quarry by simply querying the software. This gravel is similar to the one used to construct the Roman road recognized near our plot. If we imagine that we have discovered one of the places where the Romans stockpiled gravel it is possible to calculate the length of road they could have laid. Our figures revealed that they could have built 100m of road, 5.80m wide and 0.20m thick.

Moreover, we could visualize how anthropic settlements evolved in the landscape, adapting themselves to the special topography of the terrace, the slope and the quarry. The medieval dwellings, the remains of which were very scarce (22 holes for the oldest, and a fragment of a rectangular stone base for another), needed 3D reconstructions to check our configuration hypotheses. And indeed, the 3D approach brought out several discrepancies that we could correct. These would have remained unseen with a standard 2D perspective drawing. It also helped us in choosing between several configurations for the buildings.

3.2 The educational perspective: workshop unrolling

Audiences (groups or individuals) were invited to discover not only the history of the archaeological site through the scale model, but also to understand how we created it. The use of 3D tools applied to archaeology was as important as the site itself. For many of the people who visited us, 3D printing and 3D modelling were completely new. This is why the workshops were designed from the beginning to be dialogues between ‘makers’ and archaeologists, and it was this feature that made the events successful (around 350 people and pupils came to the workshops over 3 days).

Posters and an informative booklet were provided to help in understanding the evolution of the settlement, as well as the restitution process, and archaeologists and makers were also on hand to answer questions.

The ‘historical’ component of the workshop revolved around the scale model that was exhibited and available for manipulation. When school classes visited, the archaeologists and teachers handled the model themselves. The model could be used by the public in two ways. Disassembling the layers one by one, the subsoil could be explored as an archaeologist does during an excavation. Alternatively, if one starts to assemble the scale model from the first layer, it is possible to apprehend the evolution of the landscape from the Würm to the current period. Moreover, it is possible 'to dig' (i.e. remove), only half of a layer so we can see the stratification between sedimentary and anthropic deposits (fig.6a). This allows an easy understanding of the main principles of stratigraphy: why are the older layers below, what is sedimentary accretion, why are the remains of ancient buildings buried, etc. Of course, these are all aspects that are obvious to archaeologists, but not so easily interpreted by the general public and school children.

The 'computing' component of the workshop, undertaken in collaboration with the makers of the FabLab, presented the reconstruction of a medieval cooking pot in real time: a shard found in the excavation was presented; its profile was then drawn on a laptop before being imported, reconstructed and converted into a virtual object in 3D software (Blender). A 3D printer then reproduced it at a scale of 1:20 in real time, while the finished virtual reproduction could be manipulated contactless thanks to the Leap Motion controller. All school classes, as well as a few other visitors, would then keep the small printed pottery reproduction as a souvenir along with the workshop's booklet.

4 Discussion

'Archaeology in plastic' was the title of the workshop, intended as a dialogue between past and present, false and true relics. It was a way to bridge the gap – associating new technologies and human sciences can sound like forced marriage to many. However, we demonstrated that this association can be beneficial for both archaeological research and cultural mediation. The fact that a single initial set of data can be converted into several media, both digital and physical, while preserving their scientific objectivity, is remarkable.

3D printing has taken a long time to reach archaeological studies and museums. It is 30 years old now (Hull 1986; Lipson & Kurman 2013) – and it is time for humanities to give it a try. This tool, invented to make industrial prototypes (Chua *et al*. 2003), is now being used for many more purposes, including cultural education, especially to produce replicas of archaeological artefacts, and in general for museography (Chaumier and Françoise 2014). It is definitely a do-it-yourself approach, because it is now low-cost and readily available. Much software is now open-source, and tutorials are easy to come by (Schelly *et al.* 2015).

Concerning the interactive virtual media, many enhancements have to be made to this first experiment to provide a better educational experience. The Leap Motion controlled objects were, in the case of the dwellings, very simplified models of real houses. More detailed models are needed (a compromise has to be found between realism and performance) and they have to be completed by informative conventional media (texts, pictures, etc.). During the science festival, no other content or explanation was provided with it. Thus, the presence of an archaeologist was needed to provide relevant information to the public. As it was, the application was more of a technological demonstration than a complete, standalone educational product. This was also the case for the Oculus Rift VR simulation, which has not been widely tested yet. We also have to remember that these kinds of human/computer interaction systems are still nascent. The ease of implementation of these tools is getting better every day, and we are convinced that they will have a huge impact on scientific mediation. Improving the quality of the simulations by adding more realistic textures and interactive characters is also becoming easier thanks to more powerful hardware. A realistic soundscape can also hugely enhance the virtual simulations (Pardoen 2015). Finally, the development of APIs (i.e. WebGL), allows content as rich as this to be hosted online.

The integration of 3D within the archaeological research process can also bring benefits: better understanding of complex stratigraphy, testing and validating hypotheses, etc. One of the limits of our approach was the disappearance of all metadata when we transferred from GIS to 3D modelling software. A fully 3D GIS would solve this issue, but, at the moment, we could not find a single piece of software encompassing all the features we needed, despite this being a long running issue (De la Losa and Cervelle 1999). Geologic modelling software, on the other hand, does provide full capacity for 3D stratigraphic modelling, but it is harder to integrate with archaeological research workflow (Apel 2006).

Setting up this project took approximately 40 days (to which we must add the printing phase, an additional 5 days, but most of it being purely machine time). Considering that this was a first experiment, we advanced a lot by trial and error. The process has since been established, tested and validated, and even if further refinements are needed, we could now probably reduce this time by a considerable amount. We also must not forget that the scale model can be reused for further exhibitions, and that the digital media can be improved, thus increasing their value.

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Bibliography

Apel, M. 2006. From 3D geomodelling systems towards 3d geoscience information systems: Data model, query functionality, and data management. *Computers & Geosciences 32*: 222–9.

Blaizot, F., Berard, F., Bonnet, C., Cecillon, C., Franc, O. 2010. *Archéologie d'un espace suburbain de Lyon à l'époque romaine. Paléogéographie de la plaine alluviale, axes de communication et occupation*, Gallia 67, 1: 1-157. Paris, CNRS.

Bouavrd, E., Ramona, J., Tronchere, H. 2015. *7ème avenue. Construction d'un immeuble de logements, 23, rue Marc Bloch 69007 Lyon, rapport de fouille d'archéologie préventive*. Service régional de l'archéologie, Direction régionale des affaires culturelles, Rhône-Alpes. Lyon.

Bravard, J.-P., Verot-Bourrely, A., Franc, O., Arlaud, C. 1997. Paléodynamique du site fluvial de Lyon depuis le Tardiglaciaire, in J.-P. Bravard and M. Prestreau (eds.), *Dynamique du paysage. Entretiens de géoarchéologie*. Actes de la table ronde de Lyon, 17-18 nov. 1995. Document d'Archéologie en Rhône-Alpes, Lyon) DARA 15, ALAPARA: 177-201.

Chaumier, S., Francoise, C. 2014. Museomix : l'invention d'un musée du XXIe siècle. *La Lettre de l'OCIM* 156: 7-11. [Online] http://www.museomix.org/ [Accessed 12 may 2015].

Chua, C. K., Leong, K. F., Lim, C. S. 2003. *Rapid prototyping – principles and application*. Singapore, World Scientific Publishing.

Combe, C. 2007. *La ville endormie ? Le risque d'inondation à Lyon*. Unpublished PhD thesis, University Lumière Lyon 2, Lyon.

De La Losa, A., Cervelle, B. 1999. Virtual reality & 3D GIS, 3D topological modelling and visualisation for 3D GIS, *Computers & Graphics* 23: 469-78.

Fantini, M., De Crescenzio, F., Persiani, F., Benazzi, S., Gruppioni, G. 2008. 3D restitution, restoration and prototyping of a medieval damaged skull. *Rapid Prototyping Journal* 14, 5: 318-24.

Faure-Boucharlat, E. 2001. *Vivre à la campagne au Moyen Age. L'habitat rural du Ve au XIIe s. (Bresse, Lyonnais, Dauphiné) d'après les données archéologiques*, DARA 21, ALAPARA, Lyon.

Gentili, F., Lefevre, A. 2009. *L'habitat rural du haut Moyen Age en Ile de France, 2ème supplément au Bulletin archéologique du Vexin français et du Val-d'Oise, PCR Bilan 2004-2006*. Collectif d'archéologie rurale du haut Moyen Age. Centre de recherches archéologiques du Vexin français, Guiry-en-Vexin.

Hull, C. W., *Apparatus for production of three-dimensional objects by stereolithography*. US patent n°US4575330 A.

Lewis, C. J., Mcdonald, E. V., Sancho, C., Pena, J. L., Rhodes, E. J. 2009. Climatic implications of correlated Upper Pleistocene glacial and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy. *Global and Planetary Change* 67: 141-52.

Lispon, H., Kurman, M. 2014. *Fabricated: The new world of 3D printing*. Indianapolis, John Wiley & Sons.

Knabb, K. A., Schulze, J. P., Kuester, F. 2014. Scientific Visualization, 3D Immersive Virtual Reality Environments, and Archaeology in Jordan and the Near East. *Near Eastern Archaeology (NEA)* 77, 3: 228-32.

Mace, S., Verot-Bourrely, A., Bravard, J.-P. 1993. Genèse et fonctionnement holocène de la plaine alluviale du Rhône à Lyon. in *Archéologie et environnement des milieux aquatiques : lacs, fleuves et tourbières du domaine alpin et de sa périphérie*. Actes du 116e colloque du congrès national des sociétés savantes, Chambéry, 29 avril - 4 mai 1991. Paris, éd. Du CTHS.

McLellan, C. 2014. The history of 3D printing: a timeline. http://www.zdnet.com/article/the-history-of-3d-printing-a-timeline/ [Accessed: 12 may 2015].

Pardoen, M. 2015. Les oreilles à l'affût! Restitution d'un paysage sonore : œuvre de l'imaginaire ou recherche d'authenticité ? In J. Aubrun, C. Bruant, L. Kendrick, C. Lavandier, N. Simonnot (eds.). *Silences et bruits du Moyen* Âge *à nos jours : Perceptions, identités sonores et patrimonialisation*. L'Harmattan.

Schelly, C., Anzalone, G., Wijnen, B., Pearce, J. M. 2015. Open-source 3-D printing Technologies for education: Bringing Additive Manufacturing to the Classroom. *Journal of Visual Languages & Computing* 28: 226-37.

Spiegelmock, M. 2013. *Leap Motion Development Essentials*. Birmingham, Packt Publishing Ltd.

Wohlers, T. 2013. *Additive manufacturing and 3D printing State of the industry*. Fort Collins, Wohlers Associates.

Teaching Digital Archaeology Digitally

Ronald Visser
r.m.visser@saxion.nl

Wilko van Zijverden
w.k.vanzijverden@saxion.nl

Pim Alders
p.g.alders@saxion.nl

University of Applied Sciences, School of Business, Building & Technology, Archaeology, Deventer

Abstract: In this paper we discuss teaching digital archaeology at Saxion University of Applied Sciences. The broader archaeological curriculum is introduced and the didactic concepts are explained. The main difference with other courses is that it is based on demand rather than the accidental presence of researchers at the faculty. In addition to this the curriculum is always evaluated and updated. We focus on a practical approach that not only consists of teaching the necessary knowledge and tools, but also the expected application and integration thereof in other courses. This leads to a high overall proportion of digital archaeology. When teaching digital archaeology digitally several tools are used to overcome the dichotomy between the digital native and the digital immigrant. The integration of knowledge, skills and attitude, results in an education that produces young professionals.

Keywords: Didactic methods, Digital Archaeology, Higher Education, Netherlands

Introduction

New legislation, theoretical frameworks and the development of computer hard- and software have changed archaeological practices in the Netherlands considerably during the last decades. Influenced by New Archaeology computer technology became a common tool for the archaeologist from the seventies onwards (van der Leeuw and Voorrips 1980). Computer applications like GIS were introduced and mainly used for analytical purposes, although fieldcomputers were already used in the early eighties (Kamermans and Voorrips 1986). During the late eighties modern geodetic equipment like tachymeters were introduced in the field and the first experiments with devices such as Psions were carried out. In the nineties small hand held computers and GPS-systems were introduced in the field. After the turn of the century field computers and laser scanning systems were introduced into fieldwork. Nowadays archaeologists are rarely drawing on paper with pencil and ruler in Dutch archaeology and publication of an excavation report follows usually within two years after the actual excavation.

The development of computerizing in Dutch archaeology was accelerated by the acceptance of the Valletta treaty. In 1992 the Valetta treaty was signed, which led to a considerable increase of the amount of archaeological work (Eickhoff 2005). Although it should be noted that working under the concept of the treaty started already in the beginning of the 21st century, it was not until 2007 before the treaty was implemented in Dutch law (Willems 2008). These combined changes in policy and legislation have resulted in more development-led excavations (Bazelmans 2012) and therefore an increasing number of excavations carried out by various companies (van Londen *et al*. 2014).The large number of archaeological field research and the high costs asked for more efficiency in the fieldwork and analysis afterwards. This stimulated the computerizing of archaeological work in the field and after the fieldwork during the analysis.

The need for well-trained in field archaeologists led to the start of a new course in field archaeology in 2006. BAAC, one of the larger Dutch archaeological companies, and Saxion University of Applied Sciences joined hands to start a new four-year Bachelor course in practical archaeology in Deventer. The duration of a Bachelor course at Dutch universities of applied sciences is traditionally four years, whereas the other universities have a three-year Bachelor course. The course at Saxion has developed and matured into a stable curriculum (see below) over the years. The main focus of the course is practical archaeology, ranging from excavation and survey to IT-applications and material culture. Practical skills form the basis, without neglecting the necessary theoretical and historical background.

In this paper we will address teaching digital archaeology within our course. Therefore the curriculum is discussed shortly first with special attention to digital knowledge and skills. The didactic concepts are shortly discussed with special attention to teaching digital archaeology digitally.

1 Curriculum and digital archaeology

Whereas education in most archaeological courses in the Netherlands is more or less research-led, the curriculum at Saxion is largely based on demand from the archaeological community. This demand is always evaluated by staff, students, advisory board (its members are working in various archaeological organisations, both public and commercial) and management. This leads to a stable and actual curriculum educating Bachelor archaeologists who have skills and knowledge needed by archaeological organisations. The demand-led development of the curriculum leads to a curriculum that is not dependent on researchers working at the university on occasional bursaries or within occasional research programs. At Saxion University the teachers are selected on skills that are determined by the curriculum and

Fig. 1. The didactic pyramid (after Miller 1990).

trained in didactic skills at the Saxion Academy, the didactical training centre of Saxion University.

The Miller's didactic pyramid (Fig. 1) is used as a model for the development of students during their education. The foundation is knowledge, the *knows*-level. The knowledge of a student can be applied for example to solve a problem (*knows how*). When a student can show how he/she can act in a simulated environment the *shows how* level is attained. The top of the pyramid is formed by *does*. When this level is reached a student is able to apply all knowledge and skills with the necessary attitude in complex situations of the real world (Miller 1990). The combination of both practical and theoretical aspects within the course ascertains that the learning cycle (Kolb 1984) can always be followed completely.

The curriculum includes several larger bodies of subjects taught during the first three years of the course (Fig. 2). The fourth year is dedicated to the Bachelor-thesis and a minor. During the first three years the focus lies on knowledge and practical skills (*knows*/*knows how*). Different courses include material culture and the cultural developments of all archaeological periods, starting with the Palaeolithic in the first year and ending with the most recent periods in the third year. Various courses deal with practical measuring and documenting in the field. Since research is an integral part of archaeological work, research skills are taught and tested in various courses. Written and oral communication is an important part of education, not only in Dutch, but English and German languages are also taught. All knowledge and skills have to be combined in integrative assignments and internships (*shows how*/*does*), since practical application is the best way to pertain knowledge and skills (Dale 1946; Kolb 1984). To give our students enough IT-knowledge we incorporated various digital courses in the curriculum. In addition to this we expect our students to apply the digital knowledge and skills they gained in other courses. By applying the technological knowledge and skills in other courses the knowledge is pertained and the learning cycle (Kolb 1984) will be fulfilled.

The digital curriculum is the same during the first two years. During this period they learn to work with various software for databases, spreadsheets, GIS, CAD, DTP. Some attention is given to basic descriptive statistics during these first two years. The choice of software and tools is based on those most commonly in use by archaeological companies and institutes. However, developments in the field, both nationally and internationally, are followed closely and when it is expected that something will become common we try to anticipate by reviewing and updating our choices within the curriculum. At the moment the following software is taught: Access, Excel, ArcheoLINK (www.archeolink.org), ODILE (www.raap.nl), AutoCAD, ArcGIS, MapInfo, Photoshop, Illustrator and InDesign. We expect that either ArcGIS and/or MapInfo will be replaced by QGIS as the most common GIS-software in the near future and encourage our students to explore this package as well. The archaeological finds and sites database Archis (Roorda & Wiemer 1992) (https://archis.cultureelerfgoed.nl/) is also part of the education. Next to these software packages our students are taught to work with digital tools such as a (robotic) Total Station. The practical application of these skills and knowledge is expected in the Fieldschool, where the first year students have to fill in databases and georeference and digitize their analogue field drawings. During their internship in the second year many students have to apply their skills practically, attaining the *does* level. Furthermore, during various integrating courses we expect our students to apply what they have learned at the *shows how* level. For example first year students have to provide GIS-maps that at least meet the Dutch Archaeology Quality Standard (Willems and Brandt 2004; http://www.sikb.nl/richtlijnen_detail.aspx?id=11934&tag) during the field school and the course Desktop-study.

The proportion of digital courses during the first two years is summarized in Fig. 3 based on the distribution of ECTS (European Credit Transfer System - European Commission 2009). During these two years 120 ECTS can be obtained and 21 ECTS are devoted to the teaching of digital knowledge and skills. In another 21 we expect our students to apply this. As mentioned before we also expect that they use these skills during the field school and internship, although with the latter it depends on the company or institute where they are working. The graph shows that nearly half of the ECTS in the first two years are (at least partly) devoted to digital aspects of archaeological research.

In the third year the students can specialise into three directions: *Digital Archaeology*, *Field Archaeology* and *Material Culture & Conservation*. Next academic year we will add a new specialisation: *Cultural Heritage management & Communication*. The proportion of digital archaeology depends on the specialisation, but all specialisations include a final course on digital skills. In this course they have to integrally apply all digital knowledge, for example by digitizing an old excavation and building a database that has to be linked to the field drawings. This combines archaeological skills, digital skills and insight. The students who have chosen the specialisation *Material Culture & Conservation* learn to draw and photograph objects. The drawings and images are also digitally produced, edited and/or enhanced to publication standards. Within the specialisation *Cultural Heritage management & Communication* students are expected to create policy maps and apply digital ways to communicate to the wider public. *Digital Archaeology* and *Field Archaeology* share a course on remote sensing, photogrammetry and geophysical methods, including its application in the field. For the field

<table>
<tr><td rowspan="4">Knowledge & practical skills</td><td>Material culture/cultural developments</td><td rowspan="6">Digital skills and knowledge</td></tr>
<tr><td>Fieldwork: documentation, registration & measuring</td></tr>
<tr><td>Research</td></tr>
<tr><td>Communication</td></tr>
<tr><td rowspan="2">Integration and practical application</td><td>Combining all knowledge/skills</td></tr>
<tr><td>Internship</td></tr>
<tr><td colspan="3">Personal development</td></tr>
</table>

FIG. 2. CURRICULUM PLAN OF THE ARCHAEOLOGY COURSE AT SAXION UNIVERSITY OF APPLIED SCIENCES.

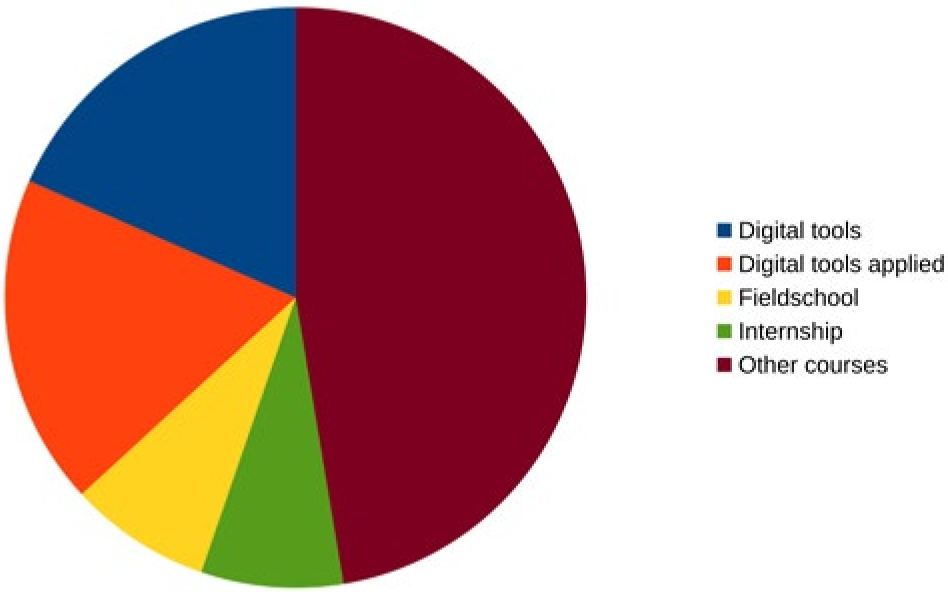


FIG. 3. PROPORTION ECTS OF DIGITAL COURSES DURING THE FIRST TWO YEARS OF THE BACHELOR COURSE AT SAXION UNIVERSITY OF APPLIED SCIENCES.

archaeologists this is followed by a more practical application of these tools. In the *Digital Archaeology* specialisation the students learn all aspects of working with digital data, starting with acquisition, analysis, diffusion and archiving. For this purpose we teach them about the basics of programming, statistics, spatial analysis, spatial databases, 3D modelling, 3D analysis, archiving and sharing guidelines such as INSPIRE (inspire.ed.europe.eu), and communicating research results to a wider audience.

The proportion of digital archaeology in the fourth year depends on choices the students make. During this year they do their minor for 30 ECTS and their bachelor research assignment (also 30 ECTS). For their minor they can chose from a wide range of minors both within Saxion University and on other universities (www.kiesopmaat.nl). The final research project is always an assignment by an archaeological organisation. The subjects vary from studying material culture (Roeke 2015; Schoute 2015), analysing a small excavation (Kuijpers 2014; Koster 2011), creating a digital tool for comparing house plans (Duistermaat 2015) and analysing Egyptian frescos digitally (Franken 2015). Since nearly all students use at least some digital tools during their final research or in their minor, the amount of digital archaeology can be estimated to range between 20% to nearly 80% of the final year.

To summarize, it can be stated that all students who study archaeology at Saxion University should be able to apply the most commonly used digital tools and have some understanding of the concepts of databases, GIS and statistics. They are well equipped to participate in most aspects of the archaeological research.

2 Teaching digital natives?

One of the challenges of teaching digital archaeology can be explained by the concept of the digital native versus the digital immigrant, a concept coined over a decade ago (Prensky

2001). It has been argued that the generation of people born between 1980-1994 have lived in a world that is immersed with technology and are therefore digital natives. Furthermore, the teachers are often born before this period and were raised in a world that *became* immersed with technology (Prensky 2001).This model has been used to claim that education should be adapted to students being digital natives, but research has shown that that claim might be too strong (Bennett *et al*. 2008). The attribution of people to either one of these groups is also open for discussion, because digital tools are not used by all people with the same intensity. One could even argue that digital natives are born nowadays after the wide scale adoption of smartphones. Nevertheless, the model is interesting to explain problems with teaching digitally. Most students are raised in a world where digital tools are common, nearly all students have a smartphone, most of them a laptop and many a tablet. The current generation of students is therefore even more immersed in technology than before. This generally leads to natives who expect software to work just as it is, without a deeper understanding of the how or why. People who immigrated, on the other hand, have learned to work with digital tools by understanding more intricately what happens on a computer. A zip-file for example is for most immigrants a compressed (collection of) file(s), while a native considers it a folder, because that is how Microsoft Windows deals with it. This leads to some kind of misunderstanding when a program doesn't see the files in the zip-file when students try to open it from within a program. The largest difference between the native and the immigrant is therefore the intuitive use versus the intricate understanding. This means that the students have to start understanding what happens and the teacher has to adapt to the level of the student. This poses a challenge for both parties.

Most students experience digital courses as tough. This might be due to the digital native-immigrant dichotomy. Digital natives are used to learning to work with something intuitively, whereas GIS or databases also involve a deeper understanding of the process. It often takes a lot of effort for students to grasp the concepts of these tools, although applying the program often goes very well. Generally, after hard working and a lot of practice, the grades are good. Interestingly, because digital archaeology is such a normal part of the curriculum, the students often forget that the level they attain is one that various older archaeologists have never reached. It is not surprising that our students are often praised for their knowledge of digital archaeology.

3 Teaching digitally

Teaching digital archaeology digitally poses several didactic challenges. The teacher has to overcome the digital native-immigrant dichotomy. As mentioned before, most students experience difficulties learning software, which sometimes leads to the formation of a myth within the student community when students start telling to each other how hard it is. To help teaching and activate the students several tools are available. A choice of these tools will be discussed below. Most tools are easy to use and benefit both teacher and student. Furthermore, the use of various tools is often intuitive, helping both the digital native and the immigrant.

The most commonly used tool is the digital learning platform that we use: Blackboard (http://www.blackboard.com; https://leren.saxion.nl). This digital environment works very well for the communication between student and teacher, in all directions. Information is given by sharing slides from lectures, assignments, literature and other information by the teachers on Blackboard. Students can upload their assignments and teachers can grade either online or offline. This speeds up the process for both parties, although it must be stated that the current version is not very suitable for use on mobile devices.

Another very useful digital tool for teaching is Socrative (http://www.socrative.com). This free online tool can be used for asking the students questions. The students answer either on their smartphone, laptop, computer or tablet. The results can be made visible instantly via a projector, providing the students with instant feedback. We have used it quite successfully during lectures. After about 15 minutes of explaining the students are asked a couple of multiple-choice questions related to the lectures. Questions that many students answer wrongly often concern subjects that are not fully understood. These can be explained again by the teacher. This tool enables therefore both teacher and student to get a better insight in the learning process.

We have also started to use a RPAS (Remotely Piloted Aircraft System) as a teaching tool, although its application in the Netherlands is somewhat hindered by all the legal obligations. The application of our RPAS will give our students a chance to work within the whole process, although flying is legally speaking only allowed by trained and certified people. A RPAS mission starts with the preparation of a flight plan and a mission plan. Students should be able to write these plans when supervised. The technical check before flight should always be done by a trained person, but students can help out and learn the process of checking. The placement of Ground Control Points (GCP) can be performed by students. While a certified pilot is flying, students can, after training, help observing. Students can do a lot of things after the mission, depending on the kind of data that is acquired. At the moment we are working with a digital SLR-camera with a 50mm lens. Processing of the aerial images can done by students, for example by creating 3D models using SfM (Nex and Remondino 2013; Colomina and Molina 2014).The dissemination of the results to the public can also be done by students. The use of an RPAS integrated in the curriculum provides students with the necessary skills giving him/her an advantage as a young professional.

4 Conclusion

Since the education of young archaeologists lays the foundation of the future of the archaeological profession, we consider our students the future. Therefore the curriculum at Saxion is broad, includes many digital tools and is taught digitally. The curriculum is kept up to date by always keeping track of both international and national developments and trying to incorporate these. The application of digital tools is considered normal by our students. The digital courses are characterized by both active usage and understanding of the software. It is not important which software is taught, it is important that students know what they can do with for example a GIS or a database. We try to be aware of and overcome the dichotomy between digital natives and immigrants when teaching digital archaeology and have various digital tools at our disposal for this purpose.

Bibliography

Bazelmans, J. 2012. Serving two masters: Dutch archaeology since the Valletta Convention. In R. Bradley *et al*. (eds.), Development-Led Archaeology in North-West Europe: 9–21. Oxford, Oxbow Books.

Bennett, S., K. Maton, L. Kervin, 2008. The ‘digital natives’ debate: A critical review of the evidence. *British Journal of Educational Technology* 39, 5: 775–86.

Colomina, I., Molina, P. 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing* 92: 79–97.

Dale, E. 1946. Audio-Visual Methods in Teaching. New York, Dryden Press.

Duistermaat, R. J. 2015. *Huisplattegronden Als Digitale Referentiecollectie. Een Uitwerking van Midden-Bronstijd Huisplattegronden Uit Het Utrecht-Gelders Rivierengebied in Een Ontwerp van Een Algemene Digitale Referentiecollectie*. Unpublished Bachelor thesis, Saxion University of Applied Sciences, Deventer

Eickhoff, M. 2005. Van Het Land Naar de Markt. 20 Jaar RAAP En de Vermaatschappelijking van de Nederlandse Archeologie 1985-2005. Amsterdam, RAAP Archeologisch Adviesbureau B.V.

European Commission 2009. ECTS Users’ Guide. Brussels, Luxembourg: Office for Official Publications of the European Communities. [Accessed 25 may 2015]. Available at: http://ec.europa.eu/education/tools/docs/ects-guide_en.pdf

Franken, Y. 2015. Painted Amarna Floor Fragments. A Study of Batch No. 4079 in the Collection of the Allard Pierson Museum, Amsterdam, the Netherlands. Unpublished Bachelor thesis, Saxion University of Applied Sciences, Deventer

Kamermans, H., Voorrips, A. 1986. Digging for data: the use of field computers at IPP excavations and surveys. *Pact, Journal of the European Study Group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology* 14: 109–14.

Kolb, D. A. 1984. Experiential Learning: Experience as the Source of Learning and Development. Financial Times/ Prentice Hall, New Jersey.

Koster, C. 2011. Wonen En Werken in Het Centrum van Prestedelijk Zutphen. Zutphen: Gemeente Zutphen, Sector Ruimte, afdeling BMA/Archeologie.

Kuijpers, C. 2014. *De Steenbouwindicatoren van Elst-Brienenshof*. Unpublished Bachelor thesis, Saxion University of Applied Sciences, Deventer.

Van Der Leeuw, S. E., Voorrips, A. 1980. Moderne ontwikkelingen in de archeologie. In M. Chamalaun and H. T. Waterbolk (eds.), *Voltooid Verleden Tijd? Een Hedendaagse Kijk Op de Prehistorie*: 213–28. Amsterdam, Intermediair.

Van Londen, H. *et al*. 2014. *Discovering the Archaeologists of the Netherlands 2012-14*. Amsterdam, Universiteit van Amsterdam.

Miller, G. E. 1990. The assessment of clinical skills/ competence/performance. *Academic medicine: journal of the Association of American Medical Colleges* 65, 9 suppl.: 63–7.

Nex, F., Remondino, F. 2013. UAV for 3D mapping applications: a review. *Applied Geomatics* 6,1: 1–15.

Prensky, M. 2001. Digital Natives, Digital Immigrants. Part 1. *On the horizon* 9, 5: 2–6.

Roeke, M. G. 2015. *Van Medicamenten Tot Hemelse Vloeistoffen. Een Onderzoek Naar Een Beerput van Een Dokter En Wijnkoopman Uit Deventer 18e-19e Eeuw.* Unpublished Bachelor thesis Saxion, University of Applied Sciences, Deventer.

Roorda, I., Wiemer, R. 1992. The ARCHIS project: towards a new national archaeological record in the Netherlands. In C. U. LARSEN (ed.), *Sites and Monuments: National Archaelogical Records*: 117-22. Copenhagen, National Museum of Denmark.

Schoute, N. 2015. *Soldaat Aan Boord. Een Scriptie over de Conservering En Restauratie van Twee 17de-Eeuwse Haardplaten*. Unpublished Bachelor thesis Saxion, University of Applied Sciences, Deventer

Willems, W. J. H. 2008. Archaeological resource management and preservation. In H. Kars and R. M. Van Heeringen (eds.), *Preserving Archaeological Remains in Situ. Proceedings of the 3rd Conference 7-9 December 2006, Amsterdam*: 283–289. Amsterdam.

Willems, W. J. H., Brandt, R. W. 2004. *Dutch Archaeology Quality Standard*, Den Haag, Rijksinspectie voor de Archeologie.

Websites

Blackboard 2015. http://www.blackboard.com [Accessed: 1th july 2015]

Saxion Blackboard 2015. https://leren.saxion.nl [Accessed: 1th july 2015]

Socrative 2015. http://www.socrative.com [Accessed: 1th july 2015]

Sikb 2015. http://www.sikb.nl/richtlijnen_detail.aspx?id=11934&tag [Accessed: 1th july 2015]

3D Archaeology Learning at the Paris 1 Pantheon Sorbonne University

François Djindjian
University of Paris 1 Pantheon Sorbonne & UMR 7041 Arscan

Abstract: The 3D Archaeology course including seminar and practical works, created in 2008, is now a part of the curriculum of Archaeology at the second level master in the Institute of Archaeology of the Paris 1 Pantheon Sorbonne University. The present paper aims to discuss the difficulties of creating a new course in a negative context and the technical problems for developing a hardware and software platform of virtual reality and digital photogrammetry for the practical works and student projects. At the opposite, it must be pointed out the enthusiasm of the French specialists of the 3D archaeology to participate to the course and the motivation of the students which is the reason of the creation of a student association for the promotion of 3D archaeology. Actually, the course of 3D archaeology is chosen by 25% of the students of Master 2, while the course of GIS is chosen by 70% of students.

Keywords: 3D Archaeology learning, Pantheon Sorbonne University, Paris 1

Introduction

The curriculum of Archaeology in the University of Paris 1 Pantheon Sorbonne has been very updated between 1980 and 2000, with the creation of a chair of 'Archaeological Methods and Theory', and the development of numerous courses of computing archaeology, embedded in the learning of archaeological methods. The present paper shows the difficulties of creating the last new course of 3D archaeology and how they have been overcome, revealing nevertheless an increasing ditch between professional archaeology and academic archaeology, which probably exists not only in France.

1 The Computing Archaeology curriculum in the University of Paris 1 Pantheon Sorbonne

Since 1995, the 'Computing Archaeology' curriculum in the University of Paris 1 Pantheon Sorbonne (UFR 03; Institute of Art and Archaeology) is under the responsibility of the chair of 'Archaeological methods and Theory', as it is considered to provide the conceptual and practical tools for the formalization of archaeological approaches and the applications of archaeological methods.

For the first two degrees of the University according to the European Bologna terminology adopted in France in 2002 ('License' Year 1 and Year 2, equivalent to the US first bachelor's degrees), the curriculum, common to archaeology and history of art, is limited to a general course of archaeological methods and a general training on basic software tools (word processing, spreadsheet, presentation, Internet, use of data retrieval systems, etc.).

The third degree ('License' Year 3) is then a curriculum totally dedicated to Archaeology. Two fundamental courses are compulsory for all students (two hours per week during a semester for each): '*Archaeological Methods and Theory*' and '*Archaeometry*', and a practical works of computing archaeology (2 hours per week during the first semester) is dedicated to applications of statistics and database in archaeology.

2 Archaeology Master, Year 1

For year 1 of the Master's (equivalent to the US Graduate or Master cursus), the students have then to choose one among three specialties: Prehistory and Protohistory (1), Archaeology of Historical periods (2) and Archaeology and Environment (3), but they share the same common curriculum for the courses of Archaeological Methods and Theory.

A general course of Computing Archaeology (2 hours/week during the first semester), compulsory for all students, is the main course. The course is completed by practical works of Computing Archaeology (2 hours/week during the first semester), limited to 22 students (organized in four groups) in the archaeological computer center. The content is Quantitative Archaeology: statistics including an introduction to multidimensional data analysis, databases and an introduction to G.I.S.

3 Archaeology Master, Year 2

For year 2 of the Master's, four specialized practical works (a training of 5 full days over a month and an individual project) are proposed to the students who have the obligation to follow at least one course among 4 ones :

- Multidimensional Data Analysis,
- Geographic Information Systems in Archaeology (GIS),
- Archaeological data recording (including Harris matrix processing),
- 3D Archaeology

But the students of the specializations called Master 2 Pro (for those having chosen to work in Rescue Archaeology or in Archaeological Heritage Management) and Master 2 Environment have the obligation to follow the four practical works. All the courses are developed in a manual of Archaeology (Djindjian, 2011) dedicated for students of Archaeology from License until PHD.

4 The 3D Archaeology course project

The decision to develop a curriculum in Virtual Archaeology and 3D Archaeology has been taken early from 2000. But, at that time, very few students were really interested for such knowledge, and it has been decided to give to those pioneers an individual support. The agreements signed between the University of Paris 1 and many worldwide universities have been useful for that, offering exceptionally a six-month experience in VR in another university. An example of such cooperation was the Virtual Reality project directed by Brown University (Providence, USA) on the site of Petra (Jordan), which has integrated two Master 2 students.

From 2005, the progress of the 3D technology had persuaded us it could be a real revolution for the archaeological methods. The decision was then taken to create a 3D archaeology course in our University.

But it has been necessary to overcome some difficulties due to critics against the project:

- Why again a new course of methods?
- There are already too many methods in the curriculum of Archaeology!
- We have too few students (80 in Master 1 and the same in Master 2) for too many courses.

It was evident that the decreasing number of students in Archaeology since ten years in the universities of Human Sciences in Paris (Paris 1, Paris 4, Paris 10), while their number is increasing in legal studies and in economics, create some stress, especially when the university decides to close the courses with less than 5 students. More than ten Master courses in Archaeology were concerned. At the opposite, the Master 2 practical works of Computing Archaeology were so successful; for example the GIS courses interest 60 students over 80, that they obliges to organize three sessions of 20 students.

Of course, it was possible to solve partially the question in increasing the number of compulsory courses in Master 2 (as it was already the case for the Master Pro and the Master Environment). But it was not in the tradition of the archaeological curriculum regrouping the 13 chairs (from Prehistory to Middle Age via classical archaeology), which want to have courses mainly focusing to their specialty. In addition, there is no written examination in the two years of Master (paradoxically numerous written exams are the general case in Master 2 of Physics or Mathematics or Geophysics or Medicine of Faculties of Sciences) while there is a project to achieve for a note in the courses of computing archaeology.

The context is then not really in favor of an evolution of the curriculum adapted to the progress and changes of Archaeology. Such a context is, at the opposite, very conservative and even oriented to continue to create new chairs, reducing de facto the average number of students by chair (actually less than 5), the two last being Archaeology of Oceania and Archaeology of Arctic societies. The major risk is to weaken the curriculum of methodology, because the lecturers who have not enough courses (and students) are obliged to give methodological courses for which they have neither the ability nor the motivation to be successful in place of lecturers specialized in methodology and computing archaeology, even if they have another specialization in archaeology.

5 An example of difficulties of relationships between Parisian universities

This chapter is more anecdotic than of worldwide value. After a final reading, we have hesitated to keep or cancel it. Several colleagues who have read it, finally have considered it was interesting also for colleagues from other countries who have also other (if not the same) local difficulties to overcome.

When I was student in archaeology in the early seventies, I cannot imagine not being able to follow courses as an auditor in other Universities of Paris. And I do that, receiving a positive attitude of my professors. The relations are now more strained between universities and it is unwelcome today for a student to choose a curriculum ‘à la carte’ and not the menu of its university, if he is expecting to be supported to obtain a PHD bursary.

Moreover, in Archaeology, the relations between the University of Paris 1 Pantheon Sorbonne and the University of Paris 4 Sorbonne have always been struggling, as a result of the dismemberment of the University of Paris into 13 universities in 1970, after the 1968 crisis, for this concerns at that time on a political basis, Paris 1 being political left and ‘progressive’ while Paris 4 was politically right and ‘conservative’. But for Archaeology and History of Art, they were obliged to share the same building, the ‘Institute of Art and Archaeology’, with separate floors (floors 1 and 3 for Paris 1; floors 2 and 4 for Paris 4) and common floors (ground floor and the library). Such ‘*Kommunalka*’ has for example prevented the CAA 2014 Paris to be held in the Michelet building, forced to be located in the Pantheon building, owning to Paris 1 University.

It is the reason why the use of a plate of the bronze model of the antic Roma for a practical works of laser scanner 3D acquisition has created big problems. The model of the antic Roma was realized in 1911 by the French architect Paul Bigot (1870-1942) who also constructs the building of the Institute of Art and Archaeology of rue Michelet (1925-28) sponsored by the marquise Arconati-Visconti, for receiving the gift of the famous library of Art and Archaeology of Jacques Doucet, and the antic Roma bronze. The original plaster was given to the University of Caen where it is wonderfully exposed and where a scientific team is working on with 3D techniques (Fleury and Madeleine 2011). A plaster color copy was given to the Museum of Art and History in Brussels. The unfinished bronze model, initially exposed on the fourth floor of the Michelet building is ‘stored’ since the seventies in the boiler room of the Michelet building, where we have discovered it (what is not surprising for archaeologists!).

6 The 3D archaeology course

In the initial version, there were five main courses. The practical works of Virtual reality were provided by the very best VR laboratory of «*Ecole Nationale des Mines de Paris*», an Engineering High School, located 500 meters from the Michelet center, which friendly has accepted to make the experience with us, thanks to professor Philippe Fuchs, head of the chair of ‘*Robotic and Virtual Reality*’ of the Mines Paristech school. But the VR practical works were mixing both students in engineering and students in Archaeology and were given at a level of engineering courses, too difficult for most of our students! At the opposite, the practical works of 3D recording, learning the use of a scanner laser 3D (nicely lent by Faro), which were organized by Quentin Borderie, a PHD student, had the good level of difficulties for our students.

In the second version of the course, we try to develop the archaeological content, postponing the difficult software and technical training to PHD time, distinguishing students interested to use 3D archaeology from students motivated to become specialist of 3D archaeology.

The seven main courses of the second version were focusing on VR and 3D photogrammetry:

1. Virtual reality in archaeology. A general introduction,
2. Augmented Virtual Reality (AR) in archaeology,
3. Virtual training in archaeology,
4. Virtual museums in archaeology,
5. Virtual reality in archaeology: actors and projects,
6. Digital photography in archaeology,
7. Digital photogrammetry in archaeology.

But a large place was also attributed to invited lecturers, all French specialists of VR and 3D: Robert Vergnieux (VR) from University of Bordeaux III (Ausonius); Philippe Fleury and Sophie Madeleine (Roma VR) from University of Caen; Yves Egels (digital photogrammetry) from ENSG (Ecole Nationale des Sciences Géographiques); Christian Père (Ecole Nationale Supérieure des Arts et métiers, Cluny). Their lectures were particularly useful as they delivered a real practice and a large return of experience.

The practical works were mainly dedicated to the training of 3D photogrammetry. The 3D digital photogrammetry has made recently its digital revolution, developing new efficient algorithms for 3D reconstitution from a digital photography record, easier to do. We have considered such technique as more suitable for archaeological 3D recording than scanner laser 3D technology, which is well adapted to heritage reconstitution. The students have to develop a project of 3D photogrammetry, using easy to use software like 123Dcatch, Agisoft Photoscan and others. The practical works of 3D recording with the use of scanner laser 3D were continued.

7 PHD support for students who want to specialize in 3D Archaeology

For students who want to specialize in 3D archaeology, the Master 2 courses are only a preliminary training that needs complement on 'how to do'. Then, a PHD support has been organized on an 'à la carte' base:

- Support to inscription to specialized practical works outside France,
- Long training course in French research VR laboratory (Bordeaux, Caen),
- Long training course in private VR company,
- Creation of a 3D student archaeological association,
- Opportunity to make a PHD specialized in 3D archaeology in our University.

The opportunity to get a job in 3D archaeology is a very new matter, yet unpredictable. In France, the archaeological institutions (CNRS) will certainly recruit ITA (technicians) in a next future as they have done for GIS needs in the last ten years. It is unfortunately an unsuccessful solution because ITA people are computing 'small hands' for archaeological searchers, and in such non-evolutionary context, they are losing rapidly motivation and technical competence. INRAP (the French Rescue Archaeological quite-monopolistic institution) will probably recruit also its specialist as it has been done for GIS. But the recruitment of a person is not a strategy, and sometimes marks only the will of no strategy at all. Small private specialized company could develop on such activity, but their ability to recruit numerous people is limited. The most interesting place for recruitment is the Heritage management, at different levels: urban, department, region, asking for VR and 3D photogrammetry in a service where the GIS specialist is already there.

8 Conclusions: Return on experience

The weakness of technical background of students in archaeology, which is a strong limitation to the development of computing archaeology, may be bypassed:

- by using most easy to use 3D tools, progressively themselves easier to use,
- by continuing a more technical training after the Master 2 year.

But a revolution is probably necessary for creating a modern Archaeology by the creation of an archaeological curriculum out of the tradition of 'Archaeology and History of Art' and based more on the archaeological profession than on the archaeological erudition.

Bibliography

Djindjian, F. 2011. *Manuel d'Archéologie*, Paris, Armand Colin, collection U.

Madeleine, S., Fleury, P. 2011. Le « Plan de Rome » de Paul Bigot à l'Université de Caen et son double virtuel : de l'objet patrimonial à l'outil scientifique ». *In Situ, revue des patrimoines*, 2011, 17.

How to Teach GIS to Archaeologists

Krzysztof Misiewicz[(1)], Wiesław Małkowski[(1)], Miron Bogacki[(1)],
Urszula Zawadzka-Pawlewska[(2)], Julia M. Chyla[(3)]
[1] Institute of Archaeology, University of Warsaw;
[2] College of Inter-Faculty Individual Studies in Mathematics and Natural Sciences, University of Warsaw;
[3] Antiquity of Southeastern Europe Research Centre, University of Warsaw

Abstract: At the University of Warsaw, 'GIS for archaeologists' classes have been provided since 2008. We would like to share our program, created on the basis of pedagogical principles for higher education. Also we would like to show our experience in connecting GIS theory, methodology and work in the office with archaeological field survey. We explain to the students how to prepare themselves for such research, how to proceed and collect data in the field and digitize results of their work. Part of the program is to explain and perform statistical analysis and present it as proper, cartographic and digital maps.

We would like to highlight problems connected with preparing exercises for different levels of students, with and without theoretical knowledge. Also we would like to point out problems connected to data copyrights that might occur just as well as problems of obtaining data form national sources.

Keywords: GIS, Didactics, Theory, Practice, Field survey

Introduction

'GIS for archaeologist' classes in the Institute of Archaeology of the University of Warsaw have existed for five years. Until the academic year 2014/2015, they were presented in the form of lectures followed by exercises. This year we had to change the program because of the need of applying the same exercises for BA students who didn't have the theoretical background of the lectures. During the past years we created a program, tailored to the needs of archaeology students. We connected theoretical and methodological classes with exercises and field surveys on the grounds of the pedagogical principles of higher education. Our main goal is to connect GIS theory, methodology and work in the office with the practical knowledge of archaeological field surveys.

Theoretical classes are both for bachelor and master students (for 30 hours per semester which means one class for 1.5 hours a week), during the second semester.[1] Practical exercises in computer laboratory for bachelors are done during the first semester for 30 hours (once a week 1.5 hours). This means that BA students receive a practical type of knowledge first and straight after this, a theoretical one. Master students have their exercises during the second semester for the same amount of time. The field survey practices, which most of the time are part of the conservation program of the 'Polish National Record of Archeological Sites', take place during autumn and spring. Also students are ought to be part of excavations during their summer practice.

1 Didactics: theory

The theoretical classes use general pedagogical methods like 'exposition', 'lecture' and the 'description of examples' (tab.1) (see Groźlińska 1997, Szlosek 1995).[2] The goal of classes is to provide students with basic geographical and GIS terms and definitions. Also students are taught methods of how to create and collect data and they are introduced to basic literature.

Theoretical lectures are conducted, as it is mentioned at the beginning, in the summer semester. We can therefore assume that students at this time have the basic knowledge about the software and GIS systems' theory acquired in the winter semester. So we designed lectures mainly to present the problems that may arise during the practical application of spatial information systems. At the beginning we present information about the maps and geographical coordinate systems used in Poland and try to explain how to use and integrate the data mapped in different systems. Next, we discuss the ways of using data in GIS systems obtained by aerial archeological surveys and as the result of satellite image analysis. Then we present the issues related to different ways of collecting, processing and integrating data into the GIS data from photogrammetric and topographic measurements. This process is emphasizing the development of different types of digital terrain models including models for land cover and digital elevation models. Finally, we present the equipment used for field surveys. The results of surveys done by students can be used to create databases and to map their projects in GIS. We discuss mainly various types of geodetic equipment (also based on GPS technology), but also devices for geophysical prospecting and facilities for terrestrial and air born laser scanning. The knowledge acquired by the students is verified in practice during the summer fieldwork, which is an integral part of the classes.

2 Didactics: practice

The goal of exercises in the computer laboratory is the practical use of commercial and open source programs. Our classes are split into inter-site and intra-site foci. This gives the opportunity to introduce students to two different approaches and to allow

[1] In Poland we have two semesters: winter (from October till February) and summer (from March till June).

[2] All didactic methods are based on methods proposed by polish theoreticians of pedagogy: K.Sośnicki, Cz. Kupisiewicz, B. Nawroczyński, Z. Wiatrowski, K. Kruszewski, J. Zborowski, W. Okoń, T. Nowacki, F. Szlosek (see W.M. Francuz 1995).

TAB. 1. PEDAGOGICAL METHODS USED DURING DIFFERENT TYPES OF CLASSES IN THE 'GIS FOR ARCHAEOLOGIST' COURSES (SEE GROŹLIŃSKA 1997; SZLOSEK 1995).

Type of classes	**Pedagogical methods**
Theoretical	• exposition • lecture • description of examples

Practical (computer-based)	• Clear rules from the beginning
	• Giving:
	  ○ lectures with visual learning
	• Problems:
	  ○ Casual talk on problematic topics
	  ○ Activating:
	    ▪ snow ball, brain storm, different types of discussion etc.
	    ▪ simulations
	• Exposing
	  ○ Demonstrating

Practical (field based)	• Exercise
	  ○ organizational and preparatory actions
	  ○ preliminary instruction
	  ○ instruction while proceeding
	  ○ final instructions and conclusions
	• Exposing
	  ○ demonstrating
	  ○ crash course
	• Projects method
	  ○ research problem

them to work on different data sets. Our sources of data are mostly of archival ones, so it is also necessary to stress how important it is to prepare an analogue field documentation - that it will contain all information needed later in a process of digitalization and vectorization. With the use of data that students prepare by themselves (including the field data) we teach them statistical analysis (with the basic introduction to statistics). After a short introduction into cartography, students can create maps as well as do basic statistical analysis.

We start our classes with introducing clear rules for passing the class, this is one of the main regulations of teaching - students have to know what is expected from them and what they receive in return (see Okoń 1992). They are ought to prepare several homework for which they receive points. At the end of the course they should prepare their own projects and present them. This work is receives a description and points. Students are informed about errors and ways how to correct them. Additionally, because of the increasing level of difficulty of exercises from week to week, they are ought to be on most of the classes. At the end, we calculate the average from the received points and transform them to a final mark.

Because bachelor students during their first semester do not have theoretical lectures, we are giving them classes with the method 'visible learning' – a short seminar about the topic of the exercise is presented. We try to make all our topics 'problem based', which are presented as a 'casual talk' about the applied method. Students are also encouraged by the use of simulations and stimulated with methods such as 'brainstorms' or 'snowballs' (see Groźlińska 1997; Szlosek 1995). For BA students we prepare lessons in an 'exposing way' - demonstrating a work flow, what they can follow. Furthermore students are expected to think themselves with the help of homework – making a description of the use of GIS on a site and a region, or writing a small grant application for the use of GIS in a research project.

The most important tool for the course is the syllabus (Fig.1). The self-study based tutorial is basically an instruction, organized in points for some easy tasks like: georeferencing, digitizing, DEM interpolation. The scripts are prepared before the classes by the lecturer. Tutorials are based on either Open source software (QGIS, GRASS, ILWIS, R) or on ArcGIS for which we have a student license. The syllabus is the same for the students of BA or MA courses, but the way of execution is not. Bachelors, as mentioned above, receive semi-lectures at the beginning of the classes. Also teachers complete tutorials with them. Master students are expected to follow the instructions by themselves and to finish the exercises at home if they did not manage them during the classes. Students are learning not only to push the buttons but also the mechanics of some procedures, additionally we are helping students to overcome the difficulties. The syllabus starts on a very easy

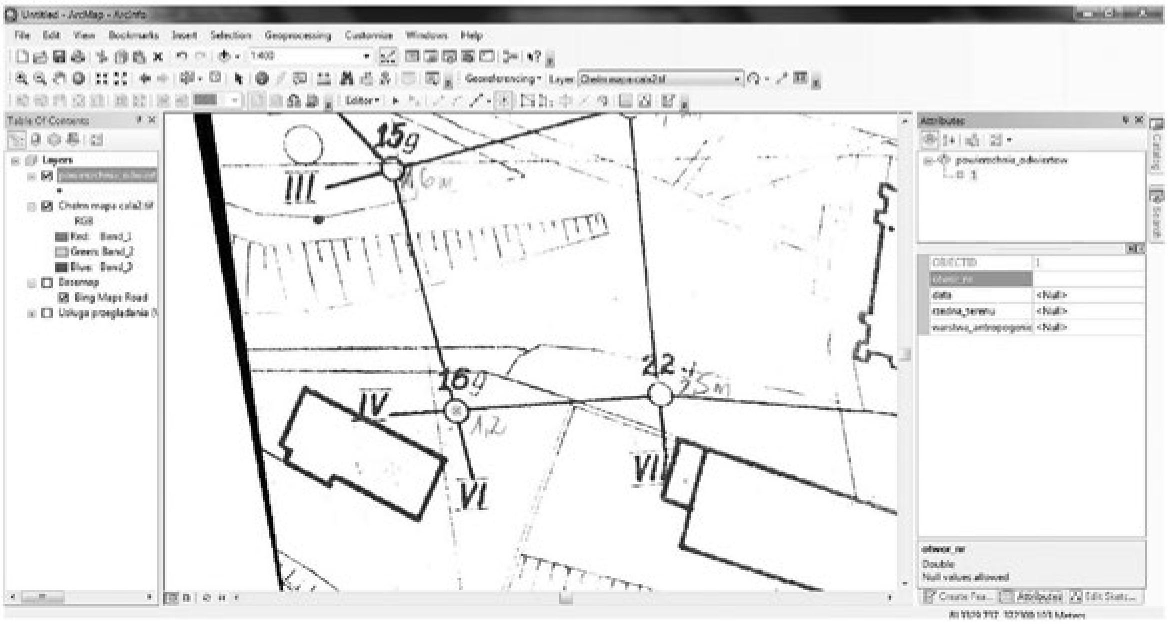
Creation of vectors and it's attributes - points

7. With the use of the *Add data* add created earlier file

8. In the strip choose *Editor*.

In further windows choose the file that you want to edit. In the next window, which just showed up, choose *Construction tools>Point*. At this moment you start to create points.

After clicking on the chosen spot the point will be "added" to preferred localization. Now you can add attributes. In the *Editor* choose *Attributes*. Here you can fill up information for created earlier attributes.



Create all the points with their attributes

Question: why you cannot create points in all localizations showed on the map?

9. There is possibility to add coordinate Z in the sketch. Turn on *Edit Sketch* option. Next choose point twice. In the sketch you will see only to coordinates X and Y. Z coordinate have to be write down manually. This is one of possible option of giving high value to the vectors.

10. To finish choose *Editor>Save edits,* and next *Stop editting.*

Fig. 1. Syllabus - a self-studying script for GIS classes.

level, it is very detailed and instructions are very descriptive. It finishes in a form of short commands and a description of what should be the result.

During our courses we try to show the students how theory affects their comprehension of practical use of GIS. The most useful examples that we use are projections. The first step is to explain the theoretical usage of projections - why is it necessary, how is it calculated, what are the differences between projections and which ones are used in Poland and why. Later on, during the exercises we explain them one more time, why and how should they use projections and show them how it effects the data. After that students take part in a tutorial which shows them the application of projections in GIS. The final step is to show students how the projections effect the way of collecting data in the field and the way of transferring it to and from the mobile tools into computer.

During our courses we teach students how to calculate simple spatial statistics and perform spatial analysis. All complicated

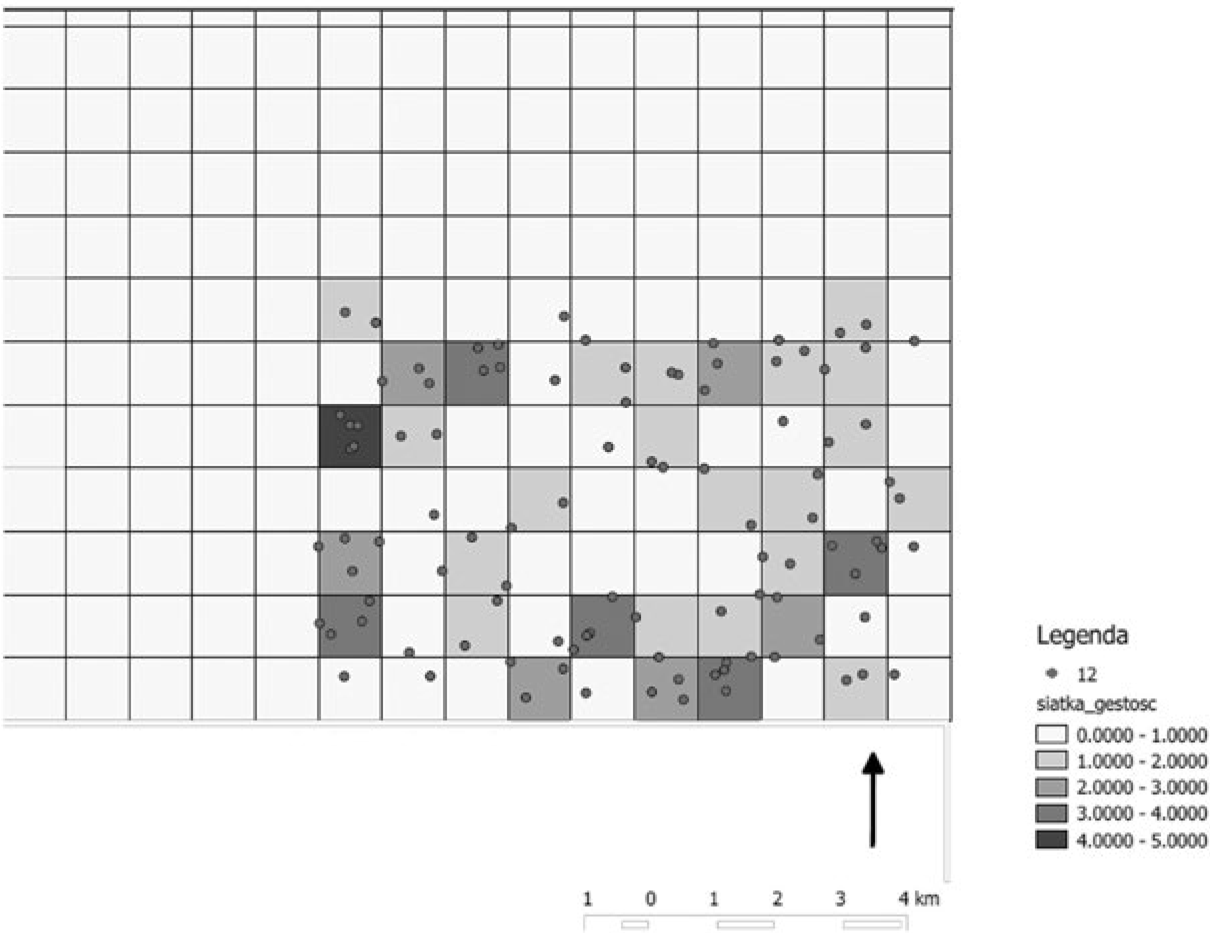


Fig. 2. Results of statistical analysis exercises done by students.

procedures can be constructed from simple functions that are easy to understand. Scripts were prepared for the task which explained simple descriptive statistics for points with one attribute (Fig.2). Since they are future archaeologists, we try to use as much archaeological data as we can. Our base however has to be mainly artificial data or data that are shared with us by our colleagues form the Universities that are conducting excavations. Although we have national registers of archaeological data we cannot use them directly on our classes.

The main Polish, official register of archaeological data is the Polish National Record of Archaeological Sites (PNRAS). It is a dataset of archaeological artefacts from field surveys which have been conducted in Poland since the 1970's. Nowadays it is supervised by the National Heritage Board of Poland. The survey covers over 435 000 records and over 83% of Poland's surface. It aims to be a genuine open source for archaeological GIS exercises, however we need to obey the regulations which are connected with this kind of data source.

First of all if we would like to use this data we should ask the National Heritage Board of Poland for a special permission. The Board shares the data for non-commercial purposes (private and scientific), which is directly specified in the application form. It contains also the following clause: the user is aware of threats that follow from the not authorised sharing of data about the sites (NID 2015). This notice is especially important in connection with the localisation of the sites, because unauthorised access to archaeological sites can be destructive. In our opinion it complicates the possibilities of the usage of this data to provide exercises. If we would like to use them we should at the beginning use some kind of algorithm that would attach false coordinates to points. In our opinion it is not worth the time spent on such procedure, it is also not worth the time spent on agreeing on some artificial topographic conditions to such sets.

The other problem with the PNRAS data is that the cards on which the records were collected are too complicated. They contain too much information that are not important from the viewpoint of spatial analysts. Much information is connected with the conservation process or details of localisations. To summarize, if we would like to use the cards of PNRAS in our lectures we would need to digitize more information that we need from a didactic point of view.

Due to the above-mentioned facts we decided to develop our own, simple database of artificial artefacts. They are named the 'Monolithic Eastern Eggs'. The database is constructed from clustered organized points, with coordinates and attributes describing different types of materials of artefacts. The database is printed, cut out and placed in a box. During the first classes of the semester students are randomly choosing 50 out of 1000 records for their own smaller sample database. From

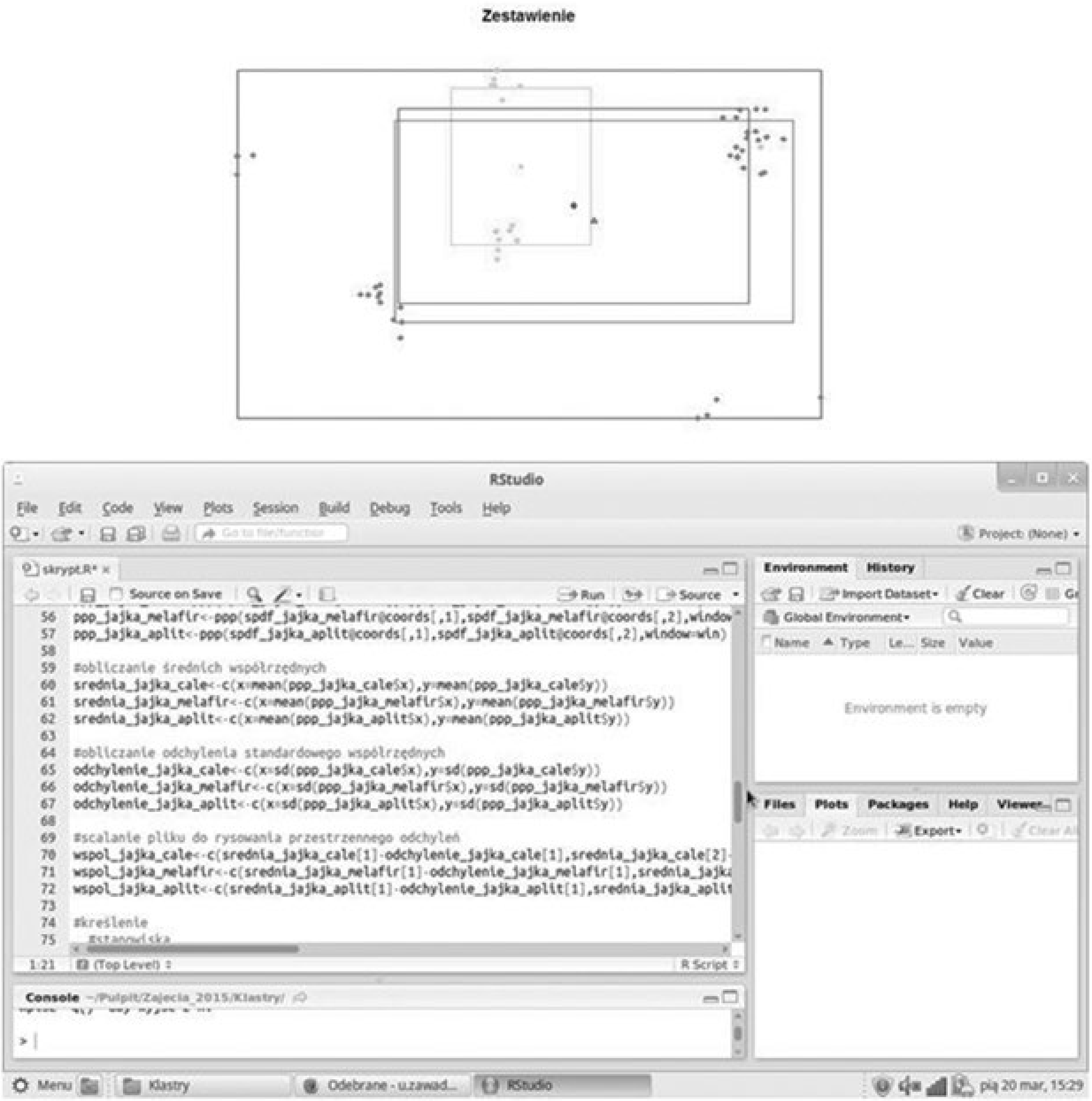


FIG. 3. MATERIALS WHICH ARE USED DURING THE CLASSES ARE INVENTED AS A SIMPLE DATABASE OF POINTS, COORDINATES AND MATERIAL. HERE IS AN EXAMPLE OF AN EXERCISE WITH 'R SCRIPT'.

this sample they are creating a '.csv' file with columns for coordinates and material (Fig. 3). Advantages of such approach are as follow:

- data is simpler than normal archaeological data so we explain the rules of data processing on easier examples,
- we are not limited by the rules of sharing of real data,
- we can artificially modify data,
- students can see what are the differences between samples and the total population results
- such database can be developed to a proper level of complexity depending on the skills of the audience.

Another way of finding data for teaching is to ask for the data that archaeologists in our Institute have: GPS, mobile GIS, total station measurements, analogue drawings, aerial photographs and satellite images. Also archival data such as military maps turned out to be very useful sources.

3 Didactics: fieldwork

Field surveys and students' participation in excavations are great opportunities for them to use the theoretical and computer-based knowledge in the field. During excavations they can practise the creation of documentation following the instructions given during the course. Over this process they will have in their mind that they should not only make good field documentation but also make it usable for later use i.e. after digitalisation or in GIS programmes.

Fig. 4. Students learn how to use balloon for taking aerial photos.

Photogrammetry as a tool for archaeologists is suitable for different types and sizes of objects. It is a great method used during the work on the ground and from the air as well. For documenting works in the trench and for documenting artefacts nowadays it is also much easier to create 3d models and ortophotographs because of the much more advanced computer software, which are more easily available. All students in the Institute of Archaeology during the second year of studies have a class called: Archaeological Photography. Students are informed about photograph theory, different methods of taking pictures and, later on, those classes supplemented with GIS courses in the field, show students how to make measurements depending on which photogrammetric software is used. Students must be familiar with the theoretical background and the procedure of taking photos for later processing them into 3d models. If they know the principles of photography and photogrammetry they can achieve better quality of documentation. So during the GIS courses they can improve their skills in documenting sites and small finds by the use of photographical methods and data. During the field work their knowledge about photography principles is checked. They have also opportunity to use professional photographical equipment for their work. It is also possible to use their own cameras and get the same information about what parameters in what situation should be used to get the best quality of photographic and photogrammetric documentation.

The applicable approach of taking pictures depends on the type and topography of the site where practical classes take place. Students get also information about possibilities of merging geodesic data from classic GPS receivers, laser theodolites and more accurate GPS RTK or DGPS with photographic documentations. As a first step they learn how to geotag digital photos with the longitude and latitude from GPS receivers. This is a very useful skill especially during the survey work and it speeds up the process of data collection (Ejsmond, Chyla, Baka 2013). The second step is to show students how to use theodolites or GPS RTK's by geolocalisation of photo points and other important parts of the sites. All collected data are later processed by students during the practice classes, where they can not only post-process but also learn how to interpret them.

If the weather is favourable and the site is located in the safe zone for flying students can practice taking photos with the use of a kite, balloon or multirotor (Fig.4). In the Institute of Archaeology small format aerial photography (SFAP) (Aber, Marzolf, Ries 2010) is developed from 2005 (Bogacki, Małkowski, Misiewicz 2008). Despite this, information about practical use of the airships in archaeology and problems with its adaptation are not so easy to get. During these courses students get cheap and verified methods of working with SFAP. Kites, balloons and drones are also compared to each other. Additionally we introduce students to others methods of acquiring data with the use of aerial photos and remote sensing. In the field, it is crucial to point out the problems, limitations and solutions of this method of documentation, and to stress how it differs depending on the type of the sites and topography of the region. Furthermore we give them our support when they decide to construct their own equipment and work with photos, which were obtained from SFAP in projects they are involved in.

4 Conclusions

The presented programme of the GIS courses for archaeologists contains theoretical and practical aspects. It is supplemented by photographic and photogrammetric theory and field surveys. Moreover courses are complemented by geophysical classes. The course is a result of five years of experience and work with students. We tried to follow the rules of higher education pedagogy (tab. 1), to introduce students to theory based in geography, cartography, photography, remote sensing and statistics. Also we set up a goal to help students to use their theoretical knowledge in practice. We teach students the processes of making documentation, post-processing collated data and how to represent and interpret these. Nowadays we can see our students working in international projects or even starting their own. However our main goal is to present to students that non-destructive methods and new technologies are a great help for archaeologists in the field, if they use them wisely, with a full theoretical background.

Bibliography

Aber, J. S., Marzolff, I., Ries, J. 2010. *Small-Format Aerial Photography: Principles, techniques and geoscience applications*. Netherlands, Elsevier Science.

Bogacki, M., Małkowski, W., Misiewicz, K. 2008. *Kite Aerial Photography (KAP) as a tool for completing GIS models. Ptolemais (Libya) case study.* In W. R. Lasaponara, N. Massini (eds.), *Remote sensing for Archaeology and Cultural Heritage Management*: 329-33. Rome, EARSel.

Ejsmond, W., Chyla, J., Baka, C. (in press). Report from Field Reconnaissance at Gebelein, Khozam and el-Rizeiqat. Polish Archaeology in the Mediterranean. Research 25/1.

Francuz, W.M. 1995. *Dydaktyka przedmiotów zawodowych. Przewodnik metodyczny dla słuchaczy studiów pedagogicznych w wyższych uczelniach technicznych*. Poland, Politechnika Krakowska: 31.

Goźlińska, E. 1997. *Słowniczek nowych terminów w praktyce szkolnej*. Poland, CODN: 65.

NID 2015. *Internet Site of National Heritage Board*. Available at: http://www.nid.pl/pl/Dla_specjalistow/Badania_i_dokumentacja/zabytki-archeologiczne/archiwum-azp/AZP_WNIOSEK.pdf. [Accessed: 24 june 2015].

Okoń, W. 1992. *Słownik pedagogiczny*. Poland, PWN.

Szlosek, F. 1995. *Wstęp do dydaktyki przedmiotów zawodowych*, Poland, WSI.

Utilisation of a Game Engine for Archaeological Visualisation

Teija Oikarinen
teija.oikarinen@oulu.fi
Archaeology, Faculty of Humanities, University of Oulu, Finland

Abstract: A game engine is a software framework aimed at designing video games. Besides developing entertainment based applications, a game engine can be used for visualisation purposes, thus providing improved access to scientific data and presenting 3D models of real-life objects to different kinds of audiences. There are examples of using game engines for archaeological purposes. However, relatively little information is available about the technical characteristics and demands of using a game engine in context of archaeological visualisation. The potential and challenges of using a game engine for archaeological research and dissemination were analysed by developing a prototype of an interactive virtual exhibition. Unity game engine was used. Based on the research, it seems likely that Unity can be used for visualisations that conform to the international archaeological visualisation principles. Since the technical demands for visualisation purposes are project-specific, the feasibility of using a specific game engine must be evaluated accordingly.

Keywords: Archaeology, Game engine, Unity, Visualisation

Introduction

A game engine is a software framework aimed at designing video games. Game engines, such as Unity, have a plenty of potential usages for digital heritage and serious games (Anderson *et al*. 2009, 2010). Besides developing entertainment based applications a game engine can also be used for visualisation purposes thus providing improved access to scientific data and even presenting digital 3D models or reproductions of real life objects to academics and also to the general public as interactive virtual exhibitions or as games including features for education (also known as edutainment or game based learning).

Use of a game engine enables creation of virtual environments and the typical features of game engines like moving of the game character(s), levels and game objectives also support enhancement of user control, participation and experiantility (e.g. Anderson *et al*. 2009, 2010). There exists a diverse range of potential usages, and already there are some examples of game engines being used for archaeological visualisations (e.g. Anderson 2004, 2008; Champion 2011; Forte *et al*. 2012; Lercari *et al*. 2012; Scapa Flow Historic Website, n.d.). A game engine can also be used to e.g., combine archaeological information, historical information, background information of the project and technical data related to 3D modelling (e.g. Ch'ng 2007; Champion 2011; Christopoulos *et al*. 2011; Forte *et al*. 2012; Getchell *et al*. 2010; Gillam and Jacobson 2015). However, relatively little information is available about the compatibility between the technical characteristics of game engines and the demands set by archaeological projects.

In this study, the technical properties and functionalities of Unity game engine have been analysed, i.e. the potential of using a game engine for archaeological research and dissemination was analysed by developing a prototype of an interactive virtual exhibition using Unity game engine. The nature of the demonstration can be loosely described as proof of concept. Proof of concept (also referred to as 'proof of principle') is commonly used to demonstrate feasibility of a product concept. It will provide feedback to the product stakeholders about the potential issues and challenges. Proof of concept is typically developed as an incomplete version of the actual product, and it can also be used as an effective means of communication between the product developers and stakeholders that lack technical knowledge (see also Manninen 2007: 174-7, 194).

1 Background: Untapped Potential of Game Engines for Cultural Heritage

As mentioned before, Anderson *et al*. have (2009, 2010) discussed use of game engines in the context of serious games. They have analysed and described the level of use and potentiality of game engines for cultural heritage field in general:

'Although the widespread use of gaming for leisure purposes has been well documented, the use of games to support cultural heritage purposes, such as historical teaching and learning, or for enhancing museum visits, has been less well considered. The state-of-the-art in serious game technology is identical to that of the state-of the-art in entertainment games technology. As a result, the field of serious heritage games concerns itself with recent advances in computer games, real-time computer graphics, virtual and augmented reality and artificial intelligence. On the other hand, the main strengths of serious gaming applications may be generalised as being in the areas of communication, visual expression of information, collaboration mechanisms, interactivity and entertainment.' (Anderson *et al*. 2010: 255.)

There are multiple definitions of the concepts 'game' and 'serious game'. Game engines can also be utilised to develop non-game applications or without applying gamification principles. These topics will be discussed briefly in the subsequent section.

2 Some Definitions of Games

Abt has formulated a well-known definition for a serious game (1970: 6-7):

'Reduced to its formal essence, a game is an *activity* among two or more independent *decision-makers* seeking to achieve their *objectives* in some *limiting context*. A more conventional definition would say that a game is a context with rules among adversaries trying to win objectives.'

He continues (Abt 1970: 9):

'We are concerned with serious games in the sense that these games have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement.' So he highlights that the difference to games is that serious games are not just for amusement.

Recently Zyda has described the roles of different kinds of games (2005):

Game is: 'a physical or mental contest, played according to specific rules, with the goal of amusing or rewarding the participant.' (Zyda 2005: 25.)

Video Game is: 'a mental contest, played with a computer according to certain rules for amusement, recreation, or winning a stake.' (Zyda 2005: 25.)

Serious Game is: 'a mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives.' (Zyda 2005: 26.)

Whether a serious game should be amusing and entertaining is debatable (see e.g. Susi, Johannesson, Backlund 2007: 3-7), but at least the general consensus is that it should require and enable a mental contest. Use of a game engine just for immersive visualisation such as virtual reconstruction is not enough to be described as a serious game. It should (also) be noted that games of non-entertainment purposes have existed long before the concept of 'serious game' was established or Serious Games Initiative was launched in 2002 (Serious Games Initiative 2002 cited in Susi *et al*. 2007: 2).

Visualisation in archaeology is broadly published area (see, for example, the edited book by Ch'ng, Gaffney, Chapman 2013). Besides relying on traditionally produced highly detailed 3D models, also files of lower resolution (so-called low-poly models) can be used for visualisation purposes. The growing use of game engines within the field of cultural heritage is related to the technological advances in the field of game industry, which allow the ever-improving graphics and expanding areas of use. From the point of view of cultural heritage the main challenge of digital visualisation is that it cannot truly replicate the past – visualisations are always just estimations of reality (Ch'ng *et al*. 2013: 5-6).

3 Categorisations of Serious Games in Cultural Heritage

Anderson *et al*. (2010: 257) categorises three types of computer-game-like applications in cultural heritage:

1. prototypes and demonstrators: visualisations and virtual reconstructions of archaeological sites to academic use; education, simulations of behaviour, reconstruction
2. virtual museums: entertain and educate
3. commercial historical games: depict real historical events (frequently wars and battles), which the human player can then partake in (Anderson *et al*.: 257-9).

These categories may also overlap within archaeology and the field of cultural heritage, e.g. there may exist virtual museums that have game-like features.

According to Zyda's definition a game should always include some kind of mental contest to be categorised as a serious game. Therefore, it can be debated if virtual museums without interactive features can be categorised as serious games, even if a game engine has been used as technological platform.

4 Use of Game Engines for archaeological purposes

Game engines have been used to some extend for archaeological and cultural heritage purposes. About forty articles written about game engine utilisation can be found from the technology-oriented journals (e.g. Bellotti *et al*. 2011; Grace 2011; Leite-Velho and Oosterbek 2009; Reynolds *et al*. 2005; Woolford and Dunn 2013), and archaeological and cultural heritage journals (e.g. Rua and Alvito 2011). However, most likely there have also been experiments that have not been published.

Features of Unity game engine have been extensively used in 'The Fort Ross Virtual Warehouse' project, which also incorporates educational aims (Forte *et al*. 2012). Forte *et al*. (2012) have, for example, used the heightmap import feature of Unity to generate a game terrain based on real-world topographical data. Unity has also been used to present interactive city environments (Merlo, Dalcò, Fantini 2012) and to visualise Etruscan tombs (necropolises) of Italy (Pietroni *et al*. 2012).

The books by Champion (2011) and an edited book by Gillam and Jacobson (2015) about utilisation of game engines are likely to be the only large-scale publications targeted at archaeologists who either have IT skills or are able to co-operate with IT professionals (see also Champion 2012, 2015). Although the gaming-oriented features of game engines have occasionally been utilised, the main focus has been on digital representation of an object, for which a game engine acts as a useful and convenient publishing platform. The more advanced features of game production platforms seem to have been used only rarely. Those features include advanced collision detection between (moving or animated) game objects and raycasting operations for detecting remote objects in a specific direction related to origin (e.g. the playable character) of the ray. Game engines also incorporate physics engines that provide realistic physical behaviour within the game world. Game developers typically utilise physical materials provided by game engines to create impressions of various types of surface materials of game objects (e.g. slippery, bouncy).

5 International standards for archaeological visualisation

From archaeological perspective it must be asked if a specific game engine can be used to produce a reliable and authentic reconstruction. The limitations of a using game engine technology for visualisation must also be recognised. Also, the current archaeological standards for visualisation need to be followed and taken into consideration. The London Charter for the Computer-Based Visualisation of Cultural Heritage (Denard 2012; London Charter [2006] 2009a, 2009b) states:

'[--] a set of principles is needed that will ensure that digital heritage visualisation is, and is seen to be, at least as intellectually and technically rigorous as longer established cultural heritage research and communication methods' (London Charter 2009a).

The archaeological standards do not rely on technical criteria. Whether visualisation process has been successful or not is determined by the quality of modelling of a real-life object from the archaeological point of view. The most important factor when evaluating a visualisation is its suitability for the intended use, which is also stated in the principles of visualising cultural heritage, London Charter (2009a, 2009b). For archaeological visualisation also a specific set of objectives, the Sevilla Charter (Lopez-Menchero and Grande 2010), has been implemented.

In this research example material was used for testing and developing a proof of concept, but when aiming to build a final product the following principles are especially important. The principle 4.4 considering authencity in Seville Charter (Lopez-Menchero and Grande, 2010: 4) denotes:

'[--] it should always be possible to distinguish what is real, genuine or authentic from what is not. In this sense, authenticity must be a permanent operational concept in any virtual archaeology project; it must be openly committed to making alternative virtual interpretations provided they afford the same scientific validity.' The principle 4.7 about scientific transparency (Lopez-Menchero and Grande, 2010: 5) states:

'All computer-based visualisation must be essentially transparent, i.e. testable by other researchers or professionals, since the validity, and therefore the scope, of the conclusions produced by such visualisation will depend largely on the ability of others to confirm or refute the results obtained'. (Seville Charter 2010.) The actions and decisions of designer, programmer, archaeologists and implications of software are needed to take into consideration and reveal in the final product.

6 Research Objectives

In this research the feasibility of using a game engine for archaeological research and dissemination was analysed by developing a demonstration (a proof of concept) of an interactive virtual exhibition using Unity game engine. The functionalities of a game engine were tested and evaluated by building an interactive exhibition based on example data: the aim was to utilise basic immersive and game-like interactive and multimodal features and functionalities of Unity. Implemented features were auditive (sound), gestures (clicking the mouse, menu, rotating, zooming), spatial (FPC, first person controller, movement, levels), visual (seeing, virtual environment) and linguistic (textual information, reading). Besides testing the features and functionalities of Unity, also the skill requirements related to use of a game engine were studied from a practical archaeologist's viewpoint.

Research questions were formulated as:

- What kind of potential lies in using a game engine for archaeological visualisation purposes, such as interactive exhibition?
- What kind of weaknesses does a game engine have, when used for archaeological visualisation purposes, such as interactive exhibition?
- What kind of skill requirements does the use of a game-engine set for an archaeologist?

During initial investigation it was revealed that Unity game engine is optimised towards use of low-poly polygon meshes, which must be taken into consideration when importing and editing 3D models. Another starting point for the research was that while there exists some information for the archaeologists about 3D game engines (e.g. Champion 2011, 2012; Gillam and Jacobson 2015) there is little information for an average archaeologist of how to evaluate archaeological affordances of game engines. Moreover, there are not many archaeologists that possess game developing skills. The commercial archaeological enterprises do not typically share information about their development processes.

7 Empirical Phase: Building a Proof of Concept

The proof of concept consists of two views: A 3D landscape and a viewer window for presentation of an archaeological 3D object (an axe blade based on exemplary archaeological data). The viewer window has controls for zooming and rotating around a 3D object and also viewing reference data is supported. Immersion and interactivity were provided by modelling a hypothetical 3D landscape and use of auditive (rain) and visual (wind, moving grass, fog) effects. Furthermore, some additional imported 3D objects were used as decorative elements.

7.1 Preparatory Steps

The starting point of the prototype application development was affected by the author's background information about archaeology and game engines. From the archaeological point of view it is difficult to define generalisable technical requirements for the visualising process and the end result. As mentioned before, the most important factor when evaluating a visualisation is its suitability for its intended use, which is also stated in the principles of London Charter (2009a, 2009b).

Some technical qualities (e.g. level of detail in 3D graphics) of a visualisation also depend on the intended use and targeted hardware platform. Unity game engine was selected as development tool because of (see also Craighead, Burke, Murphy 2008; World of Level Design 2012):

- free license
- comprehensive documentation
- active online user community
- cross-platform support
- compatibility with multiple 3D file formats
- interactive 3D game world view

It should be noted that besides Unity there are numerous other game engines nowadays freely available for developers. Also, the licensing situation is constantly changing. For example, in September 2014 Unreal Engine 4 was made freely available to schools and universities, and in March 2015 it eventually became free for everyone to use (Epic Games Inc., 2015). Ultimately, in real-life projects game engine should be seen as a tool for filling the requirements of a specific project. Accordingly, selection of a game engine to be used should be based on specifications of product rather than e.g. familiarity of game engine or personal opinions of developers.

As Unity requires use of low-poly 3D game assets (e.g. Goldstone 2009: 443; Merlo *et al*. 2012: 623), the most feasible type of the demonstration was a virtual exhibition. During development work it was essential to identify the features and requirements of Unity that will influence utilisation of the game engine for archaeological purposes. The development of the demo application and the end product were also affected by the available materials. During the development of the application various features were implemented using example data as assets, whereas a real-world an archaeological visualisation must be constructed using reliable methods and accurate information.

Unity comes with an inbuilt collection of various assets. 3rd party assets – both free and commercial – can be acquired for example via Unity Asset Store ecosystem (see Unity Technologies 2015). When acquired and used properly, 3rd party assets can streamline development cycle by providing e.g. ready-made animated 3D objects or well-implemented source code files. However, it should be noted that implementing a Unity-based application by relying solely on imported assets is only feasible for walkthroughs in 3D world and other simple applications. More advanced implementations will require programming skills and careful editing and integration of assets.

When discussing game graphics, the concepts of frame is commonly used. Frame refers to a single instance of game view being rendered on a device screen during gameplay. The amount of frames drawn per second (FPS) is a value used to measure game performance (See also Goldstone 2009: 115-6). Frame rate of 30 FPS is generally considered to be adequate, although the topic is subjective and also dependent of the game genre.

7.2 Importing 3D Objects in Unity

One of the first development steps was to find out about the 3D file formats supported by Unity. Sometimes it was also necessary to use 3rd party software as intermediate conversion tool to allow importing files into game development environment. For example, point cloud data was converted to a compatible FBX mesh file using Blender software.

Low-poly as a 3D polygon mesh property is a relative value that depends heavily on the development environment and target platform properties. Typically it is defined as 'relatively low amount of polygons'. However, during development it was revealed that Unity has an exact limit of 65535 vertex points for a single imported 3D object. This limit can be circumvented by presenting several combined 3D meshes as a single visual object. An axe blade used for the prototype was converted from point cloud data to FBX format. Accuracy of conversion was estimated to be adequate because the geometry of the object remained approximately unchanged. The texture used for rendering the axe blade is not based on the original object surface, but a freely licensed stone-like texture was used instead.

To develop games that run fluently on various device platforms, 3D models are optimised by simplifying the geometries of the models. Overall, optimising 3D graphics performance is a complex topic that involves various factors (e.g. textures of 3D meshes, programming code and lightning effects) along with managing the polygon count of the 3D objects. Unity provides several tools and features for measuring and optimising graphics performance (Unity Technologies 2015).

Because target platforms of games (especially mobile devices) often set limitations to the quality of game graphics, game engines typically allow creation of 3D details that are artificial in the sense that they do not actually exist at 3D data level. As an example, Unity supports use of bump map textures that respond to light and add surface height details to low-poly 3D objects, thus reducing the amount of needed 3D details and improving game speed (Unity Technologies 2015).

3D object's detail level and texturing of the mesh may be critical depending on the usage of the object. Whether the properties of an object will change or disappear during 3D scanning or file format conversion, must be carefully considered – especially if the 3D file is intended to be used for research purposes.

7.3 Modelling of Environment

As mentioned before, Unity supports importing real-world topographical height data as heightmap files. If desired, the imported heightmaps can be further edited. Game terrain can also be created from scratch by using Unity's terrain editor, which also supports adding plants and trees to the terrain. A cubical skybox element is used to provide an impression of 3D sky. Particle systems can be used to create dynamic effects like liquid, smoke, fire and explosions that are difficult to present as 3D meshes. To allow movement inside the game world Unity requires creation of a user-controllable game character object. 1st and 3rd person character templates are provided as ready-to-use game assets. In the demonstration application 1st person mode was used.

Creation of a 3D surroundings for the archaeological 3D object and enabling user movement in 3D landscape increases immersion, and the effect is further amplified by use of audio effects and dynamic visual clues (In the demonstration falling rain, raindrop sounds and rising smoke were used) (Fig. 1). Interactivity is provided by allowing the user to control the movement of the game character and investigate the game objects from a close distance.

In the demonstration application the user can enter a viewer window by pointing and double clicking the axe blade with mouse cursor (Fig. 2). The viewer window supports rotating and zooming around the axe blade object, thus enabling close inspection (Fig. 3). User may switch at will between the viewer window and the game screen.

Fig. 1. An example view of the 3D landscape.

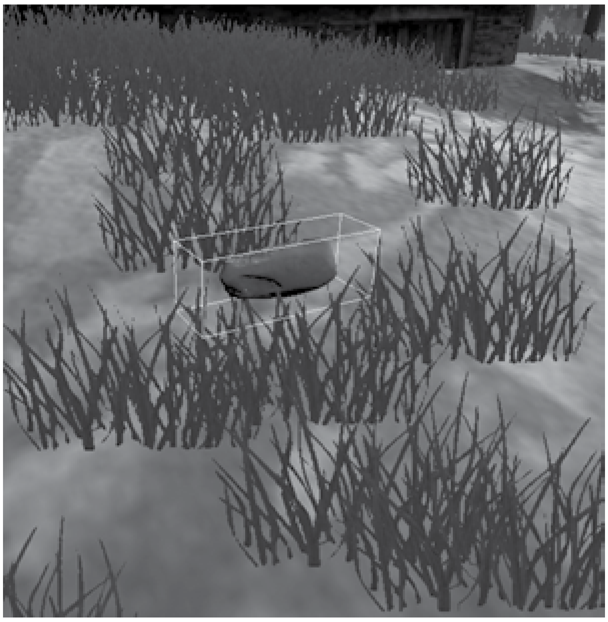


Fig. 2. 3D object that the user has to locate and click with mouse to access the viewer window.

Besides modelling the archaeological objects, presenting the visual surroundings like buildings, trees and plants accurately may require considerable effort and advanced 3D skills. In addition, programming is needed to implement the interactive features, and programming work may actually be one of the major tasks of an interactive visualisation project. Not many people are proficient in both 3D modelling and programming, which affects to the minimum resources needed for visualisation and game projects (see also e.g. Forte *et al*. 2012: 320).

7.4 Interactive 3D Object Viewer

An essential question related to archaeological use of a game engine is how to present external data to provide further

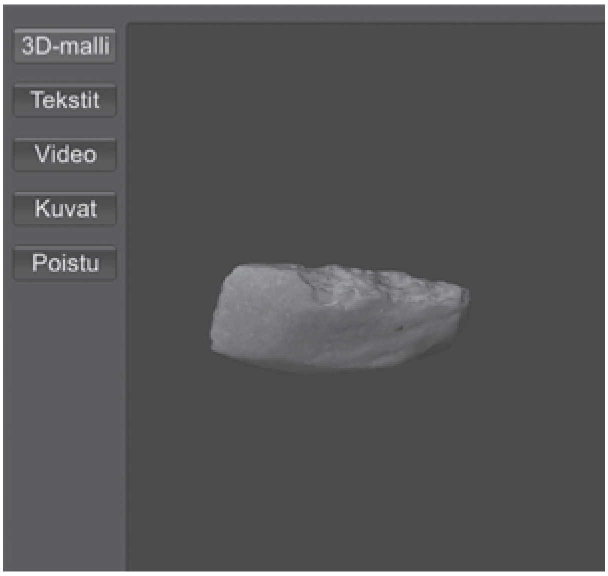


Fig. 3. The interactive viewer window with zooming and rotating options and a possibility to view reference data.

Fig. 4. The viewer window is in 2D image mode.

information about the archaeological object. In other words, the methods of displaying 2D images, textual information, WWW-links and video files must be examined.

In the demonstration application accessing additional information was implemented by providing a menu element that can be used to switch between the display modes of the viewer window. Thus, by clicking the menu buttons the user can, for example, observe digital images and textual information about the axe blade and later return to the 3D viewing mode (Fig. 4).

8 Results

8.1 Strengths and Weaknesses of Unity Game Engine

Main results of the study are consistent with the current knowledge about use of game engines in cultural heritage context: the strengths are in the areas of communication, visual expression of information, collaboration mechanisms, interactivity and entertainment (Anderson *et al*. 2010: 255). Development of the demo proved that a game engine can be used to implement a virtual exhibition with game-like functionalities and interactive features. The virtual exhibition can be published either online or as a part of a traditional exhibition. Unity's visual and auditory features can be used to enhance the user experience. The integrated game editor is user-friendly and Unity is free, which increases the potential for its exploitation in archaeology. Unity has a view for designing the 3D game world. It supports importing of 3D objects of many formats and its features are generally well documented.

Common weaknesses of game engines are the lack of documentation and some constrains which are revealed in the use phase (Friese, Herrlich, Wolter 2008: 20-1). These were present to some degree during development of the prototype application. Unity, like most of the game engines, is not a 3D modelling software but it utilises imported 3D objects, which can only be slightly modified within Unity editor. Therefore, use of Unity typically requires use of external modelling software. Also requirement of low polygon count is needed to be taken into consideration when presenting 3D objects. Also, when artificially created surfaces (textures) are used for rendering 3D objects the authentic physical properties are lost. However, this should not be seen as a weakness of a game development platform. Instead, the issue is related to the commonly used 3D scanning tools.

8.2 Skill Requirements for Archaeologists

Because a virtual exhibition will be realised as a medium to large-scale software development project, all the skills that are needed to successfully plan and executing such a project are also needed from archaeologists responsible of the exhibition. For example, collecting and documenting project requirements must be done methodically. The requirements will also often change during project, in which case the developers must be able to come up with creative solutions for technical issues.

Unity's graphical scene editor can be used to create the visual elements of a virtual exhibition, but the interactive functionalities of the exhibition will require programming skills. Also 3D modelling and image editing skills are needed. All these areas require considerable amount of practice and experience before proficiency is attained.

Besides understanding the software used directly in development, also knowledge about other technologies, such as the target platform for dissemination (pc, tablet, etc.), is required. Although Unity has been denoted as user-friendly, especially when being compared to other game engines, it must not be seen as easy or holistic software solution.

8.3 International Standards for Archaeological Visualisation

In this research the possibilities to follow the international standards and principles for archaeological visualisation were analysed. For example, the possibility of presenting various kinds of archaeological information follows the international principles for archaeological visualisation: it allows use of the original data and information related to the target of modelling (e.g. archaeological object or site) and it also supports informing the users of the exhibition about building process of the virtual exhibition. This can be seen as increasing transparency and providing information about authentic vs. non-authentic features of the virtual exhibition. Visualisation principles can be also conformed to by constructing an exhibition as separate game levels, which can be used to distinguish the original digital object from the interpreted environment, and thus dissociate the authentic features of the object from the artificial surroundings. Visualisation of archaeological objects in three dimensional game contexts requires use of 3D models that are based on archaeological information and documents / records. For archaeological purposes these models can be obtained via 3D scanning or created using 3D modelling software.

The aforementioned principles are written in qualitative manner, which presents some challenges for testing the validity of the prototype. For example, no information about required accuracy of 3D information is included to Seville Charter, so it remains unclear whether Unity's low-poly mesh demands violate against these principles. The technical and quantitative requirements are – or at least should be – defined for the real-life archaeological visualisation projects. However, no information like this was available for this research, which prevented evaluation of the prototype against quantitative criteria.

In general, it is not reasonable to require advanced IT skills from archaeologists. Therefore, close cooperation between archaeologists and programmers must be ensured to guarantee the transparency of work-flow and its implications to visualisation and its immersive and interactive functionalities. It should be noted, however, that the data sources (files) for an archaeological visualisation project can be prepared by persons without programming skills or knowledge about the features of the game engine. Clear goals of how to present the archaeological intellectual workflow and possible interpretations and how to separate these from the original data must be set.

9 Conclusion

The analysis indicated that a game engine has potential to be used for archaeological visualisation. Based on the experiment and information about the preceding research it seems that game design platforms can be used to create virtual exhibitions that follow the international principles for archaeological visualisation. However, some technical features of a typical game engine, like use of simplified 3D objects, can be seen as weaknesses from the archaeological scientific viewpoint.

In archaeology the requirements for visualisation and interactive features should be determined by the specific archaeological project. From computer science's viewpoint the challenge in archaeological development is that it is there are no shared technical requirements to regulate and support building of an interactive exhibition. Seville Charter describes the qualitative requirements for a computer-based archaeological visualisation. From developer's standpoint these qualitative concepts, such as 'authenticity', are difficult to interpret and measure. Therefore, the qualitative nature of archaeological design requirements (or rather the lack of quantitative standards) presented a major challenge when evaluating the success of the prototype.

Game engines provide numerous opportunities that are not broadly utilised in archaeological visualisation. For example, game engine enables creation of a functional and interactive virtual exhibition, provided that scanned or modelled (digital) objects are available. Heightmaps based on real world information can be utilised for creating topography. Use of Unity's graphical interface for creating 3D game world is relatively easy, but also programming skills are needed to implement the interactive features. Therefore, even if a game engine may be user-friendly (within its own software category), it is not realistic to expect that it can be effectively used by people without programming and 3D knowledge.

To summarise, the most probable areas of utilisation of game engines in archaeology are interactive exhibitions, education and dissemination. However, some features of game engines may limit their use for research purposes. The information presented in this article can be used by archaeologists, who are planning a virtual exhibition or who are considering using a game engine as a development platform.

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Bibliography

Abt, C. 1970. *Serious Games*. New York, The Viking Press.

Anderson, E. F., Mcloughlin L., Liarokapis F., Peters C., Panagiotis P., De Freitas S. 2009. Serious games in cultural heritage. In M. Ashley and F. Liarokapis (eds), *Proceedings of The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST – State of the Art Reports*. Available at: http://curve.coventry.ac.uk/open/items/8a308515-08b5-ac5f-eaf9-b61adeeaf60a/1/Serious+games+in+cultural+heritage.pdf. [Accessed: 20th June 2015].

Anderson, E. F., Mcloughlin L., Liarokapis F., Peters C., Panagiotis P., De Freitas S. 2010. Developing serious games for cultural heritage: A state-of-the-art reviw. *Virtual Reality* 14, 4: 255-75.

Anderson, M. 2004. Computer Games and Archaeological Reconstruction: The Low Cost VR. In *Magistrat der Stadt Wien. Enter the Past: The E-way into the Four Dimensions of Cultural Heritage. British Archaeological Reports International Series 1227*: 521-524. Oxford, Archaeopress.

Anderson, M. 2008. Putting the Reality in Virtual Reality: New Advances through Game Engine Technology. In A. Posluschny, K. Lambers, I. Herzog (eds.), *Layers of Perception*. *Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA),* Berlin, 2-6 april 2007, Kolloquien zur Vor- und Frühgeschichte 10: 144-150. Bonn, Dr. Rudolf Habelt GmbH.

Bellotti, F., Berta R., De Gloria, A., D'ursi A., Fiore, V. 2010. A serious game model for cultural heritage. *ACM Journal on Computing and Cultural Heritage* 5, 4: 1-27.

Christopoulos, D., Mavridis, P., Andreadis, A., Karigiannis, J.N. 2011. Using virtual environments to tell the story: 'The battle of Thermopylae'. In *Proceedings of the Third International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES), 2011, Athens*: 84-91. Available at: http://dx.doi.org/10.1109/VS-GAMES.2011.18. [Accessed: 20th June 2015].

Ch'ng, E. 2007. Using games engines for archaeological visualisation: Recreating lost worlds. In *Proceedings of the 11th International Conference on Computer Games: AI, Animation, Mobile, Educational & Serious Games, La Rochelle, France, 21-23 November 2007*: 1-6. Available at: http://www.complexity.io/Publications/RecLostWorlds-f_echng.pdf. [Accessed: 20th June 2015].

Ch'ng, E., Gaffney, V. 2013. Seeing things: Heritage computing, visualisation and the arts and humanities. In E. Ch'ng, V. Gaffney, H. Chapman (eds.), *Visual Heritage in the Digital Age*: 1-14 London, Springer-Verlag.

Ch'ng, E. Gaffney, V., Chapman, H. (eds.) 2013. *Visual Heritage in the Digital Age*. London, Springer-Verlag.

Champion, E. 2011. *Playing with the Past.* London, Springer-Verlag.

Champion, E. 2012. *Game Mods: Design, Theory and Criticism*. Carnegie Mellon University, ETC Press. Available at http://press.etc.cmu.edu/files/GameMods-ErikChampion-web.pdf. [Accessed: 8th November 2015].

Champion, E. 2015. *Critical Gaming: Interactive History and Virtual Heritage*. Farnham, Burlington, Ashgate Publishing Ltd.

Craighead, J., Burke, J., Murphy, R. 2008. Using the unity game engine to develop SARGE: A case study. In *Proceedings of the 2008 Simulation Workshop at the International Conference on Intelligent Robots and Systems (IROS 2008)*. Available at: http://www.robot.uji.es/research/events/iros08/contributions/craighead.pdf. [Accessed: 20th June 2015].

Denard, H. 2012. A New Introduction to the London Charter. In Bentkowska-Kafel, A., Baker D. & Denard H. (eds.), *Paradata and Transparency in Virtual Heritage Digital Research in the Arts and Humanities Series*: 57-71. Farnham, Burlington, Ashgate Publishing Limited.

Epic Games Inc. 2015. *What is Unreal 4?* Available at: https://www.unrealengine.com/what-is-unreal-engine-4. [Accessed: 8th November 2015].

Forte, M., Lercari, N., Onsurez, L., Issavi, J. Prather, E. 2012. The Fort Ross virtual warehouse project. In *Proceedings of the 18th International Conference of Virtual Systems and Multimedia (VSMM). Milan*: 315-22. Available at: http://dx.doi.org/10.1109/VSMM.2012.6365940. [Accessed: 20th June 2015].

Friese, K. I., Herrlich, M., Wolter, F. E. 2008. Using game engines for visualisation in scientific applications. In P. Ciancarini, R. Nakatsu, M. Rautenberg, M. Roccetti (eds.), *New Frontiers for Entertainment Computing. IFIP International Federation for Information Processing* 279: 11-22. Boston, Springer-Verlag.

Getchell, K., Miller, A., Nicoll, J. R., Sweetman, R. J., Allison, C. 2010. Games methodologies and immersive environments for virtual fieldwork. *IEEE Transactions on Learning Technologies* 3, 4: 281-93.

Gillam, R., Jacobson, J. (eds.) 2015. *Egyptian Oracle Project. Ancient Ceremony in Augmented Reality*. London, Bloomsbury Publishing.

Goldstone, W. 2009. *Unity 3.x Game Development Essentials*. Birmingham, Packt Publishing.

Grace, L. 2011. Gamifying Archives: A Study of Docugames as a Preservation Medium. In *Proceedings of the 16th International Conference on Computer Games (CGAMES), 2011. Louisville, Kentucky*: 172-176. Available at: http://

dx.doi.org/10.1109/CGAMES.2011.6000335. [Accessed: 20th June 2015].

Leite-Velho, G., Oosterbek, L. 2009. Serious games in heritage, challenges at Mação. In *Proceedings of 15th International Conference on Virtual Systems and Multimedia (VSMM), Vienna*: 217-20. Available at: http://dx.doi.org/10.1109/VSMM.2009.39. [Accessed: 20th June 2015].

Lercari, N., Forte, M., Prather, E. Scultz, J., Onsurz, L., Issav, J. 2012. Fort Ross Virtual Warehouse (Abstract). *Digital Heritage International Congress 2013. 28 Oct - 01 Nov Marseille, France* http://www.digitalheritage2013.org/fort-ross/. [Accessed: 20th June 2015].

London Charter 2009a. *A New Introduction to the London Charter*. http://www.londoncharter.org/introduction.html. [Accessed: 20th June 2015].

London Charter 2009b. *Principles*. http://www.londoncharter.org/principles.html. [Accessed: 20th June 2015].

Lopez-Menchero, V. M., Grande, A. 2010. *Seville Charter*. Available at: http://cipa.icomos.org/fileadmin/template/doc/PRAGUE/096.pdf. [Accessed: 20th June 2015].

Manninen, T. 2007. *Pelisuunnittelijan käsikirja*. Tallinna, Printing Partners Oü.

Merlo, A., Dalcò, L., Fantini, F. 2012. Game engine for cultural heritage: New Opportunities in the Relation Between Simplified Models and Database. In *18th International Conference of Virtual Systems and Multimedia (VSMM), 2012*. Milan: 623-28. Available at: http://dx.doi.org/10.1109/VSMM.2012.6365993. [Accessed: 20th June 2015].

Pietroni, E., Ray, C., Rufa, C., Pletinckx, D., Van Kampen, I. 2012. Natural interaction, in VR environments for cultural heritage and its impact inside museums: the Etruscanning project. In *Proceedings of the 18th International Conference on Virtual Systems and Multimedia (VSMM), 2012*. Milan: 339-46. Available at: http://dx.doi.org/10.1109/VSMM.2012.6365943. [Accessed: 20th June 2015].

Reynolds, R. G., Kobti, Z., Kohler, T. A., Yap, L. Y. L. 2005. Unraveling ancient mysteries: reimagining the past using evolutionary computation in a complex gaming environment. *IEEE Transactions of Evolutionary Computation* 9, 6: 707-20.

Rua, H., Alvito, P. 2011. Living the past: 3D models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage - the case-study of the Roman villa of Casal de Freiria. *Journal of Archaeological Science* 38: 3296-308.

Scapa Flow Historic Website (n.d.), *Wrecks of Scapa Flow*. http://www.scapaflowwrecks.com/wrecks/. [Accessed: 20th June 2015].

Susi, T., Johannesson, M., Backlund P. 2007. *Serious games: An overview. Technical Report School of Humanities and Informatics*. University of Skövde, Sweden. Available at: http://www.scangames.eu/downloads/HS-IKI-TR-07-001_PER.pdf. [Accessed: 20th June 2015].

Unity Technologies 2015. *Create and connect with Unity 5*. http://unity3d.com/. [Accessed: 20th June 2015].

Woolford, K., Dunn, S. 2013. Experimental archaeology and games: Challenges of inhabiting virtual heritage. *ACM Journal on Computing and Cultural Heritage* 6, 4: 1-15.

World Of Level Design 2012. *15 Recommended 3D Game Engines*. http://www.worldofleveldesign.com/categories/level_design_tutorials/recommended-game-engines.php. [Accessed: 20th June 2015].

Zyda, M. 2005. From visual simulation to virtual reality to games. *IEEE Computer* 38, 9: 25-32.

The Interplay of Digital and Traditional Craft: re-creating an Authentic Pictish Drinking Horn Fitting

Dr Mhairi Maxwell
mhairi.maxwell@btinternet.com
Digital Design Studio, Glasgow School of Art

Jennifer Gray
hello@jennifergray.co.uk
Designer and maker of jewellery and objects, Lecturer at Edinburgh College of Art

Dr Martin Goldberg
m.goldberg@nms.ac.uk
Early Historic and Viking collections, National Museum of Scotland.

Abstract: The Glenmorangie Early Medieval Research Project re-created objects from the period c.300-900 AD in collaboration with artists, designers and makers. Designs were informed directly from archaeological evidence held in the National Museum of Scotland's collection. Contemporary processes, integrating innovative and traditional crafting techniques, brought these objects to life, giving us insights into how they were made, experienced and used in the past. The commission which is the subject of this paper combined digital 3D visualisation and modelling skills with traditional silver-casting, to re-create a silver zoomorphic fitting for a drinking horn. The final object was displayed in the National Museum of Scotland's 'Creative Spirit: Revealing Early Medieval Scotland' exhibition from the 25th of October 2013 to the 23rd of February 2014. This paper raises issues of authenticity and aesthetics, which became apparent in the interplay of 3D digital design when blended with traditional craft techniques.

Keywords: Re-creation, Authenticity, Aesthetics, Craft, Design, 3D digital modelling and fabrication

Introduction

The Glenmorangie Early Medieval Research Project re-created objects from the period c.300-900 AD in collaboration with artists, designers and makers. Designs were informed directly from archaeological evidence held in the National Museum of Scotland's collection. The Glenmorangie Research Project acknowledged the intrinsic tensions that exist between the craft techniques available to Early Medieval creators and the new technologies that are available to us today. Therefore a process of contemporary situated re-creation, integrating innovative and traditional crafting techniques, was adopted bringing these objects to life and providing insights into how they were made, experienced and used in the past. In one re-creation project, the subject of this paper, contemporary digital 3D visualisation and modelling skills were combined with the traditional craft of silver-casting to re-create a silver zoomorphic fitting for a drinking horn (Fig. 1 and Fig. 2). The inspiration for the design of the fitting was a 2D image on an Early Medieval carved stone and surviving Pictish silver metalwork from this time. The re-creation was displayed as a 'work in progress' (illustrating its conception from digital 3D modelling and printing through to the final silver cast object) in the National Museum of Scotland's 'Creative Spirit: Revealing Early Medieval Scotland' exhibition, which ran from the 25th of October 2013 to the 23rd of February 2014. A 3D printed prototype of the end-piece was on display throughout the first half of the exhibition and the public were able to track the development through the National Museum of Scotland website which published up-to-date images of the making process. The finished piece was unveiled at a one-off special museum event where the public were invited to handle and view sketches and 3D printed models, which were part of the development process. Except for one specially organised handling event, as per typical museum rules of engagement the display was behind glass. The large Ankole cattle drinking horn on which the new commission would be mounted was delicately suspended in the centre of the display case alongside two smaller polished cow horns and original Early Medieval metal fittings. The horns were suspended at average eye-level meaning people could examine them at 360 degrees and from below.

This paper is in two parts. We will begin with outlining the motivations behind the re-creation and the decision to innovatively blend digital with traditional craft in order to bring alive an object inspired from fragmentary and partial archaeological evidence which is now over 1,000 years old. We give a description of our integrated process, highlighting particular moments. In the second part we will move on to discuss questions of authenticity and aesthetics which arose. In particular, this paper explores the tensions that arose in our re-creation when we blended traditional techniques with 3D digital design and modelling.

1 The commission

We took as our main inspiration the Early Medieval carved stone from Invergowrie in Angus, known as the Bullion Man (*or drunk-in-charge!* as colloquially known). This is a 2-Dimensional representation of a mounted warrior at charge clasping a large drinking horn with exaggerated beak-headed

Fig. 1. The finished silver cast fitting on the drinking horn commissioned by the Glenmorangie Early Medieval Research Project, horn crafted by Johnny Ross (Sutherland Horncraft) and silver fitting made by Jennifer Gray (designer and maker).

Fig. 2. Close up detail of the final cast silver end-piece.

Fig. 3. An Early Medieval carved stone from Invergowrie, Bullion, in Angus, Perthshire. Colloquially referred to as the 'Bullion Man' this stones naïve and comical quality is a popular draw in the National Museum of Scotland and was the main inspiration for our drinking fitting (Image: National Museum of Scotland Trustees).

mount (Fig. 3). Drinking horns of this size have only survived from contemporary Anglo-Saxon and Viking burial contexts, so this depiction is important evidence of their use in the Pictish sphere which has not survived directly. The carved stone of the Bullion Man is a popular object in the National Museum of Scotland's collection due to its comical and naïve quality. Despite not having the symbols which often define Pictish art, this depiction is otherwise clearly very Pictish in character; for example there is a concentric fluidity in the layout and framing of this depiction; man and object are one (perhaps a reference to a cosmology of shape-shifting, which is arguably referenced widely in Pictish zoomorphic art). We were interested in what we could learn by translating this unusual Pictish depiction of a drinking horn into 3-Dimensions.

The Glenmorangie Research Project commissioned designer and maker Jennifer Gray to make the silver zoomorphic fitting for a drinking horn - the horn itself had already been made by Johnny Ross, a horn-carver based in Sutherland. By bringing such an object to life again using modern-day techniques and craft it was our belief that we could gain some insight into the making and social context of these sophisticated, but now non-existent, objects in the past.

It became clear that drinking horns are testament of access to a skilled network of craftspeople (who were probably familiar with many materials, as explored below), and that this investment of materials was likely a risky undertaking and statement of status - our final fitting weighs a whopping 600 grams of silver. The silver fitting acted as a counterweight and stopped liquid from pouring out all at once and soaking the drinker (our horn held almost exactly one gallon of liquid)! These drinking horns were thus likely not designed for an individual to drink from, rather they were communal vessels. Belief systems were not exclusive in Pictish worlds, but were engaged with by the community.

1.1 Evidence

The archaeological evidence was interrogated and directly informed Jennifer's design. Much of the surviving contemporary evidence consists of artistic depictions or written sources and the challenge for us was to translate this into a 3-Dimensional object. There is very little silver-working evidence remaining from the Early Medieval period of northern Britain (pre 1100 AD). Indeed, there is much debris and material culture used or created in the metalworking process, which would not survive as it is organic or microscopic in scale.

Other inspirations included the Anglo-Saxon Sutton-Hoo and Taplow drinking horns, from Suffolk and Buckinghamshire respectively. Consistent with Anglo-Saxon metalworking, a combination of techniques were used in the Taplow and Sutton Hoo horns; cast features were combined with repoussé decorated gilded-silver sheet in order to make-up a form. There is also the Viking Age Pierowall drinking horn mount from Orkney, and objects from the Ninian's Isle treasure from Shetland, a hoard which contains what is considered the best examples of Pictish silver work. In this hoard forms are predominantly cast whole in silver and then sometimes embellished (the Pierowall mount too). This is consistent with the few moulds which have survived from Pictish sites. In order to keep with the Pictish tradition and context of the Bullion Man, we decided that our commission should be a solid silver fitting where pattern and form is cast into the design.

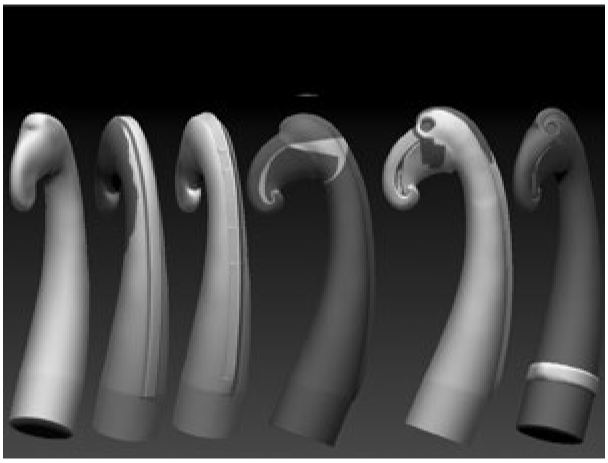

Fig. 4. Screen shot showing stages of the digital carving process in the computer program Z-brush.

Fig. 5. The ABS plastic 3D printed maquette mounted on horn.

1.2 Making

The 3D modelling program called Rhino was used to make a digital version of the horn; Jennifer worked between the actual horn and her digital model to establish the proportions and overall shape of the fitting. In this way, the basic proportions of the form and layout of the traced incised decoration could be altered to compliment the twisting angles of the digital horn, to sub-millimetre accuracy. The basic model was then turned in to a polygon mesh and imported into another modelling program, Z-Brush where Jennifer could carve it virtually as though it were made of wax (Fig. 4). An early prototype was then 3D printed in ABS plastic to act as the maquette for temporary display in 'Creative Spirit' (Fig. 5).

Although ABS plastic is not the most appropriate material to use to represent fine nuances of detail, surface pattern and the subtle angles of edges, it was useful to represent the intended overall form and appearance as an interim display during the exhibition. It strangely appeared like an out of place prosthetic when it sat on the horn in the exhibition. At this moment, it was not in-keeping with the other objects on display; abrasive because of its rapid production and cheap plastic-y quality.

The virtual carving was done using a software programme called Z-brush where a block of wax appears on the computer screen and you carve it as you would by hand. The computer software programme was able to simulate surface and material interaction. Manipulating the virtual wax and 3-Dimensional form digitally was invaluable, especially since most of the surviving evidence is 2-Dimensional. Even objects, including the Ninian's Isle chapes, are very flat in form almost as if the pattern were applied in 2D. By using this method the steel wax carving tools were substituted with a USB drawing tablet. In order to retain a 'hand-made' quality, only manual settings were used to mimic the hand. Jennifer had originally intended to digitally carve the entire piece which would then have been 3D printed in high resolution Objet resin, moulded and then cast in silver. However, no matter how many different manual settings were used in the digital carving programme, the depth of relief carving was always totally consistent. This aesthetic quality of the digital object, it was felt, made it appear too artificial. At this point, Jennifer decided to take the object back into the physical world and incorporate hand carving using steel hand tools. To Jennifer, this was a natural seamless shift as the digital software programmes were completely integrated within her toolbox, each tool as having its own creative potential when used by skilled hands as creative tools just as McCullough states in 'Abstracting Craft: the practiced digital hand' (1998).

Looking closely at Pictish sources, one can clearly observe the original maker's inconsistency of depth in carving and the asymmetry of the surface pattern when trying to cram complex patterns into limited space. Thus in order to create a piece that would sit convincingly amongst other objects from the Early Medieval period, incorporating a natural sense of inconsistency in the incised pattern was visually important. The digitally modelled fitting was 3D printed with only basic outline surface patterning in high-resolution Objet resin which was then moulded in silicone. Carving wax was poured into the silicon mould, and the resulting wax piece carved into with steel tools. It was this carved wax piece which was then used to make the final mould for casting in silver.

The digital toolbox developed by Jennifer allowed her full control over the process based in the first instance in the immaterial and hence was low-cost-to-failure (in contrast economic risk was high for the Early Medieval craftsperson firmly rooted in a material world). It also brought to attention the immaterial and material aesthetic qualities involved in the making of these objects. Furthermore, and most importantly, by blending innovative technologies with traditional hand-crafting a more authentic result was arguably achieved.

2 Re-creation

The collaborative process of re-creation allowed us to experience ancient objects as new, giving us insights into how they were made, experienced and used. We use the word re-creation deliberately. Re-creation means to 'make anew'; indeed, craft process is a living thing and the responsibility of archaeologists is to bring the past alive. By acknowledging this, a reflexive insight into the experience of making in the past can be gained through the hands and knowledge of a skilled living craftsperson, designer or maker.

An openly reflexive approach is different to more orthodox experimental archaeology which attempts to work within the exact conditions and methods of making thought by archaeologists to have been used in the past (e.g. Foulds 2013). There are limitations to this latter approach; for example it is often constrained by the lack of surviving evidence from workshops, while ultimately it is impossible to transport ourselves into the original context of making and production in the past.

We believe that the very ethos of re-creation is encapsulated by using innovative tools available to the present generation but in constant reverence to the original objects and archaeological evidence. Jennifer Gray uses a combination of digital and traditional carving/silver casting methods which allowed us to effectively explore the tension between traditional and new techniques. Just as the makers from all eras of the past did, we were building on tradition while at the same taking advantage of the techniques available in the present day to make new work.

2.1 Truth to digital?

Above in section 1 we directed our gaze upon the crafting of the digital object as a means to create a work of art with auratic qualities. In previous CAA conferences there has been little discussion regarding the aesthetics of digital objects, while the craft of the digital is not widely recognised with the exception of Taylor and Dell'Unto's (2015) session 'Towards a Theory of Practice in Applied Digital Field Methods'. Specifically the papers given by Sara Perry (on the current practice of digital field methods) and by Piraye Hacigüzeller (about her personal experience of digital mapping at Çatalhöyük) lamented the specific nature and qualities of the digital as a knowledge-making tool, impacting upon how we interact with and see the world. To both these authors, the makers of digital records, plans and drawings, were recognised as sentient intelligent beings involved in the production/creation of good, sometimes beautiful work, and not as automated disengaged facilitators producing as a means to an end. Richard Sennett, who argues that craft and skill can be found in any activity in which one takes pride, would be pleased (2008). This is also music to the ears of Malcolm McCullough (1998) who seeks to re-root human agency into digital work and proposes to develop a critical understanding of the ways in which the computer as a medium requires a new set of creative skills. The computer is a theatre of practice, driven by the skills and knowledge of practitioners (Laurel 2003). Digital objects accrue 'auratic qualities [through their] modes of production, aesthetics and creative imagination' (Jeffrey 2015: 145).

It is not just the virtuosity of the digital craftsperson, it is also its [im]materiality which is distinctive. Akin to early 20th Century writings on truth to material, a phrase famously attributed to Henry Moore when discussing the celebration of 'stoniness' exploited by Mexican sculptors (Wilkinson 2002: 104), the very medium of the digital should be appreciated and reflexively engaged-with in reference to its own truth. Truth to digital being its particularly seductive and enchanting virtuality, accuracy and reproducibility (Huggett 2004, Jeffrey 2014), and its programmed predictability and automaticity for users (which off course can be interrupted by skilled practitioners). There is a call to address this 'tyranny of the technical' (Jeffrey 2015: 148, echoing Huggett 2004 and Perry in Taylor and Dell'Unto 2015), and we argue here that this is only currently possible through integrating the digital with the traditional in crafting.

A motivation behind the Glenmorangie project re-creations was for people to be able to access what it may have been like to live in the Early Medieval period, therefore it was paramount to avoid the museum audience feeling estranged or alienated. Issues of aura and affect, and how to accommodate these intangible qualities in exhibition practice, have been discussed much in museum contexts (e.g. Dorian 2014, Hazan 2001, Pearce 2003: 19-29). Particularly relevant to this discussion is Jeffrey's paper (2015) entitled 'Challenging Heritage Visualisation' [and Replication]. Jeffrey lays out a series of conditions of why we perceive the digital object, and our interactions with them, as 'weird' (Jeffrey 2015: 146): the most relevant for us being how the 'digital medium somehow breaks the chain of proximity [to the past] (Jeffrey 2015:147).' In our case we tried to avoid this by showing the re-creation as a work in progress in order to include the audience, updating the display periodically throughout the exhibition duration. However, ultimately so as to achieve a finished object ,which was deemed more *authentic* to the museum visitor we reverted to traditional carving methods prior to silver-casting. We explain this decision using the discussion of the 'weirdness' of the digital object as put forward by Jeffrey (2015). A solely digitally designed object sat uncomfortably in this situation where proximity to the past had to be revered. This aligns with the accepted definition of authenticity within heritage, which is deemed as integrally tied to historicity, materiality and context (Benjamin 1936, Holtorf 2013, Jones 2010, Lowenthal 1995). Since the motivation of the commission was to bring archaeological evidence of drinking horns to life again, the final object (although a reflexive interpretation) had to evoke a clear lineage to the evidence which was its inspiration and ultimately it had to sit comfortably alongside this evidence in a museum display case. Jennifer's creation was to be another event added to a chain of tradition. This was successfully achieved through appropriate choices of material, the execution of design and hand-finish which beckons archetypal Early Medieval material culture as outlined above in section 1.

Another justification for our decision to make the shift back to the hand was that an intimate iterative relationship with accurate 3D visualised form, the virtual wax, and Z-brush tools was only privy to us, whereas the viewer was fundamentally physically disengaged from the actual making. Jeffrey points out that people are generally disengaged from the production process of digitally designed objects. As a result the digital medium and resulting object is unfamiliar to people, occupying an uncertain space in presently situated experience (Jeffrey 2015). Additionally, '[such] weirdness, unless mitigated, tends to produce sanitised and alienating representations, which many audiences find difficult to engage with, let alone to use and re-use (Jeffrey 2015: 145).'

Following on from this, Latour and Lowe (2011) argue that by using sophisticated modern technology which is part of the making but not overpowering the overall visual experience of the replicated object, the seductive 'aura' from the original can migrate into the re-creation. Therefore, in terms of aesthetics a purely digitally designed, modelled and carved object was going to be *just too* perfect. This would be unsettling for a viewer whose experience of the world is in reality messy and unpredictable, and although there is an illusion of measured and divine flawless design in Early Medieval art, on close inspection fallible humanity is apparent in its execution. Therefore, in our case the 'sanitised weirdness' of the digitally designed object was 'mitigated' (Jeffrey 2015) by re-introducing more familiar traditional crafting techniques which capture this authentic imperfectness which was not possible through the programmed predictability of Z-brush. The final object made by Jennifer Gray does not look or feel like a digitally produced object, in fact no-one would know. The final piece in which the hand was re-introduced, with all its imperfections and subtle flaws, made a home for the aura.

3 Discussion and conclusion

Questions of authenticity and aesthetics therefore arose out of our process. The most interesting moment was when Jennifer decided to change to carving the design into the wax, rather than continue virtually using the software Z-brush as originally planned. For the visitor their experience of the artefacts displayed was visual and the final fitting had to sit comfortably alongside Early Medieval fragments of metalwork and depictions of such objects within the museum context. Only Jennifer and ourselves had truly sympathetic appreciation of the materiality or immateriality of the craft process. Visually, it was important to capture the inconsistency and hand-made quality that Jennifer noted in the execution of the decoration on the St Ninian's Isle chapes – in comparison the Z-brush carved result would have been too rigid. When the 3D printed maquette was temporarily on display it appeared almost out of place and unfamiliar. The flow and movement of Pictish pattern had to be captured in our final design. Although planned to a degree, interestingly Jennifer talked about learning a formula through the carving/incision process directly into the wax; the geometry occupied the space and emerged iteratively through her hands and tools pressing into the material, directly informing the nature and flow of the marks made. The hand-tools used today in metalwork have hardly changed since the Early Medieval period. Embracing this relationship between the tangible 3D form of the wax, iterative design and the tools used, ultimately made the result more aesthetically pleasing and to the viewer who expects imperfections it was thus regarded as an authentic design. The digital, as yet, cannot satisfactorily replicate this necessary physical and idiosyncratic relationship with material. The move from virtual intangible pixels to physical tangible crafting was therefore necessary to mitigate this different unfamiliar and uncertain ecology.

Silver-casting in the Early Medieval period would have been an organically based craft; in our collaboration the organic was replaced by the virtual object. The distinctive qualities of the skeuomorphic shift in substance to silver from organics (or to ABS plastics from pixels in virtual 3D space) was noted; the translation of warm dull organic fittings (or cheap toy-like 3D ABS plastic prints) into cold, bright, polished and heavy silver drastically changes the haptic and visual experience of a drinking horn. The final silver objects are in fact solidified ghosts of ornate organic artefacts which rarely survive. Perhaps in a similar light for medieval people, an organic fitting for a drinking horn may have been perceived as cheap and inappropriate stand-ins like the 3D printed maquette. There is an argument that Pictish stone crosses are skeuomorphic of wooden ones which do not now exist (Kelly 1991: 105-145 and MacLean 1995) and this may have been for similar reasons.

Additionally, it had become clear to us throughout our integrated process that similar design decisions and aesthetic considerations are involved in virtual re-creation as in physical re-creation. Nevertheless, digital and the traditional crafting each have their own qualities, potentials and limitations which are creatively exploited by the craftsperson; thus a sympathetic understanding of the distinctive [im]materialities of each technique was important. The digital allowed Jennifer to experiment with the 3D form of an object which otherwise does not exist (we only have fragmentary or partial 2D evidence surviving from the Medieval period). The returning public to the 'Creative Spirit' exhibition were surprised to find that the final silver cast object replacing the ABS maquette had a very hand- crafted appearance despite being partly made through digital processes. The result sat convincingly amongst other Early Medieval objects – in the end the technologies blended naturally into the object. The unfamiliar newness of the digital had been made familiar and historicised.

To conclude we want to quote from Glenn Adamson:

'It is in forming a new relation to the past that craft proves most indispensable.'

Indeed, the hand-crafted can be blended together with the digital in order to create a result which is very relevant now and for audiences to our exhibition this meant it was not just another replica but rather they appreciated the fitting also for its own quality, beauty and skill. Thereby, in performing Early Medieval design in the present through skilful digital crafting the object had an enchanting affect upon the viewer (Gell 1998). By adopting an approach which celebrates our own skills, creativity and knowledge, its relevancy is elicited ensuring that we will continue to learn from tradition into the future, echoing Gell (1998: 256); '[art] is never neither traditional or innovatory in any absolute sense…A 'traditional' artefact is only 'traditional' when viewed from a latter-day perspective'.

There must be transparency in collaboration which seeks to understand the past from the present. This is possible by mitigating contemporary and traditional craft. Archaeologists are outsiders looking in, whereas makers have a subjective reflexive relationship with craft process which is invaluable for understanding the intricacy of design in the past and ultimately for achieving aesthetically authentic results for a museum context. Despite embracing the benefits of digital technology, in our case exploration could not be fully replaced by it: apparent authenticity for the final piece was achieved in the skill of the body-material-hand (and not computer). Jeffrey advocates that until we 'acknowledge our own creativity as digital craftspeople' (Jeffrey 2014: 150) the digital will remain in the realm of the 'weird'. Our drinking horn, and its display as a work in progress during 'Creative Spirit', can be argues as a step in this direction. On a final note, one of the most exciting things about digital technology is that it offers new possibilities for interrogating objects which would otherwise be for most heritage publicly funded institutions too risky and economically unviable to bring back to life.

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Bibliography

Adamson, G. 2013. *The Invention of Craft*, London, Bloomsbury.

Benjamin, W. 1936 (reprinted 2008). *The work of art in the age of mechanical production*, London, Penguin Great Ideas.

Dorian, M. 2014. Museum atmospheres: notes on aura, distance and affect. *The Journal of Architecture* 19, 2: 187-201. DOI: 10.1080/13602365.2014.913257.

Foulds, F. 2012. *Experimental archaeology and theory,* Oxford, Oxbow Books.

Gell, A. 1998. Art and Agency: an anthropological theory. Oxford, Oxford University Press.

Hazan, S. 2001. The Virtual Aura - Is There Space for Enchantment in a Technological World? http://www.museumsandtheweb.com/mw2001/papers/hazan/hazan.html#ixzz2TjI4nOHp

Under Creative Commons License: Attribution Non- Commercial No Derivatives. [Accessed: 13th November 2015].

Huggett, J. 2004. Archaeology and the New Technological Fetishism. *Archeologia e Calcolatori* 15: 81-92.

Holtorf, C. 2013. On pastness: a reconsideration of materiality in archaeological object authenticity. *Anthropological Quarterly* 86, 2: 427-43.

Jeffrey, S. 2015. Challenging Heritage Visualisation: Beauty, Aura and Democratisation. *Open Archaeology*, 1, 1: 144-52. Available at doi:10.1515/opar-2015-0008 [Accessed: 8th july 2015].

Jones, S. 2010. Negotiating authentic objects and authentic selves: beyond the deconstruction of authenticity. *Journal of Material Culture*, 15, 2: 188-97.

Kelly, D. 1991 The Heart of the Matter: Models for Irish High Crosses. *Journal of the Royal Society of Antiquaries of Ireland*, CXXI: 105-45.

Latour, B., Lowe, A. 2011. The migration of the aura, or how to explore the original through its facsimiles. In Bartscherer, T. (ed.), *Switching Codes*, Version 3: 1-13. Chicago, University of Chicago Press.

Laurel, B. 2013. *Computers as theatre*. Boston, Addison-Wesley.

Lowenthal, D. 1995. Changing Criteria of Authenticity. In K. E. Larsen (ed.), *NARA Conference on Authenticity in Relation to the World Heritage Convention*: 121–35. Trondheim, Tapir Publisher.

Maclean, D. 1995. Technique and Contact: Carpentry-constructed Insular Stone Crosses in Bourke, C. (Ed.) *From the Isles of the North: Early Medieval Art in Ireland and Britain: Proceedings of the Third International Conference on Insular Art Held in the Ulster Museum, Belfast, 7-11 April, 1994*. Stationery Office/Tso: 167-75.

Mccullough, M. 1998. *Abstracting Craft: The Practiced Digital Hand*, Cambridge, MIT Press.

National Museum Of Scotland 2014. *Creative Spirit: revealing Early Medieval Scotland.* http://www.nms.ac.uk/explore/collections-stories/scottish-history-and-archaeology/early-medieval-scotland/bringing-the-past-to-life/drinking-horns/ [Accessed 6th august 2014].

Pearce, S. (ed.) 2003. Objects as meaning; or narrating the past. In S. Pearce (ed.), *Interpreting Objects and Collections.* London, Routledge: 19-29.

Sennet, R. 2008. *The Craftsman.* New Haven, Yale University Press.

Wilkinson, A. 2002. *Henry Moore Writings and Conversations,* London, Lund Humphries Publishers Ltd.

Computer Applications for Multisensory Communication on Cultural Heritage

Lucia Sarti
lucia.sarti@unisi.it
University of Siena, Department of History and Cultural Heritage - Prehistory

Stefania Poesini
poesini3@unisi.it
University of Siena, Department of History and Cultural Heritage – Prehistory

Vincenzo De Troia
v.detroia@tecsette.com
Tecsette srl

Paolo Machetti
info@tecsette.com
Tecsette srl

Abstract: The paper aims to illustrate the design and implementation of subsidies for a multisensory communication of the cultural heritage for inclusive fruition through innovative processing techniques designed specifically with technological solutions and experimental studies of materials for the reproductions of mobile artefacts, plans and touch panels.

Information technologies have been added to works through experimental archaeology for the reproduction of artefacts for multi-sensory itineraries.

In our experience, some specific computer applications are important to improve the fruition of historical-artistic heritage also to people with sensory disabilities penalized by communications systems generally used in these contexts.

In this paper we show some projects and solutions for museums and naturalistic- archaeological trails accessible to all sort of visitors.

The purpose of this 'cultural routes' is to remove barriers of various types, starting with the removal of sensorial barriers. We realised reproductions of some archaeological objects to be explored using one's hands with particular interest to communicate to the blind and visually impaired people.

Keywords:Design for all, Three-dimensional modelling, Inclusive fruition, Multisensory communication, Good practices

The possibility to create inclusive itineraries, in museums or natural and archaeological parks, has led to reflect on the processing methods and means necessary to meet this objective. The importance of the Italian archaeological heritage is an opportunity to reflect on this issue (Vescovo 1996; Monzeglio 2004) as we have done, even recently, during the conference 'Accessit' (Angelaccio, Sarti, Poesini 2013).

The three-dimensional modelling is, in our experience, an effective means for the realization of multisensory media especially for users with sensory problems (blind, deaf …) or otherwise penalized by communication systems generally used in these contexts. Simplified communication has to be conceived as an integral part of the itinerary and directed to all users. In fact the transformation of the traditional paths in multisensory experiences, aims involve all visitors regardless of physical and sense-perception abilities.

For about ten years we have focused on creating a dialogue between cultural heritage and the public, taking care not to exclude anyone from this communication (Bianchi, Sarti, Poesini 2011); for this reason, the inclusive project we are presenting here needs effective and resolving means in this regard.

The project 'Not Touching Prohibited[1]'(Office of Disabled Student 2004) of the University of Siena, result of collaboration between the Department of Historical and Cultural Heritage[2] and the Hospitality Office for disabled and DSA Services[3] has aimed, among other objectives, to seek ways and new languages to communicate the cultural asset to a wide audience, following the guidelines of the 'Design for All' (Council of Europe 2009; Neumann *et al*. 2013; Angelaccio, Giorgi, Sarti 2007: 161-3).

In this perspective we have experienced a series of actions in partnership with Tecsette specialized in developing solutions and effective supports with the use of specific computer

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1 http://www3.unisi.it/vietatonontoccare/progetto.htm.

2 The Department of History and Cultural Heritage developed also researches on exhibition adopting the 'Design for All' concepts and developing specific criteria offering consultancies and thematic courses on promotion of Cultural Heritage in collaboration with the office of disabled student and DSA services.

3 The office of disabled student and DSA services supports all students with disabilities at University of Siena. The Office works towards removing the cultural, physical and psychological barriers that can prevent disabled students from participating fully in university life. The office aims to integrate all students with disabilities and improve local awareness of disability.

Fig. 1. Ceramic Bowl of Loreto Aprutino, Technical steps.

applications. The collaboration with Tecsette initially concerned projects relating to the findings and study of archaeological finds and engraved rocks for research purposes (Poesini *et al*. 2008) and have since been extended in the building prototypes for an inclusive design.

Information technologies have been added to works through experimental archaeology[4] with the reproduction of both mobile artefacts and plans and touch panels.

At this conference, we present some of the works created for temporary museum exhibitions, outdoor areas and study days, as examples of good practices to be followed for an inclusive fruition for all.

Much attention has been devoted to blind people, since they may be considered perhaps the most penalized users for the fruition of cultural heritage and also because the simplification of the information and the creation of tactile panels may be an opportunity to find an effective way to address all users.

Furthermore, considering the regulations on the preservation of cultural heritage, it is important to use three-dimensional modelling for the realization of tactile compositions to be freely used (Furferi *et al*. 2014).

For overcoming sensory barriers and, as far as possible, cognitive ones, the expedients for accessible exhibit set-up (such as tactile and orthotic paths, guides for orientation, tactile maps and other technical and technology aids) should be integrated with tactile reproductions of the objects normally exhibited inside the cabinets, representing the context where they are placed, in a word, the vocation of 'that place' attracting the visitor (cards 1 e 2; Fig. 1 e 2). These subsidies are designed as communicative enrichment for everyone, not only for certain categories of people (Conti, Garofalo 2014). From these premises the attempt to realize tactile objects that combine the technological world to the cultural one, opening to new forms of communication, originates.

The use of laser scanner allows the reproduction of an object exactly as it looks, without violating legal obligations and reproducing copies without any contact (Verdiani 2012).

[4] The collaboration with the Interuniversity Research Center for the study and promotion of Prehistoric cultures, technologies and landscapes - CRISP | Department of History and cultural heritage, is important for the reproduction of experimental artefacts for multi-sensory itineraries.

Fig. 2. Bronze statuette of Jupiter, Loreto Aprutino, Technical steps.

Fig. 3. Technical and conceptual steps.

Its use is very useful for those finds the interpretation of which would be difficult even to the most experienced eye, such as the identification of some rock carvings (card 4; Figs 4 e 5) or movable finds, or the recognition of marks as raw material processing methods.

However, the transition from an archaeological document to a multisensory work, is not always so easy and immediate, and needs thoughts and expedients that 'change' or sometimes partly simplify the original document, in order to be more effective in the communication. For instance, it occurred when we had to make accessible to the public a painted pot. Through the laser scanner it has been possible to transform the painted parts in an equivalent textured relief, making it perceptible to tactile exploration (cards 3; Fig. 3). However, this is a choice that in our experience we have taken care of interfacing with blind, deaf and who use communication systems to be integrated with the more traditional ones.

The possibility to make the object differently interactive, identifying sensitive areas that, once touched, release information, is one of the projects we are working on, in order

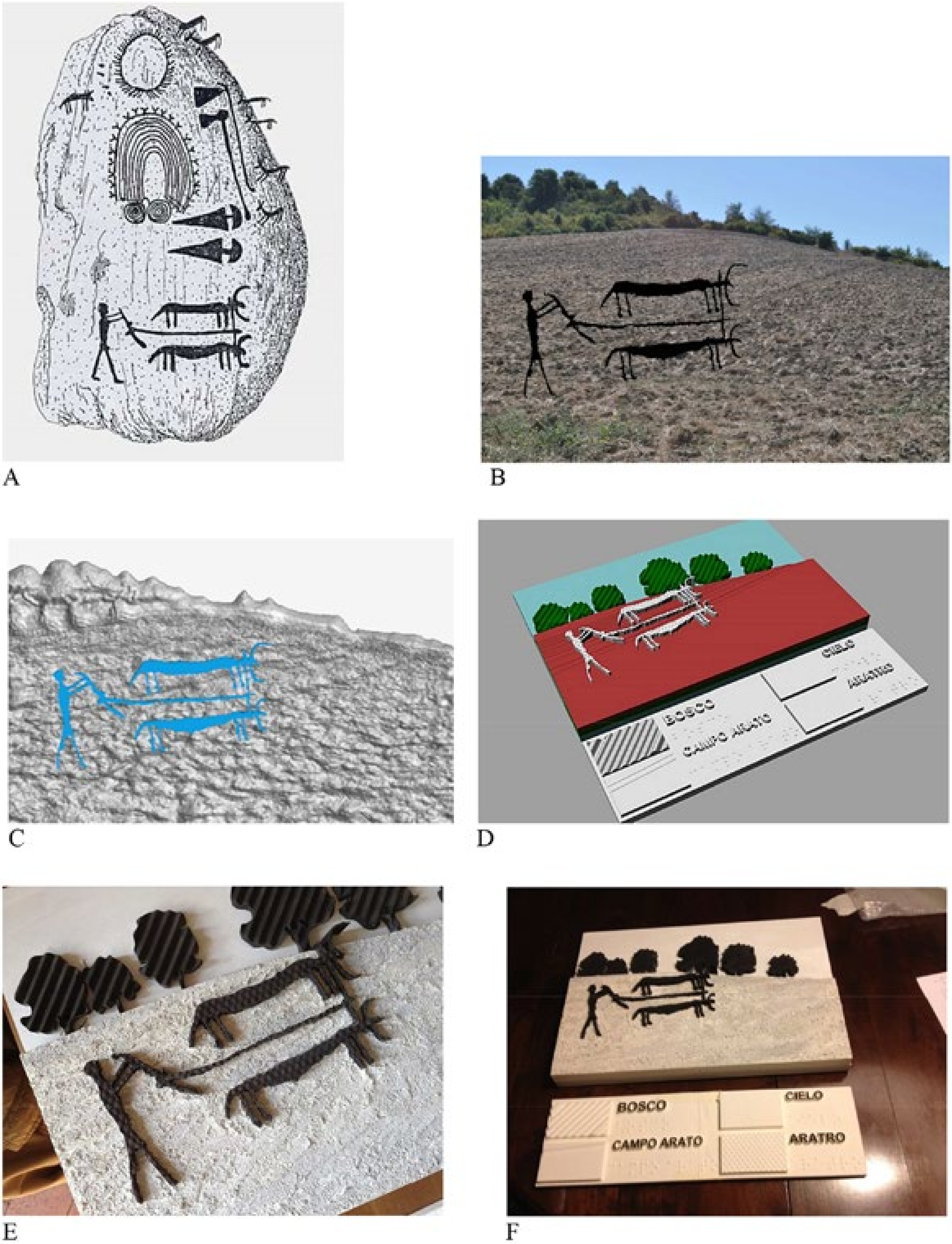

FIG. 4. TACTILE RECONSTRUCTION: A. ENGRAVED BOULDER FROM BAGNOLO, VALCAMONICA-BRESCIA, 4TH MILLENNIUM BC; B. CONTEXTUAL RECONSTRUCTION PROPOSED USING LANDSCAPE SUGGESTIONS; C. 3D LASER SCANNER RELIEF; D. ELABORATIONS OF DATA; E. FINAL RESTITUTION WITH DIFFERENT MATERIALS; F. BRAILLE AND THREE-DIMENSIONAL LETTERS.

Fig. 5. Exhibit 'Non solo Pane', 'Zero Barriers' (Matera 2014).

to integrate the tactile aspect of the model with the content-processing related one, through specific computer applications (cards 6; Fig. 9)

Through the creation of a tactile, simple and intuitive language, it is possible to characterize environments, write texts in relief and transform chromatic images in low reliefs or texture containing information or even all-round objects, simply using the characteristics of the print by addition or subtraction of material, whenever we want to build objects of small or large and/or different materials. The graphic rendering of any object or location undergoing this procedure, takes place primarily through the acquisition by 3D laser scanner technology returning a mathematical model to scale. The model, simplified (deprived of any tactile nuisance), moves to the next phase of identification of the areas for tactile recognition, by granting special 3D textures specifically designed to be extremely perceptible to the touch. At a later stage a cutter, in the case of considerably large objects, and/or a 3D printer to material accumulation, concludes the work, returning the same object adapted to the needs of the final user (Reichinger, Maierhofer, Purgathofer 2011).

Our project consists in using computer technologies, well known in the international scene (see for ex. Reichinger 2010), for the search of different materials for the copies, not only resins or synthetic materials. We propose an accurate choice for a simplification of the images, to return the different level of the pictures or photography.

The versatility of both architectural, artistic, archaeological or purely utilitarian field (plan of the building to be visited) has been tested both for indoor and outdoor installations.

In all cases, whether in museums or archaeological parks, natural as well as urban spaces, or accommodating structures, the orientation is an element we cannot disregard for the use of a given space and\or collection and, therefore, to speak of accessibility (Agostiano *et al*. 2008: 19-25).

The creation of tactile maps, both carved and in relief, as aids for orientation of all users, has been made possible thanks to three-dimensional processing, with the identification of simplified routes and the creation of a simple and direct didactic language (cards 5; Fig. 6-8).

Cards:

1) Ceramic Bowl of Loreto Aprutino (Moscetta, Maggiori 1998) (Fig. 1), Middle Bronze Age. Museo delle Genti d'Abruzzo – Pescara.

The choice of the archaeological document: document typical of the Bronze Age culture in Italy and element of cultural diffusion.

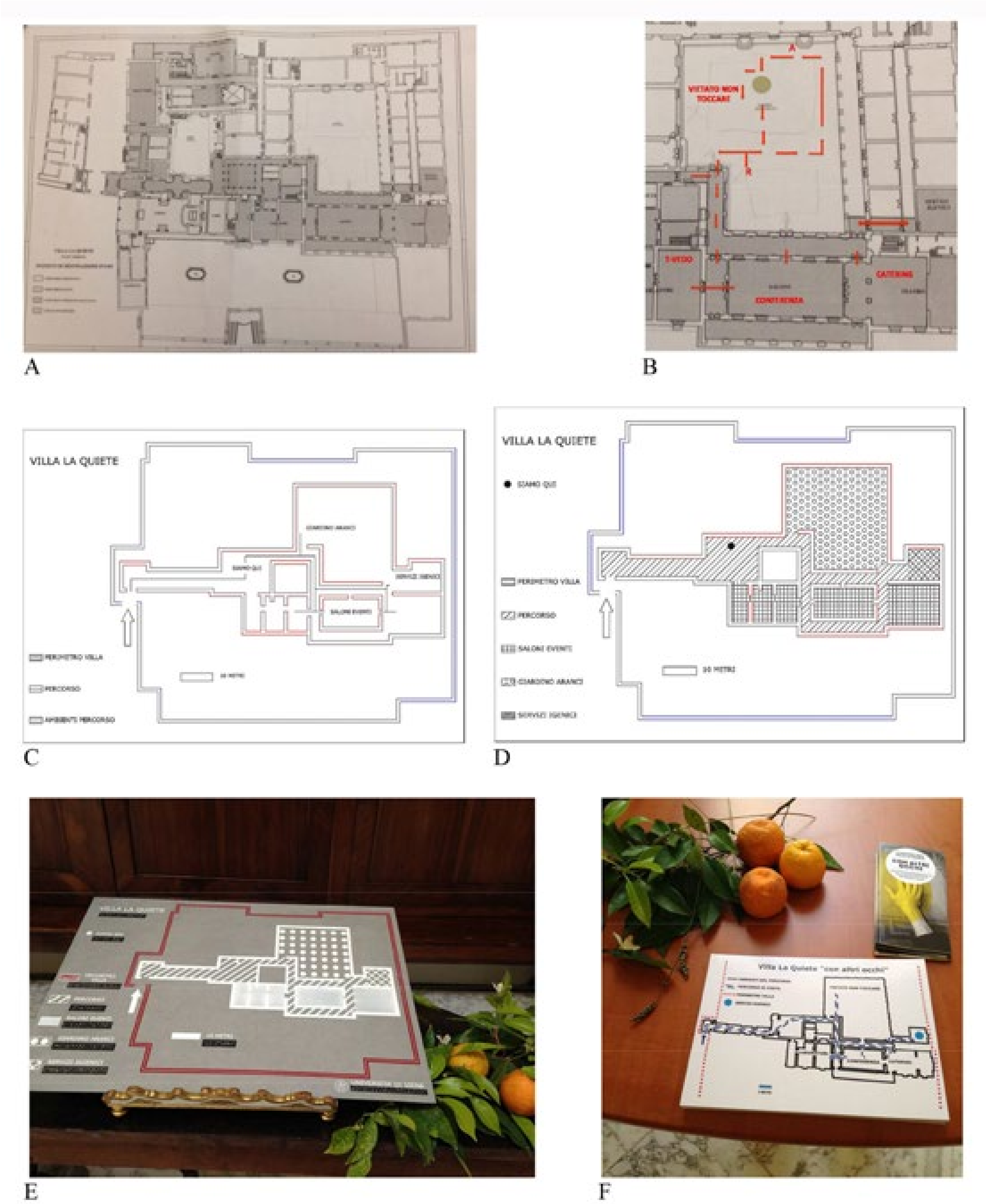

FIG. 6. TACTILE PLANS FOR HISTORIC ENVIRONMENTS, VILLA LA QUIETE, FIRENZE: A. ORIGINAL PLANT; B. STUDY OF PATHWAY; C. PROJECT OF PATHWAY; D. TEXTURED PATHWAY; E. FIXED TACTILE MAP, F. MOVABLE TACTILE MAP.

Technical steps: 3D laser scanner survey; 3D model; resin model; resin copy; mould clay; terracotta copy and coloured ceramic with different material restitutions.

2) Bronze statuette of Jupiter (Sanzi, Malavolta 1998) (Fig. 2), 1st century BC. Museum of Loreto Aprutino – Pescara.

The choice of the document: significant archaeological document of the late Hellenistic period representing a juvenile figure, probably Jupiter.

Technical steps: 3D laser scanner survey; 3D model; resin model; bronze copy.

3) Painted vase from Catignano (Genti d'Abruzzo 2008) (Fig. 3), Middle Neolithic. Museo delle Genti d'Abruzzo, Pescara.

The choice of the document: archaeological document significant to understand decorative techniques and types in pottery during the Neolithic in Italy.

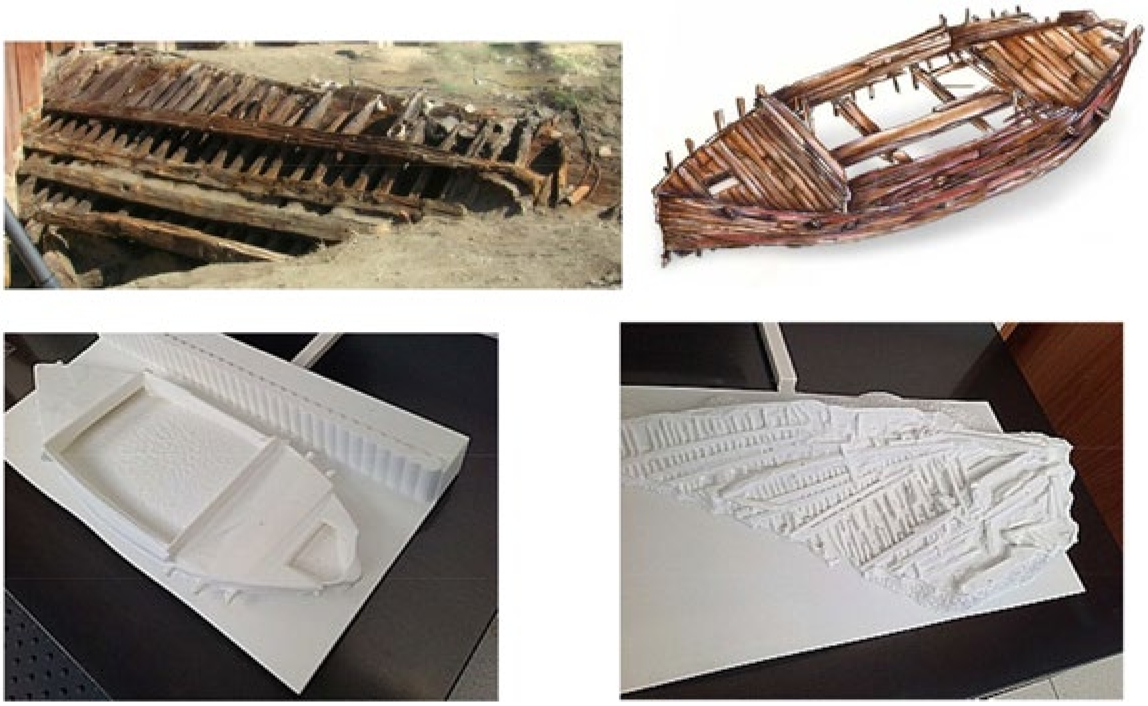

Fig. 7. Reconstruction of the models of artefacts referring to shipwrecks A and D from the excavation of the Ancient Ships of Pisa San Rossore. 'Accessit project', Tecsette.

Technical steps: 3D laser scanner survey and data processing with identification of painted areas to be textured differently from the unpainted surface; 3D model; resin model; resin copy, ceramic copy.

Insertion of the works in the traveling exhibit 'Not Touching Prohibited', Complex Ex Aurum, Pescara 2008. Project 'The province of Pescara, the first Italian tourist district on universal accessibility'.

4) Engraved boulder from Bagnolo 2 (Fig. 4), Valcamonica-Brescia (Casini 1994), IV millennium BC.

The choice of the archaeological document: one of the oldest images of ploughing in the national territory.

Difficulty of reading the original document: engraving on thin rock.

Processing needed to communicate the archaeological document to a wide audience: contextual reconstruction proposed using landscape suggestions for the understanding of the document (photo of the current agricultural landscape).

Technical steps: 3D laser scanner relief; restitution of the model; simplified model and texturing; final restitution in synthetic material.

Insertion of the work in the traveling exhibit 'Non solo Pane' as part of 'Zero Barriers,' Matera 2014, with positive feedback from the public on the effectiveness of the multisensory disclosure/dissemination (Fig.5)

5) Tactile plans for historic environments and accommodating structures -

The projects 'Accessit'[5] and 'Con altri occhi'[6] ('With Other Eyes') we took part in, with the creation of prototypes and multisensory fittings, provided the opportunity to design tactile fixed and movable maps (Fig. 6), with the simplification of the routes, the identification of landmarks and the choice of codes of universal communication, proven essential for a mobility within spaces otherwise too complex.[7]

6) Reconstruction of the models of artefacts attributable to shipwrecks A and D from the excavation of the Ancient Ships of Pisa San Rossore (Fig. 7), starting from 3D models through laser scanner acquisition. This process is realized through a photo-polymer printer. The obtained model is then used as a prototype for the insertion of tactile sensors that is micro buttons sensitive to mechanical input with a sound output and video that will transmit pulses to dedicated software.[8]

The need to integrate auditory and tactile information, to meet the needs of an audience as wide as possible, is an opportunity for reflection: IT/digital supports and applications cannot exclude tactile and material solutions, giving more concreteness to the proposed subject.

5 The Strategic Project 'Accessit', inside the Community program Italy - France Maritime 2007-2013, aims to develop a network of cultural heritage, to manage and develop in an integrated way, in four regions Tyrrhenian: Liguria, Tuscany, Sardinia and Corsica.

6 'Con altri occhi' is the title of a conference about the relationship between blind and visually impaired people and the cultural heritage which was held on May 2014 at Villa 'La Quiete', in Florence, on the initiative of the Centre for Studies and Research on the problems of disability (Cespd) in collaboration with the AIL (Department integrated institutional AOUC- University of Florence).

7 http://www.sciencemuseum.org.uk/visitmuseum/accessibility.aspx.

8 Accessit project, Tecsette.

The planning and creation of subsidies for a multi-sensory communication of cultural heritage is therefore a 'work in progress' (Poesini *et al.*, in press); with the help of flexibility and new solutions, it adapts to the identified needs, also through the rapidly changing technologies for an inclusive fruition.

Bibliography

Agostiano, M., Virdia, E., Pane, A., Caprara, G., Baracco, L. (eds.) 2008. *Linee Guida per il superamento delle barriere architettoniche nei luoghi di interesse culturale*. MIBACT.

Angelaccio, D., Giorgi, M. G., Sarti, L. 2007. Vietato non toccare. Percorso museale tattile-olfattivo. *Museologia Scientifica* 1: 161-3.

Angelaccio, D., Sarti, L., Poesini, S., 2013. Metodologie di valutazione e proposte di interventi in aree archeologiche della Toscana. 'ACCESSIT'– *Itinéraires des Patrimoines Accessibles.* Sorano-Grosseto.

Bianchi, G., Poesini, S., Sarti, L. 2011. Archeologia fra gestione e comunicazione. Parchi archeologici e accessibilità universale: l'esperienza senese tra bilanci e prospettive, in E. Vannini (ed.), *Archeologia pubblica in Toscana - un progetto e una proposta*: 85-98. Firenze, Firenze University Press.

Casini, S. (ed.) 1994. *Le Pietre degli Dei. Menhir e stele dell'età del Rame in Valcamonica e Valtellina*. Bergamo, Exhibition catalogue.

Conti, C., Garofolo, I. 2014 AA_AccessibleArchaeology. Environmental accessibility as a key to enhance cultural heritage. *TECHNE - Journal of Technology for Architecture and Environment*: 140-8.

Council of Europe (eds.) 2009. *Recommendation CM/Rec(2009)8 of the Committee of Ministers to member states on achieving full participation through Universal Design*

Furferi, R., Governi, L., Vanni, N., Volpe Y. 2014. Tactile 3D bas-relief from single-point perspective paintings: a computer based method. *Journal of Information and Computational Science* 11, 16: 5667-80.

Guidi, G., Beraldin J. A 2004. *Acquisizione 3D e modellazione poligonale - dall'oggetto fisico al suo calco digitale.* Milano, Poli.Design.

Monzeglio, E. 2004. Reserve or natural trails accessibility: is the physical disability the unique and fundamental variable? In C. Cestari Bertolini (ed.), *Interaction between science, technology and architecture in timber construction*: 187-204. Paris, Elsevier.

Moscetta, M. P., Maggiori, M. 1998. Il territorio di Loreto Aprutino nell'età del Bronzo in A. R. Staffa (ed.), *Loreto Aprutino e il suo territorio dalla Preistoria al Medioevo*: 11-13. Loreto Aprutino, CARSA Edizioni.

Museo Delle Genti D'abruzzo 2008. *Guida dal museo al territorio di Pescara*, Loreto Aprutino, CARSA Edizioni.

Neumann, P., Knigge, M., Iffländer, K., Kesting S. 2013. Developing criteria for guiding SME activities aimed at incorporating the Design for All concept in corporate practices. *Study commissioned by the Federal Ministry of Economics and Industry*. Münster, Hamburg.

Office Of Disabled Student And Dsa Services, University of Siena 2004. *'Not Touching Prohibited'*. Exhibition catalogue, Siena

Poesini, S., Angelaccio, D., Giorgi, M. G. , Sarti , L (in press). 'Vietato non Toccare' e progettazione plurisensoriale. *XXIII CONGRESSO ANMS. Allestire per comunicare nei musei scientifici, Museologia Scientifica, 13-15 novembre 2013.* Venezia.

Reichinger, A. 2010. Gallery Paintings for Blind and Visually Impaired People, *Talk at SpaceX - An Exchange Forum on Information Design for Visually Impaired People*, Vienna, 25-26 october 2010.

Sanzi, M. R., Malavolta, S. 1998. La cella del santuario di Poggioragone in A. R. Staffa (ed.), *Loreto Aprutino e il suo territorio dalla Preistoria al Medioevo*: 48-51. Loreto Aprutino, CARSA Edizioni.

Ufficio Accoglienza Disabili, Università degli Studi di Siena 2013. *'Non Solo Pane'*. Exhibition catalogue, Siena.

Poesini, S., Machetti, P., De Troia, V., Spinetti, A. 2008. Laser scanner: applicazioni relative alla definizione formale dei contenitori ceramici. sez. Poster. *Atti della XLIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria. L'età del Rame in Italia, 26-29 novembre 2008, Bologna*: 509-13.

Reichinger, A., Maierhofer, W., Purgathofer, W. 2011. High-Quality Tactile Paintings. Journal of Comupting and Cultural Heritage 4, 2: 5.1-13. New York, ACM

Vescovo, F. 1996. Zone archeologiche e accessibilità. In *Paesaggio Urbano*, nov.-dec. 1996. Rimini, Maggioli editore.

Verdiani, G. (ed.) 2012. Il ritorno all'immagine, nuove procedure image based per il Cultural Heritage. lulu.com

Website

National Science Foundation 2011. *Planning Archaeological Infrastructure for Integrative Science*. NSF Award Number 1202413 November 2011. http://www.nsf.gov/awardsearch/showAward. [Accessed: 14th july 2014].

Science Museum London. http://www.sciencemuseum.org.uk/visitmuseum/accessibility.aspx. [Accessed: 15th november 2014].

Vietato Non Toccare, Universita' Di Siena. http://www3.unisi.it/vietatonontoccare/progetto.htm. [Accessed: 15th november 2014].

Interactive Communication and Cultural Heritage

Tommaso Empler
tommaso.empler@uniroma1.it
Department of History, Representation and Restoration in Architecture, Sapienza University of Rome

Mattia Fabrizi
matfabrizi@gmail.com
Department of History, Representation and Restoration in Architecture, Sapienza University of Rome

Abstract: The advent of digital technology and new media has changed the expectations of visitors, driving the use of new solutions and technologies to deliver content that meets their demands. Cultural heritage visits are no longer solely information-based, but have now become all-round multisensory experiences.

The study proposed here aims to communicate further information about the nature and state of cultural objects, by means of the spontaneous and natural interaction of visitors physically pointing at the parts they are interested in.

A practical application of the procedure has been designed for the Forum of Nerva in Rome. The experiment was conducted with a Kinect sensor and Leap Motion 3D. A small-scale 3D print of the Colonnacce was made for the laboratory tests so that the results would be as realistic as possible.

Keywords: Interaction, Virtual reality, Communication view, 3D modelling, 3D simulation

Introduction

The new forms of communication for cultural heritage have seen an increase in methods of interaction between visitors and exhibits. Visitors are no longer the traditionally passive recipients of information, but are now more active in the exploring and learning process and are able to decide which forms of delivery they prefer. This new approach has led to more and more museum structures presenting their scientific and educational content in such a way as to be experienced 'subjectively' by visitors through the use of instruments that can detect their intentions/actions/movements and turn them into human-machine interactions. In turn, computer-developed applications enable multiple variations in the way a single object can be explored, thus improving our understanding of it.

Following this direction we propose a research where is planned an interactive exploration of the archaeological area of the Forum of Nerva in Rome: visitors can get more advanced information, on the remaining columns, called 'Colonnacce', just pointing at the parts they are interested in.

1 Recent solutions

The advent of digital technology and new media has changed the expectations of visitors, driving the use of new solutions and technologies to deliver content that meets their demands. Cultural heritage visits are no longer solely information-based, but have now become all-round multisensory experiences (Neves 2002; Chamberlain 2014).

Several studies have been made in direction to meet visitor needs (Sheng 2012; O'Flaherty 2014) and strategies used to date can be placed into three categories:

- narrative approach: communication and language are designed to engage the visitors' emotions in their experience of the cultural object (Monaci 2006).
- interaction: visitors play an active role and are not mere passive targets of the message (Antinucci 2007).
- new media and innovative forms of communication (Salerno 2013): exploration of content with various devices on several platforms. Examples include augmented reality, mobile devices (tablets, smartphones), touch screens, projection mapping etc. (Shumaker 2014).

The 'active' engagement of users enables them to interact and change the message they receive. Technological progress now allows us to take interaction beyond the screen, moving away from hardware interfaces, such as keyboards and mice, to gesture, voice, proximity and touch detection systems.

We can see how this evolution might point to the idea of natural interaction: a simple, immediate and direct way of communicating with the digital medium (Pescarin 2013).

There are numerous initiatives that help us to understand the current state of research and experimentation.

For a brief look at how Italy shapes up in this field of study, we can assess the following recent exhibitions, chosen as examples, remaining in the field of archaeological sites, for understanding the purpose of the application proposed in the next section:

- 'Order and light. A virtual journey through evolution of interior space in the history of architecture from ancient Greece to the Renaissance' – Mantua 2013-2014.
- 'Keys to Rome. The City of Augustus' – Rome 2014-2015.
- 'The Forum of Augustus. 2000 years later' – Rome 2014-2015.
- 'Journeys into Ancient Rome' – Rome 2015.

Fig. 1. Immersive/interactive reality, through body movement. Temple of Apollo Epicurius at Bassae in the exhibition/event 'The Order and the Light'.

Fig. 2. Virtual reality torch in the exhibition 'Keys' Rome. The City of Augustus'.

The exhibition/event 'The Order and the Light. A virtual journey through evolution of interior space in the history of architecture from ancient Greece to the Renaissance', held at the Centre for International Art and Culture, Palazzo Te in Mantua, from 15 December 2013 to 16 March 2014 (Centro Internazionale d'Arte di Cultura di Palazzo Te, 2013), relied on the use of 3D modelling/reconstruction of the great classic architectural monuments (such as the Parthenon, the Temple of Apollo Epicurius at Bassae (Fig. 1), the Temple of Apollo *Sosianus* in Rome, the *Domus Aurea* and the Trajan Spas) to provide visitors and scholars alike with a realistic insight in an immersive/interactive reality, through body movement.

The Museum of Imperial Fora, Trajan's Market, from 24 September 2014 to 10 May 2015 hosted 'Keys' Rome. The City of Augustus', an exhibition on the discovery of the Augustan Age centred on the use of new technology applications available to visitors (Ungaro 2014).

This museum experience consisted of films, interaction systems and interactive applications guiding the visitor through Roman history.

A map of the City in the museum great hall gave the visitor the sensation of 'walking' about in Rome some two thousand years ago, some of the rooms being equipped with interactive and multimedia aids including:

- Virtual reality torch - 'augmenting the reality of assets' (Fig. 2).
- Virtex – 'Touching the asset'.
- Matrix totem – 'Playing with the assets'.
- AR-tifac – 'Augmenting the reality of assets'.
- Admotum – 'Playing with the assets' (Fig. 3).
- Holobox – 'Augmenting the reality of assets'.

Celebrations for the bimillenary of Augustus's death (19th of August, 14 AD) helped valorise the Imperial Fora with project

Fig. 3. Use of Kinect interaction in the exhibition 'Keys' Rome. The City of Augustus'.

'Forum of Augustus. 2000 years ago', from 22 April to 21 October 2014 (Ministero dei beni e delle attività culturali e del turismo, 2014). Here, the communication tool was a multimedia installation with projection on the walls of the Forum of Augustus, representing the history of Augustus and the Forum with lights, films and projection mapping reconstructions.

The success of the 2014 edition of 'The Forum of Augustus. 2000 years later' led to the organisation of 'Journeys into

Ancient Rome' (Viaggio nei Fori, 2015), from 25 April to 1 November 2015.

Reconstructions and videos take visitors back through the history of the excavations carried out to build Via dei Fori Imperiali, when an army of 1,500 construction workers, labourers and other workers were enlisted in an operation unlike any before to raze an entire neighbourhood to the ground and dig down to ancient Roman street level.

The exhibition went right into narative, starting with the remains of the impressive Temple of Venus, whose construction was ordered by Julius Caesar after his victory over Pompey, reliving the emotional experience of life in Roman times, when officials, commoners, soldiers, matrons, consuls and senators walked beneath the arches of the Forum. Among the remaining colonnades can be seen the *tabernae*, which were offices and shops and, among these, a *nummularius*, a kind of currency exchange office. There was also a large public lavatory, some of whose remains are still in existence.

The visit tried to recapture the role of the Forum in the life of Romans, as well as the figure of Julius Caesar. To build this great public work, Caesar expropriated and demolished an entire neighbourhood and the overall cost was 100 million *aurei*, the equivalent today of at least 300 million Euros. He also wanted the new home of the Roman Senate, the *Curia*, to be built right next to his Forum. The *Curia* still exists and virtual reconstructions show us what it looked like in Roman times.

2 Proposed solution

The study proposed here aims to communicate further information about the nature and state of cultural objects, by means of the spontaneous and natural interaction of visitors physically pointing at the parts they are interested in.

The term 'natural interaction' (Alisi 2008) refers to the relationship between man and machine, where only the natural abilities of human beings are used to communicate with any system, therefore excluding mediation through artificial instruments. The aim is to find the easiest method of using digital media content.

When interfaces are included in the examination (Saffer 2008), we refer to them as Natural User Interfaces (NUI), which are practically invisible and need no training to be used. Everything in these systems has a counterpart in the real world to be certain that it is already part of the human experience. In other words, the basic idea is to apply to the interaction between humans and machines the natural instruments used in interpersonal communication such as the voice, posture, facial expressions and gestures (Pescarin 2013).

In the specific solution proposed, it was decided to use a gesture to select, choose, elements of the real world that can be activated. Pointing is a natural gesture, which we use from early childhood to indicate, obtain information and get to know. The interface thus becomes invisible as a device and part of reality, and hence is easy to interpret and does not need to be learned.

In 'natural design' (Norman 2013), information should be visible and convey the right message so that it can be understood without the need for awareness. All the restrictions and invitations expressed by the object help the user build a mental model, a subjective image of how the system works. This is in opposition to the conceptual model, where operating design is transferred from the mind of the designer to the system. The more the two models converge and overlap, the more users are able to seamlessly understand and interpret the object.

An example of invitation within the project can be observed in signage indicating the place/position the user should be. Icons, which have a strong semantic value in the mind, show users, with no effort on their part, what position they should be in in order to interact with the installation.

Two other elements that are important for creating a mental model are experience and feedback, which inform users what actions have already been completed and what the outcome is.

A laser pointer and the lighting of the area selected are, for example, ways of showing the person what action they are doing and what the purpose is.

By 'pointing' they receive feedback with information about the object they have selected (Saffer 2008).

The procedure behind this applied methodology involves a series of related operations:

1. detection of the object or the area of interest by 3D laser scan. This throws up a 3D model with the dual function of (self-) representation of the object and allowing the Cartesian coordinates (x, y, z) of each point of the model to manage the interaction of the person exploring it.

2. development of the interactive application and creation of an effective interface for interaction between humans and machines.

3. creation of interaction between humans and machines by using tools designed for video games, such as Kinect and Leap Motion 3D.

4. design of an app for portable devices where additional information can be obtained on the cultural object of interest.

5. design of the physical setting where the interactive information is delivered, sectioning off specific areas (boxes, corners, walls) and placing input/output tools within them (projectors, Kinect, Leap Motion 3D).

One concrete application of the procedure has been designed for the Forum of Nerva in Rome, east of Via dei Fori Imperiali, where a number of imperial Roman friezes and columns can still be found. From a given position, visitors can quite naturally point to the part of the object they are interested in, when they are in front of it. For visitors at the site, a spotlight shows what part the visitor is pointing at and Leap Motion 3D tracks their pointing finger.

On the app, Leap Motion 3D detects the position of the pointing finger on the 3D laser model that has been made 'invisible'. When visitors point for longer than five seconds at something

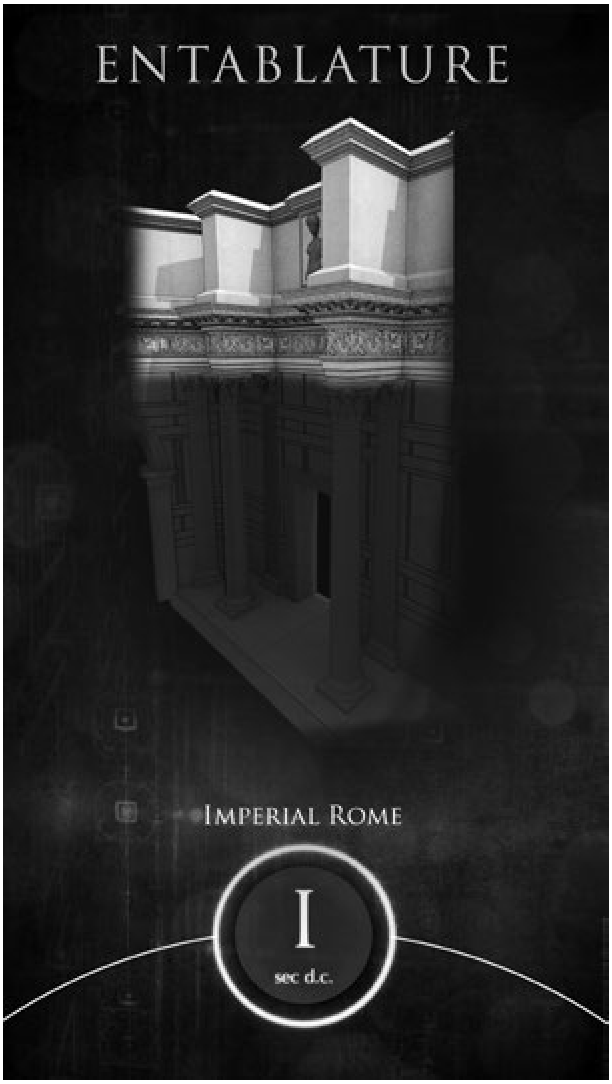

Fig. 4. Forum of Nerva: use of Leap Motion 3D. When visitors point for longer than five seconds at something they are interested in, a video starts illustrating the history or the nature of the object selected.

they are interested in, a video starts illustrating the history or the nature of the object selected (Fig. 4).

The video is projected onto a section of floor in front of the visitor if they are on site or on their iOS smart device if they have downloaded the 'Nervar' App (Empler 2014).

The same exploratory method can be used in the Forum of Nerva hall at the nearby Museum of the Imperial Fora.

3 Experimental results

The experiment was conducted with a Kinect sensor and Leap Motion 3D (Marin 2014). A small-scale 3D print of the *Colonnacce* was made for the laboratory tests so that the results would be as realistic as possible.

The Kinect sensor (Borenstein 2012) can detect with sufficient precision joints and other points that are important in the movement of the body, thus reproducing a schematic model of the human skeleton.

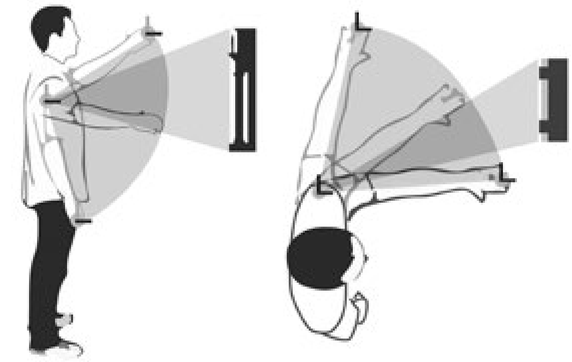

Fig. 5. Forum of Nerva: Kinect interactive working scheme.

In this particular project, Kinect is used to track two of these joints: the shoulder and the hand.

The sensor provides the spatial x, y and z coordinates of these points to draw a vector. The projections can be determined on the zx plane and on the zy plane. The angles formed by these two projections and by the z and y axes respectively provide a value for the rotations of the user's arm around the x and y axes.

Using a conditional structure, the values obtained can relate to the real world to virtual reality. With restrictions on the rotation values (measured on site) to highlight an area (Fig. 5), the hypothesised interactive effect can be achieved.

Leap Motion Sensor 3D (Leap Motion 2014) uses two IR cameras to return the spatial coordinates (in mm) of hands and fingers moving within a specific detectable area of approximately one cubic metre.

The Software Development Kit (SDK) distributed with the sensor orders the x, y, z coordinates and the vectors describing the skeleton of the hand so that these values can be used with leading development tools and platforms: Unity, Unreal, Javascript, C++.

Before focusing further on the development of the interaction with one of the two systems, some tests were conducted on the usability of the Kinect and the Leap Motion, involving 30 volunteers.

Though it's possible to integrate the two systems (Vinkler 2014), we decided to choose the one that provided best results in terms of usability (Marin 2014), compared to the place where the system was supposed to be located (open archaeological area just in front of the 'Colonnacce').

The test showed a greater usability and easiness of use of the Leap Motion 3D than the Kinect for the following reasons:

- Kinect, to be activated, requires a specific body posture (arms raised up), while the Leap Motion requires only that the hand (fingers) enters the range of action of the device;

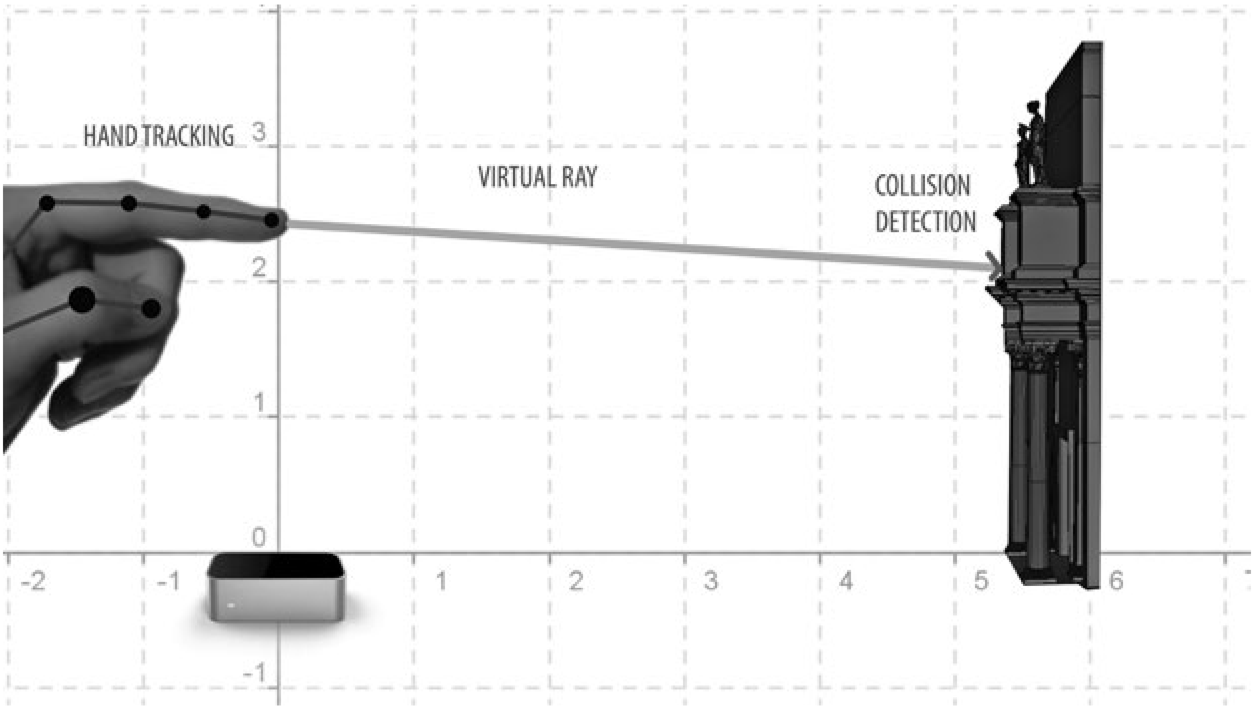

FIG. 6. FORUM OF NERVA: LEAP MOTION 3D WORKING SCHEME.

Leap Motion facilitates an immediate interaction without the users were previously instructed on how to use the instrument (85% of the volunteers preferred the use of the Leap Motion, 15% were still satisfied also with the use of the Kinect).

- Kinect requires that nobody else or nothing stands in the sensor area of action (up to 3.5 meters from the device), otherwise can occur some tracking errors, while the Leap Motion uses a limited space of detection, in close proximity to the sensor (1 cubic meter). The Leap Motion excels at reading minute movements. It was designed to be accurate to within 1/100 of a millimetre in order to be useful for applications that require precision, such as 3D-modeling.

At the end of the tests we decided to choose the Leap Motion 3D. In order to recreate virtually the actual location and shape of objects and relate them to the data collected from the hand, a special C++ language software has been developed which integrates with the SDK and open source Cinder ++ libraries. This script defines the functions for importing 3D models into the relevant space, management of events, control of selections and the uploading and launch of multimedia files.

After the experiment with the software program and the sensor, it was found that data from the hand and the object (detected as described above) matched, provided the following are true:

- both are expressed using the same scale (1:1) and units of measurement (mm).

- the distance and the height difference between the sensor and at least one point on the detected object are known.

This means everything within one reference space originating at (0,0,0) in the centre of the device (Fig. 6).

Once the skeleton of the hand has been translated into virtual space, rendered by the ray casting procedure often used in video game programming, the application creates a ray from the tip of the finger depending on which direction it is pointing. The system then calculates the intersections of this ray with the 3D elements in the scene.

This makes it possible to associate collisions with certain parts of the object with a number of events, such as playing specific multimedia content, confirming to the user that they have made the required selection.

These instruments were used to build the installation that describes the *Colonnacce* of the Forum of Nerva.

Once the original state of the colonnade has been printed in 3D, it is placed on a plane 30cm away from the sensor (Fig. 7). The 3D model of the same area of the Forum was divided into two parts, columns and entablature, which have been made sensitive by the program. The computer running the application is connected to a projector positioned so that users can see the videos.

Users can select one of the two parts of the object by pointing at it while their hand is near the sensor. This input is recognised instantly and the data sheet with basic information (name, period, 3D reconstruction) on the selected part is projected (Fig. 7). A 5-second timer is also launched, after which, if the finger has not moved during this time, multimedia content about the selected part is played of its history and peculiarities. As an alternative to projection, the output can be transferred to the user's mobile device.

At the end of the video, the installation returns to waiting mode ready for the user to select another part.

Fig. 7. Forum of Nerva: simulating the Leap Motion 3D use on the small-scale 3D print of the Colonnacce.

This approach means the software can interface with objects of any size, moving easily from scale models (e.g. the 3D printing of the *Colonnacce*) to actual-sized objects.

4 Conclusion

In order to have a more effective interactive communication in cultural heritage, with particular regard to open archaeological sites and museums, we can suggest additional lines of research, where the proposed application provides three levels of use:

- implementation of the Nervar app for the Forum of Nerva (Empler 2013), where the *Colonnacce* were studied and analysed.
- creation of a fixed station near the *Colonnacce* as an extension of 'Journeys to Ancient Rome' or similar projects.
- exploration station to reconstruct the 3D printed model, set up in the Forum of Nerva hall at the nearby Museum of the Imperial Fora.

These instruments provide complete and correct information on several levels of communication and interaction in Cultural Heritage and engages as many target users as possible.

By keeping the focus on direct experience of the cultural object, their spatial and functional aspects can be understood better than from images and reconstructions alone.

The result has been to combine the technical data with modern forms of delivery and entertainment to develop procedures that can be replicated in different places and situations, even for difficult-to-access cultural objects.

Bibliography

Alisi, T. M., Del Bimbo, A. Valli, A. 2008. Natural interfaces to enhance visitors' experiences. In *IEEE Multimedia*, 12, 3: 80-5.

Antinucci, F. 2007. *Comunicare nei musei*. Bari, Laterza.

Borenstein, G. 2012. *Making Things See: 3D vision with Kinect, Processing, Arduino, and MakerBot.* Make Books. Sebastopol Maker Media.

Centro Internazionale D'arte Di Cultura Di Palazzo Te 2013. *L'ordine e la luce.* Un viaggio virtuale nell'evoluzione degli spazi interni nella storia dell'architettura: dai greci al Rinascimento. http://www.centropalazzote.it/scheda-mostra.php?id=6 [Accessed: 10th june 2015]

Chamberlain, G. (ed.) 2014. *Museum Ideas: Innovation in Theory and Practice*. London, Museum Identity Ltd.

Empler, T., Fratarcangeli, M., Murru, G. 2013. Practical Augmented Visualization on Handheld Devices for Cultural Heritage. In *21st International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision (WSCG 2013)*: 97-103. Plzen, Union Agency.

Gorny, D., Madeira, R. 2013. *Cinder Creative Coding Cookbook*. Birmingham, Packt Publishing.

Leap Motion Inc. 2014. *Leap Motion SDK Documentation*. Available at: https://developer.leapmotion.com/documentation/. [Accessed: 10th june 2015]

Marin, G, Dominio, F., Zattunigh, P. 2014. Hand gesture recognition with leap motion and kinect devices. In *IEEE International Conference on Image Processing (ICIP), Paris, 27-30 october 2014*, Piscataway, Institute of Electrical and Electronics Engineers.

Ministero Dei Beni E Delle Attività Culturali E Del Turismo 2014. *Foro di Augusto. 2000 anni dopo*. http://www.beniculturali.it/mibac/export/MiBAC/sito-MiBAC/Contenuti/MibacUnif/Eventi/visualizza_asset.html_763742144.html [Accessed: 10th june 2015]

Monaci, S. 2006. La comunicazione nel museo. Relazioni e interazioni mediate al computer. In *Giovani Sociologi 2005*: 131-46. Napoli, Scriptaweb Online Publishing.

Neves, C. M. P. 2002. *Exhibitions and their audiances: actual and potential*. Washington D.C., Smithsonian Institution.

Noble, J. 2012. *Programming Interactivity.* Sebastopol, O'Reilly Media.

Norman, D. A. 2013. *Design of Everyday Things: Revised and Expanded.* New York, Basic Books.

O'flaherty, N. 2014. The way to meet museum visitors' expectations is by defying them. *ICOM News*.
4: 10-1.

Pescarin, S., Pietroni, E., Rescic, L., Omar, K., Rufa, C., Wallergard, M. (2013). NICH: a preliminary theoretical study on Natural Interaction applied to Cultural Heritage contexts. In *2013 Digital Heritage International Congress (DigitalHeritage*), Marseille, 28 October – 1 November 2013, Piscataway, Institute of Electrical and Electronics Engineers.

Tidwell, J. 2011. *Designing Interfaces.* Sebastopol, O'Reilly Media.

Saffer, D. 2008. *Designing Gestural Interfaces.* Sebastopol, O'Reilly Media.

Salerno, I. 2013. Narrare il patrimonio culturale. Approcci partecipativi per la valorizzazione di musei e territori. *Rivista di Scienze del Turismo 4, 1-2, Gennaio-Dicembre 2013*: 9-26. Milano, Edizioni Universitarie di Lettere Ecomonia Diritto LED.

Sheng, C. W., Chen, M. C. 2012. A study of experience expectations of museum visitors. *Tourism Management*. 22: 53-60.

Shumaker, R., Lackey, S. (eds.) 2014. *Virtual, Augmented and Mixed Reality. Applications of Virtual and Augmented Reality. 6th International Conference, VAMR 2014, Heraklion, 22-27 June 2014*. Cham, Springer International Publishing.

Ungaro, L., Meneghini, R., Milella, M. (eds.) 2014. *Le Chiavi di Roma. La Città d'Augusto*. Roma, Mercati di Traiano – Museo dei Fori Imperiali.

Viaggio Nei Fori 2015. *Forum of Caesar*. http://www.viaggioneifori.it/en/ [Accessed: 10th june 2015]

Vinkler, M. 2014. Integrating Motion Tracking Sensors to Human-Computer Interaction with Respect to Specific User Needs. In *Proceedings of CESCG 2014: the 18th Central European Seminar on Computer Graphics, Smolenice, 25-27 may*, Wien, Technische Universitat Wien.

Palaeontology 2.0 - Public Awareness of Palaeontological Sites Through New Technologies

Tommaso Empler
tommaso.empler@uniroma1.it
Department of History, Representation and Restoration in Architecture, Sapienza University of Rome

Fabio Quici
fabio.quici@uniroma1.it
Department of History, Representation and Restoration in Architecture, Sapienza University of Rome

Luca Bellucci
luca.bellucci@uniroma1.it
Department of Earth Science, Sapienza University of Rome

Abstract: This research is part of a wider project concerning the use of new technologies to communicate, disseminate and promote palaeontology.

There is a clear need to pursue this objective, which, when translated into the cultural context of Italy, has led us to start working with palaeontologists to find a way to use new technologies to develop applications specific to the field of palaeontology. Dissemination methods based on new technologies are collectively known as Palaeontology 2.0. The main aims are: providing evidence to museums and sites using the latest visualisation technologies along with more open shared knowledge; creating an accessible network on the World Wide Web between sites and museums that are currently isolated and unknown; giving the public the opportunity to interact with scientific knowledge through Real Time 3D during their site visit or via remote, web-based access to information.

Keywords: Palaeontology, APP, 3D modelling, Interactive multimedia, Real time 3D

Introduction

This research is part of a wider project concerning the use of new technologies to communicate, disseminate and promote palaeontology, in which the last 2 million years, which have been fundamental for the evolution of humans and modern ecosystems, are taken as a case study (Kahlke 2011).

How can a greater knowledge and understanding of palaeontology – the gateway to an understanding of complex concepts such as 'deep time', the evolution of ecosystems and 'landscapes' – be brought to a non-specialist audience? How can scientific research and dissemination come together to deliver information to a wider audience?

Since 2009, thanks to the Palaeontological Resources Preservation Act (PRPA, United States Congressional Record, Omnibus Public Lands Act, 2009), within a regulatory framework aimed at safeguarding palaeontological resources located on federal sites, the US government has also been promoting a planned action to make the general public more aware of the importance of these sites. Awareness is considered the best tool for preserving this heritage.

There is a clear need to pursue this objective, which, when translated into the cultural context of Italy, has led us to start working with palaeontologists to find a way to use new technologies to develop applications specific to the field of palaeontology. Applications (App) for smartphones and tablets now enable us to translate the information obtained from scientific research into visual information that is easier to understand for the general public. Traditional cataloguing and storage tools translating scientific data into accessible information in museums are no longer considered adequate.

Today, people can learn about palaeontology at museums and prehistoric and palaeontological sites, which are opened for access with the intent to preserve the link between the digs and their actual place of discovery.

Museums are still largely organised as places of research and scientific communication as they were in the nineteenth century. The use of excavation sites as educational resources, as opposed to merely places of scientific research, is a more recent phenomenon based on policies that are trying to take hold in exhibition circuits and specific methods for communicating their history and content to the general public.

Museums introduce people to a kind of traditional knowledge based on the collection, cataloguing and systematisation of data and finds. As 'knowledge hubs' traditional museums with their large heterogeneous collections tend not to be identified with the particular area of origin of their exhibits.

Since the nineteenth century, palaeontology has been based on a taxonomic organisation, where message boards and display cabinets are used to present the collections of remains, along with reconstructed of skeletons and reconstructive illustrations of men, animals, plants and entire ecosystems. Over the years, the increasing success among children and the general public

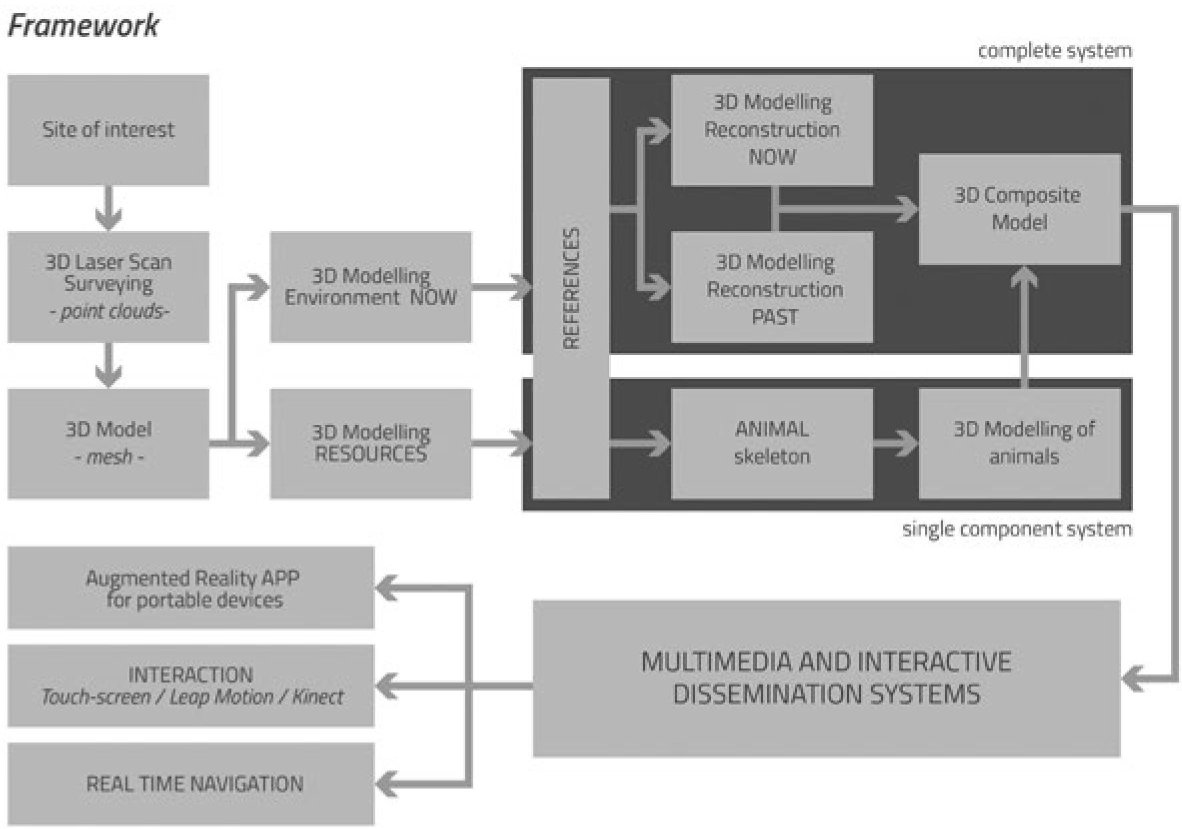

Fig. 1. The organization of the framework research named Palaeontology 2.0.

of full-scale three-dimensional models (Cameron 2010) of dinosaurs in theme parks and museums has made palaeontology more popular than ever before, thanks also to the success of films such as the Jurassic Park series.

Palaeontological sites open to the public first undergo excavations before being turned into museum sites with the relocation of the finds to where they were initially recovered. This method of exhibiting objects highlights their place of origin and, because they are seen in their original state of conservation, it also familiarises the public with the research and excavation methods used.

Some finds, however, are ‘invisible’. These are sites which are covered back up after digs – which is what makes them invisible – because , although interesting scientifically, the finds have insufficient evidence and physical substance to make them ‘visitable’ or understandable to most people.

Lastly, in addition to ‘invisible’ sites, we should also consider sites that have ‘disappeared’, namely those that have been destroyed, for example by urban expansion and the construction of roads or buildings (Lipps 2009). Our knowledge of these sites is based ‘only’ on fossils and the photographic archives found in museums and/or scientific institutions. In order to bring these sites ‘back to life’, it is essential to preserve and disseminate the historical memory of ‘landscapes’ that have been lost forever.

1 What is Palaeontology 2.0

In all of those places dedicated to the dissemination of palaeontological knowledge (Ferrara 2007), recent technologies provide several tools to organise and display information that can enhance knowledge, promote the places where artefacts are studied and preserved and narrate the evolution of ‘landscapes’ over time.

Dissemination methods based on the use of new technologies can be named Palaeontology 2.0[1] when referring to systems that implement traditional scientific information with new experimental tools for knowledge.

The main objectives of Palaeontology 2.0 are:

- providing evidence to museums and sites using the latest display technologies along with more open shared knowledge;
- creating an accessible network on the World Wide Web between sites and museums that are currently isolated and unknown;

[1] We can define Palaeontology 2.0 a new mode of address and communicate all that is connected to the field of palaeontology using visualization technologies. For Palaeontology 1.0 is meant the traditional mode of communication, linked to a communication logic lasts until 10 years ago.

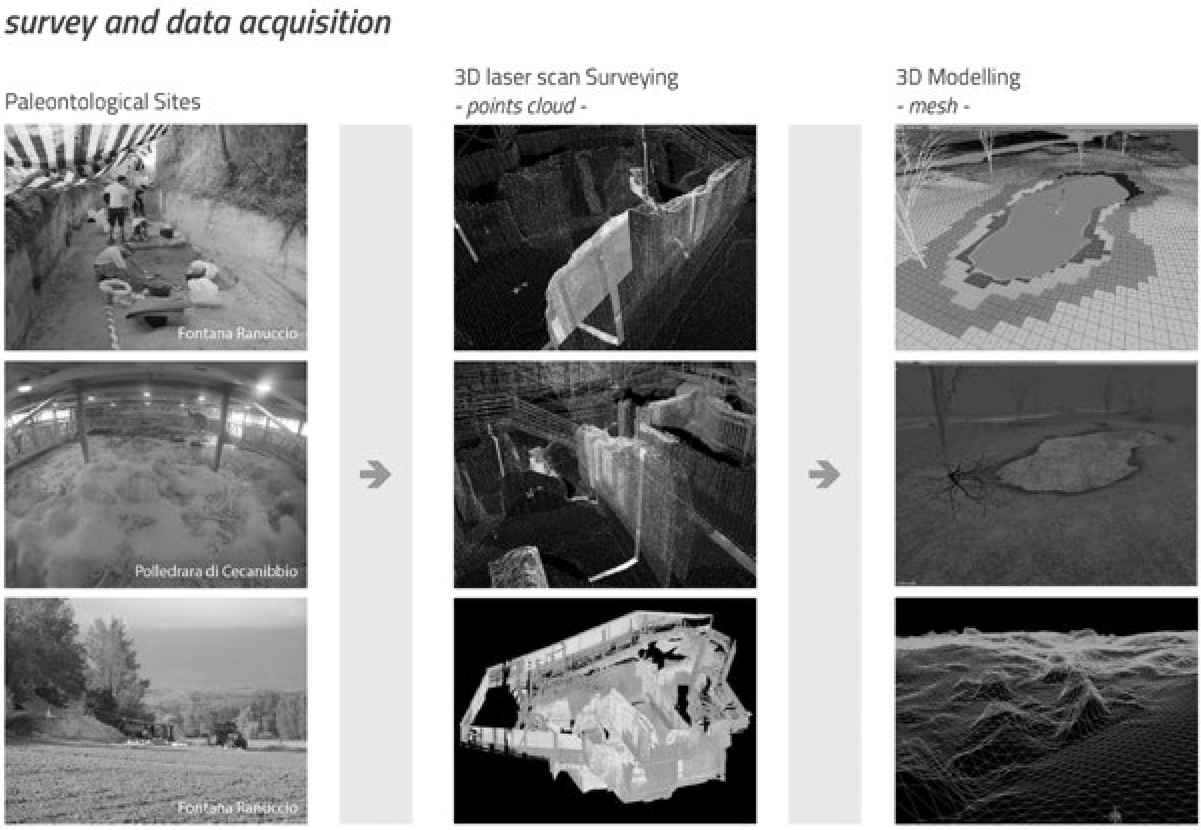

FIG. 2. SURVEY AND DATA ACQUISITION OF PALAEONTOLOGICAL SITES: FROM ANALOGUE TO DIGITAL DATA.

- giving the public the opportunity to interact with scientific knowledge through Real Time 3D during their site visit or via remote, web-based access to information.

2 The Framework

The research framework (Fig.1) for Palaeontology 2.0 methods of the implemented applications is organised into a series of related stages.

After the prehistoric site has been identified and excavated (if the site is 'invisible'), or the finds have been located (if the site is 'visible'), the first operation is to map the area morphologically (Fig. 2), which can be done by photogrammetry or 3D laser scan and also provides a 3D point cloud geometric model (Barber, 2011). The point cloud is later decimated and transformed into a 3D polygon mesh model (Fig. 2), which is easier to manage with a solid modelling application. This step enables us to select, separate and place on different layers the various elements that make up the landscape detected, distinguishing the 3D model of the area from the 3D model of the finds.

The whole modelling process is handled with an open source modeller as Blender[2] (Brito 2010).

Blender allows us to manage a large part of the procedure described in this framework using tools and routines that support multiple modes of representation (Siddi 2010).

The method described allows researchers to assess reconstruction hypotheses on different scales.

Documentary sources and the assistance of the palaeontologists who analyse fossils and the palaeo-botanists and geologists who provide an understanding of the environment in deep time, reconstruction hypotheses can be made of the landscape and the animals that once inhabited it.

The work of geologists and palaeo-botanists helps reconstruct a model of the 'lost' landscape, which can be compared with the model of the same place today. The types of seeds found, along with the stratigraphy of the soil, give us a reliable reconstruction of environmental factors (Fig. 3).

Palaeontologists (Bellucci 2012) cross analyse the finds with other more complete discoveries and similar reconstructive hypotheses to identify the animals that once belonged existed on site. The reconstruction method uses systematic and morphological studies of living animals and fossils found in museum collections (Fig. 4). This leads to the 3D

[2] Overview Engine Game. Blender has its own built in Game Engine that allows you to create interactive 3D applications. The Blender Game Engine (BGE) is a powerful high-level programming tool. Its main focus is Game Development, but can be used to create any interactive 3d software, such as interactive 3d architectural tours or educational physics research. See *Blender* in wiki.blender.org

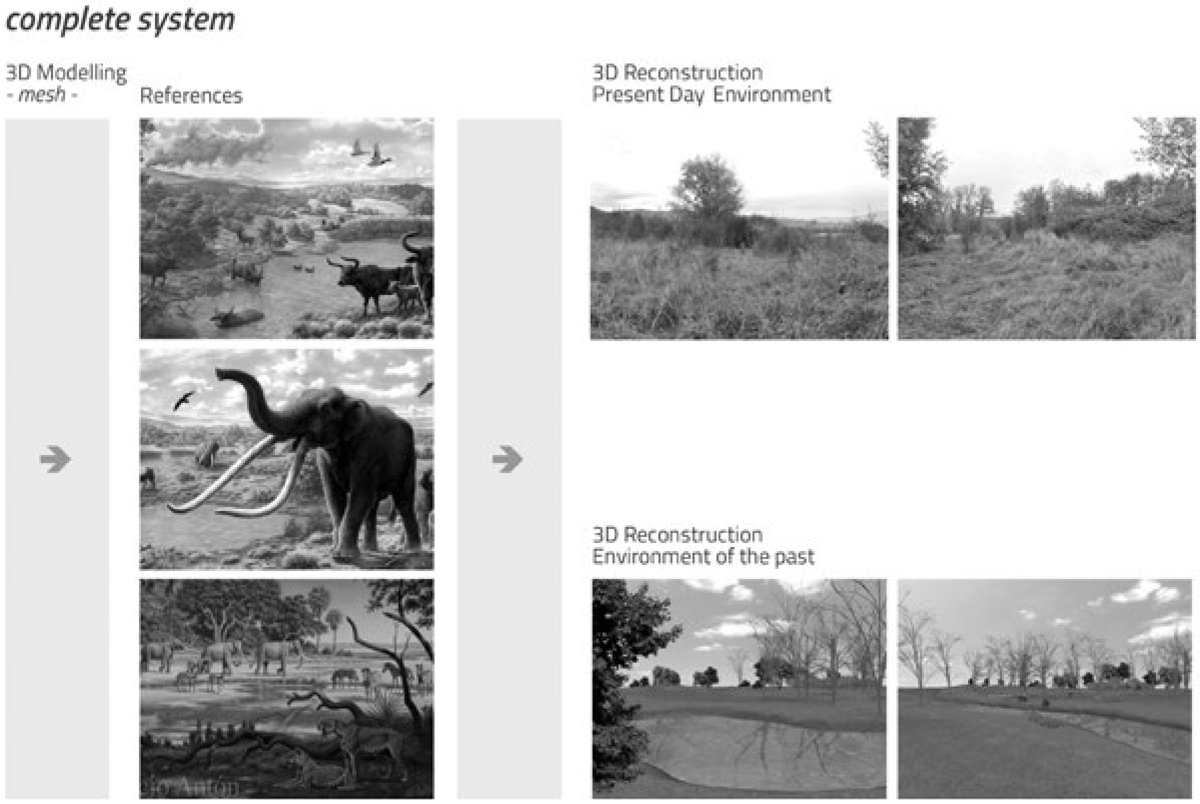

Fig. 3. 3D reconstruction of the site's condition: from present day environment to the visualization of lost landscape. The traditional work of the illustrators is translated into a digital way of working.

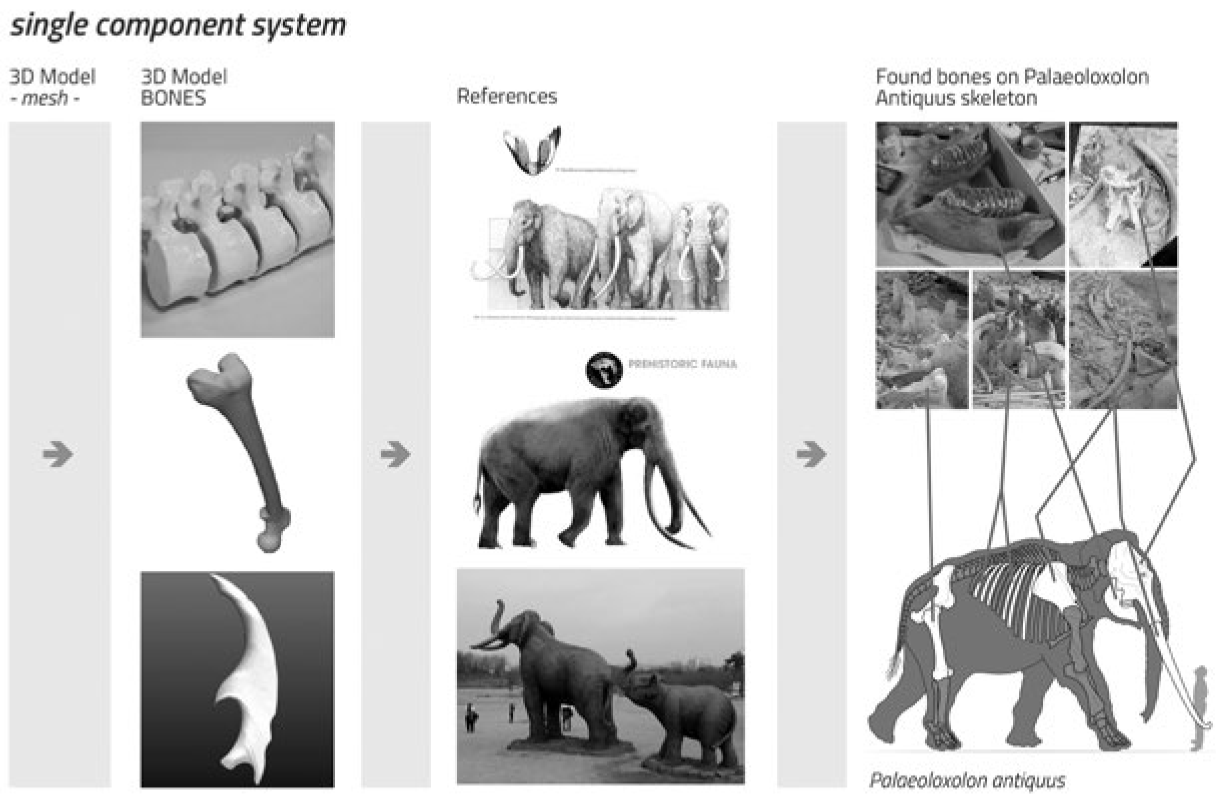

Fig. 4. Single component of the research framework: the reconstruction method uses systematic and morphological studies of living animals and fossils found in museum collections.

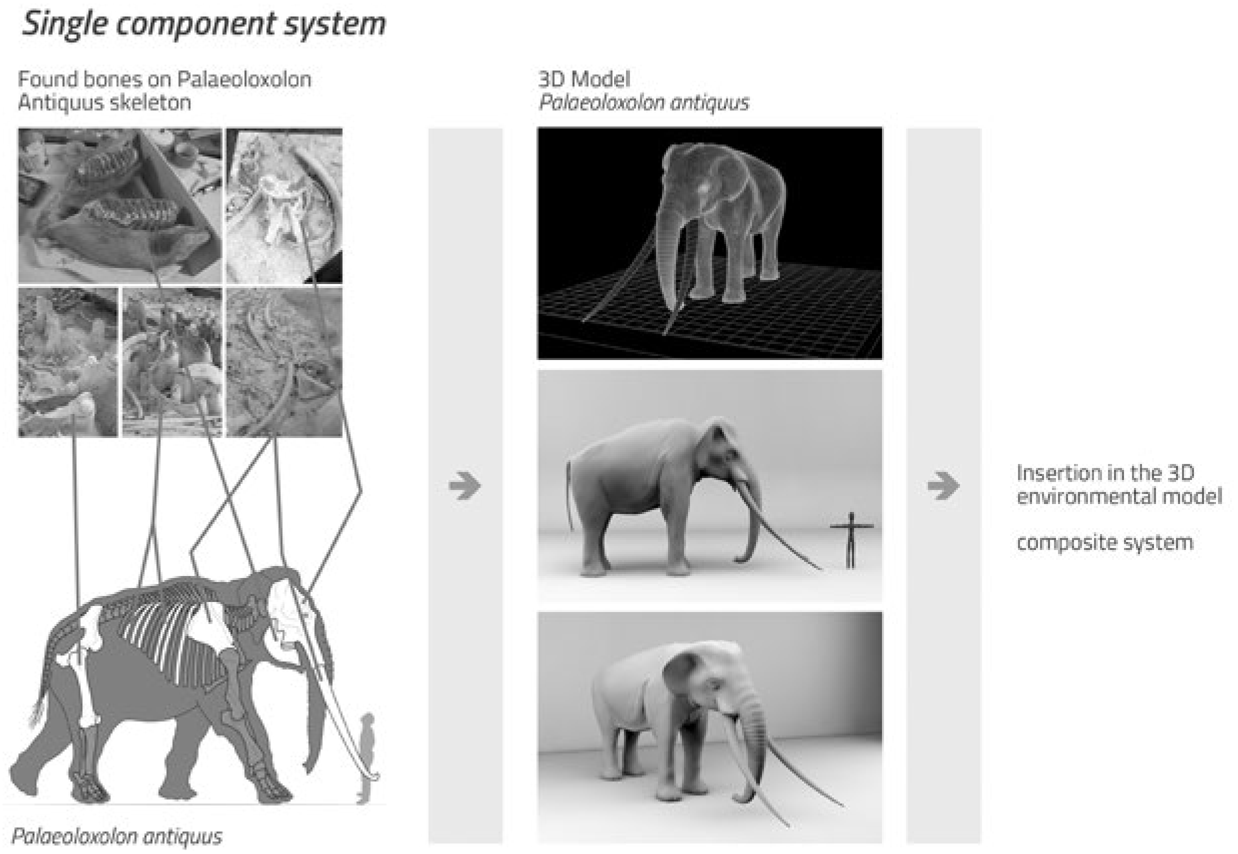

FIG. 5. SINGLE COMPONENT OF THE RESEARCH FRAMEWORK: 3D MODELLING OF THE ANIMALS BASED ON FOUND BONES.

FIG. 6. INTEGRATION OF DATA: THE "TIME BUBBLE" VISUALIZATION SYSTEM PROVIDES AN IMMERSIVE LINK BETWEEN THE PAST AND THE PRESENT CONDITION OF THE ENVIRONMENT.

FIG. 7. INTEGRATION OF DATA: THE "TIME BUBBLE" VISUALIZATION SYSTEM PROVIDES AN IMMERSIVE LINK BETWEEN THE PAST AND THE PRESENT CONDITION OF THE ENVIRONMENT.

reconstruction of the area (Fig. 5), where an inclusion of 3D models of animal enables the complete reconstruction of the prehistoric environment.

Two of the most important methods used for displaying the complete prehistoric environment are the '360° time bubble' and real-time 3D navigation.

The 'time bubble' provides an immersive link between the past and the present, enabling us to compare in real time the view of the current landscape with the view obtained from our graphic reconstruction of its condition millions of years ago (Fig. 6). The operation is possible thanks to photorealistic reconstruction (which uses synthetic images integrated with photographic images). This is an innovative operation to a sector where reconstructions are mainly assigned to the communicative effectiveness of traditional sketched drawings. To display a 360° view of the current state of the site, photographs are taken which are then mounted into a sphere using photo editing software (Fig. 7). These are then edited to reconstruct a past view of the site. This graphical intervention is somewhat

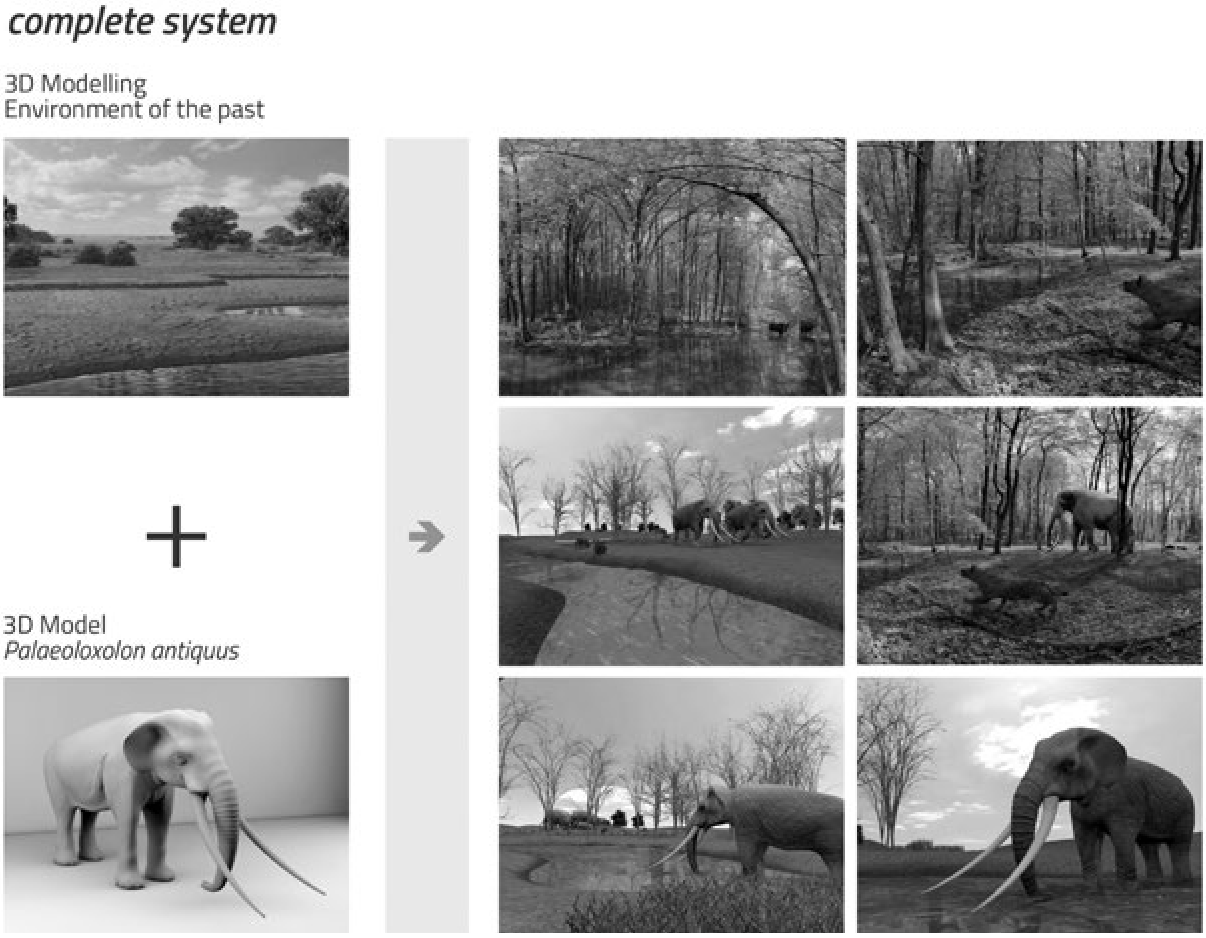

Fig. 8. Integration of data in real time 3D navigation interface.

complex, as it has to adapt to the 360° development of the image. Indeed, in order to work optimally in a photo-editing program, a raster image should be applied to an undistorted sphere so that images of vegetation and prehistoric animals can be inserted.

Real-time 3D navigation (Fig. 8) involves the use of Blender, which contains several internal tools and/or modules to gain directly explorable real-time 3D output via a *game engine* and *blender4web.* These can be used on portable devices, such as smartphones and tablets. Adaptation of the tools to 3D models not only requires Logic Bricks[3], but also works on the source code and programming strings to manage the controllers used in the interactive exploration.

Links, tabs and references to other 3D models and documentation about the former environment can be inserted into the 3D model implemented with the Game Engine.

[3] The core of the BGE's structure are Logic Bricks. The goal of Logic Bricks is to offer an easy-to-use visual interface for designing interactive applications without any programming language knowledge. There are three types of Logic Bricks, Sensors, Controllers and Actuators. There are Sensors Links Controllers. You can write games using Python, the game engine also has its own Python API, separate from the rest of Blender, which you can use to write scripts to control your game. This is done by creating a Python Controller and linking it to a python script. See *Blender* in wiki.blender.org

3 Conclusions and Results

By reconstructing the environment and 3D models of the animals found, we can create/manage interactive and multimedia systems of dissemination (Fig. 9).

The first output is in real-time 3D, possibly moving between a 3D model of the object today and a 3D model of the reconstructed object.

Another output is the IsIPU App[4] which augmented reality guiding visitors through several prehistoric sites, and displaying an information sheet for each of them containing scientific/descriptive texts and important iconographic support, as well as 3D reconstructed models of the animals living there millions of years ago.

The final output is the creation of interactive systems to teach students about the nature of the prehistoric sites and the importance of finds, however small and apparently insignificant, which are important for identifying the characteristics of animals that are now extinct.

[4] App for iOS, download free at: https://itunes.apple.com/it/app/isipu/id743901181?mt=8.

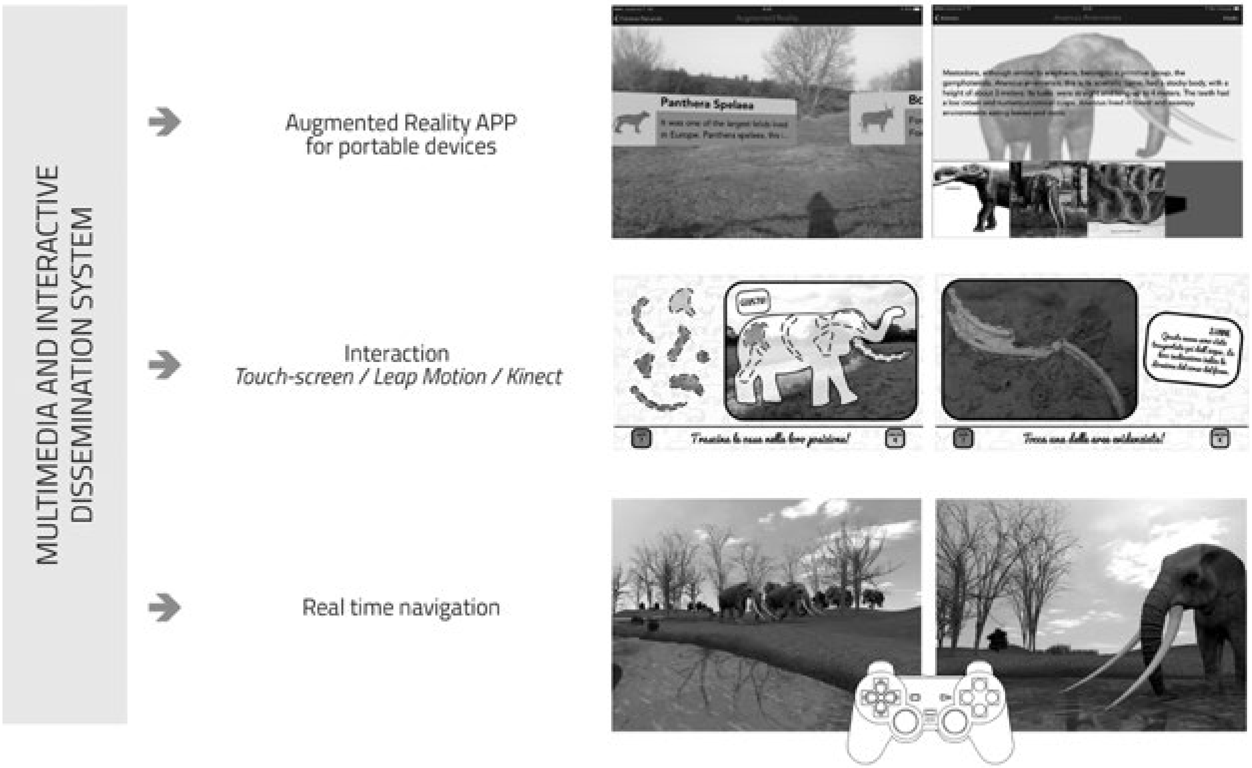

Fig. 9. Palaeontology 2.0 involves the use of interactive and multimedia systems of dissemination for palaeontological sites. Augmented Reality, Interaction systems and Real-Time navigation technology are data visualization tools that can be used in order to guide visitors through prehistoric sites, and make available scientific information.

Bibliography

Barber, D., Mills, J. 2011. *3D Laser Scanning for Heritage. Advice and guidance to users on laser scanning in archaeology and architecture*. Swindon, English Heritage Publishing.

Bellucci, L., Mazzini, I., Scardia, G., Bruni, L., Parenti, F., Segre, A. G., Segre Naldini, E., Sardella, R. 2012. The site of Coste San Giacomo (Early Pleistocene, central Italy): Palaeoenvironment analysis and biochronological overview. *Quaternary International* 267: 30-9.

Brito, A. 2010. *Blender 3D 2.49. Architecture, Buildings and Scenery*. Birmingham, Packt Publishing Ltd.

Cameron, F., Kenderdine, S. 2010. *Theorizing Digital Cultural Heritage: A Critical Discourse.* Cambridge, Mit Press.

Ferrara, C. 2007. *La comunicazione dei Beni Culturali. Il progetto dell'identità visiva di musei, siti archeologici, luoghi della cultura.* Milano, Lupetti.

Falser, M., Juneja, M. 2013. Archaeologizing Heritage? Transcultural Entanglements Between Local Social Practices and Global Virtual Realities. In *Proceedings of the 1st Intenational Workshop on Cultural Heritage*. Berlin, Springer-Verlag.

Kahlke, R. D., García, N., Kostopoulos, D. S., Lacombat, F., Lister, A. M., Mazza, P. P., Titov, V. V. 2011. Western Palaearctic palaeoenvironmental conditions during the Early and early Middle Pleistocene inferred from large mammal communities, and implications for hominin dispersal in Europe. *Quaternary Science Reviews* 30, 11: 1368-95.

Lips, J. H. 2009. PaleoParks: Our paleontological heritage protected and conserved in the field worldwide. In J. H. Lipps and B. R. C. Granier (eds.), *PaleoParks - The protection and conservation of fossil sites worldwide.* Carnets de Géologie / Notebooks on Geology: 1-10. Brest, Book.

Segre Naldini, E., Muttoni, G., Parenti, F., Scardia, G., Segre, A. G. 2009. Nouvelles recherches dans le bassin Plio-Pléistocène d'Anagni (Latium méridional, Italie). *L'anthropologie* 113: 66-77.

Siddi, F. 2010. *Grafica 3D con Blender*. Milano, Apogeo.

Lucus Feroniae and *Tiber Valley Virtual Museum*: from Documentation and 3d Reconstruction, Up to a Novel Approach in Storytelling, Combining Virtual Reality, Theatrical and Cinematographic Rules, Gesture-based Interaction and Augmented Perception of the Archaeological Context

Eva Pietroni[(1)]
eva.pietroni@itabc.cnr.it

Daniele Ferdani[(1)]
daniele.ferdani itabc.cnr.it

Augusto Palombini[(1)]
augusto.palombini]@itabc.cnr.it

Massimiliano Forlani[(2)]
massimiliano.forlani@evoca.org

Claudio Rufa[(2)]
claudio.rufa@evoca.org

[1] CNR - ITABC, National Research Council - Institute of Technologies Applied to Cultural Heritage
[2] E.V.O.CA.srl

Abstract: The Tiber Valley Virtual Museum aims at providing digital applications for the valorisation of the landscape and cultural heritage of the medium Tiber Valley, north of Rome.

In this context an evocative virtual reality installation has been presented in the National Etruscan Museum in Rome, where we propose a multi-modal approach to the narration of the landscape considered in its several aspects: geological, natural, historical, archaeological, poetic, evocative and symbolic. Through gesture-based interaction the visitor explores the landscape experiencing four different scenarios, two of them related to aerial and underwater landscapes and two others related to specific archaeological sites. This paper will focus on the design of the installation and on the communicative approach followed, in particular, for the scenario of Lucus Feroniae. The methodological approach will be described, from digitization and 3D reconstruction of the site in Tiberian and Trajan ages up to the creation of innovative integration of different media.

Keywords: Virtual museum, Interactive storytelling, Integration of media, Gesture based interaction, 3D reconstruction.

1 'Tiber Valley Virtual Museum': aims and general strategies (E.P.)

The 'Tiber Valley Virtual Museum', lead by CNR ITABC and supported by Arcus S.p.A., has been conceived in order to increment and disseminate the knowledge, the interest and the affection towards the territory north of Rome, crossed by the Tiber river and by two important Roman consular roads, via Salaria and via Flaminia, an area 40 km long x 60 km wide (Fig. 1), (Arnoldus-Huyzendveld *et al*. 2011).

To do this an integrated communicative system has been created, including a website (still in progress at the moment of writing), virtual reality and multimedia installations placed in local museums of the area (*Museum of the River* at Nazzano, *Lucus Feroniae* archaeological museum) and in Roman museums.

These applications have been conceived to encourage people to visit this territory and to support them before, during and after the visit of the real sites, providing cultural contents at different levels.

Starting from the study and documentation of the territory and of its evolution across time (from 3 million years ago until today), 3D representations at different scales have been realized, from the whole landscape to specific sites (Pietroni *et al*. 2013).

One of the most important results of the project is a virtual reality application characterized by gesture-based interaction and by an innovative approach in interactive storytelling, following an artistic and evocative style, based on scientific contents. It is permanently accessible in the National Etruscan Museum of Villa Giulia, in Rome, since December 2014.

It consists of four different scenarios that are visualized on three aligned 65-inch screens, aiming at creating an evocative and narrative experience inside the territory of the Tiber valley.

Fig. 1. The territory interested by the 'Tiber Valley Virtual Museum' project with the sites in evidence and details of the archaeological area of Lucus Feroniae.

It allows the visitor to see the Tiber through the eyes of a fish that swims in the river, a bird that flies over the landscape, the ancient characters living in the Roman city of *Lucus Feroniae*, and a freed slave introduced to the famous Roman *Volusii Villa*, living his intimate drama (Fig. 2).

Swimming underwater in the current of the Tiber, like a fish, the visitor can experience the memory of the river; the swimmer meets fluctuating images, iconographies, sounds, literary fragments taken from ancient and contemporary poets and authors. 3D reconstructions of the geological evolution of the Tiber Middle Valley and of the potential ancient landscape in the orientalising and Roman/Augustan period have been proposed in the aerial scene, whose purpose is also to contextualize the other scenarios dedicated to the archaeological sites of the *Volusii Villa* and *Lucus Feroniae*, respectively reconstructed in the Augustan age and in the Tiberian and Trajan periods.

In this project, efforts have been oriented towards the creation of an emotional, multi-sensorial scenario, inside which visitors can feel embodied and involved, able to acquire cultural contents in a pleasant and not frustrating way. We tried to combine science, art and technology, to meet both museums and research needs (Ryan 2001), (Pietroni and Adami 2014).

The *Lucus Feroniae* scenario gave us the occasion to experiment with an innovative combination of languages: virtual reality paradigms, natural interaction interfaces, cinematographic and theatrical techniques, virtual set practices, augmented reality. Such a mix of media aims at creating an experience, stimulating the users' curiosity and motivations, their perceptive and interpretative faculties.

Several evaluations of the user experience inside virtual museums realized over the past years have shown that storytelling and interaction are the main expectations of the public: they want to enter and interact inside stories, personalizing their experience (Pescarin *et al*. 2012; Pietroni *et al*. 2013). However if we place an uninformed visitor in the midst of several hundred choices which presume some prior knowledge of the subject, we only increase the sense of disorientation. He or she will get lost without understanding fully the contents (Antinucci 2007).

Consequently our purpose was to go beyond the traditional paradigms of virtual reality and guide the user through an 'organized' story, offering progressive objectives and stimulus. In this way he does not become disoriented in such a complex world, even if he plays an active role. The need to create a general 'direction' inside the interactive experience led us towards the definition of a new language combining linear and interactive media.

Moreover the placement of the installation inside a museum requires engaging the public for a reasonable time, not too long, with the best communicative and learning impact. Therefore every media has been employed to give its best potentiality. The experience inside each scenario is 5-15 minutes long, the total duration, including all contents, is 45 minutes.

1.1 The case study of *Lucus Feroniae*

In the archaic age *Lucus Feroniae* was a very important marker in the territory for a famous sanctuary dedicated to the Italic Goddess Feronia, protecting harvest, fertility, health and freed slaves. At that time different populations coming from a wide area all around, Falisci, Capenati, Etruschi, Sabini, Latini, converged to give honour to this Goddess, in her 'lucus' (originally a sacred wood, then evolving into a sanctuary), and occasionally a site for fairs, as this place was a very important emporium as well (Moretti 1974), (AA.VV. 1986).

Dionysius of Halicarnassus *(Roman Antiquities),* Livy (*History of Rome*), Pliny the Elder (*The Natural History*), Vergilius (*Aeneid, Book*), Strabo (*Geography*) and other ancient authors refer to the life of this well-known and rich sanctuary before the Roman occupation and Hannibal's sack in 211 BC.

In the late Republican Roman age it lost its previous status, turning into a simple farming town. It was transformed into a colony in Augustan times and a new monumental urban development took place there. One century later it was restored by Trajan and few new structures were built, among which were the Thermal Baths in the *Forum*, in a place previously occupied by a third *insula* of shops.

During the imperial age the Goddess Feronia was discarded and replaced by Salus Frugifera, with similar characteristics. However her ancient sanctuary was not destroyed by the Romans, it was left outside the area of the new colony, beyond the *Forum*, excluded even from sight by the construction of a high wall.

Feronia's memory remains alive to this day in the surrounding area, echoed by the names of a cinema, a shopping centre, a motorway service area, etc.

In the past years the sanctuary was investigated with partial excavations, directed by Anna Maria Moretti Sgubini, and then re-buried: it is no longer visible today. For this reason we were asked to work on 3D reconstruction of the Roman site, as it might have appeared in the Tiberian and Trajan ages, whose pertinent structures are much more evident for visitors to the archaeological site today.

Fig. 2. Lucus Feroniae implemented in the VR installation. Little images below show the other three scenarios.

The 3D reconstructions that have been realized can be enjoyed not only in the Villa Giulia Museum in Rome, but also in the *Lucus Feroniae* archaeological Museum (as soon as it will be re-opened to the public after restoration), to offer a more immediate contextualization of the artefacts coming from the Roman site nearby.

2 Data gathering, 3D modelling and reconstruction guidelines (D.F.)

Along with an archaeological interpretation of the remains, a detailed topographical and architectural survey has been carried out, aiming at checking and integrating the pre-existing plans, the dimensions of the structures and creating a graphic documentation for the study of the construction phases and building technologies.

In addition, all the data related to the history of the archaeological sites have been gathered adopting a homogenous criterion.

On this basis a 3D reconstruction in Tiberian and Trajan periods has been realized, based on archaeological evidences and comparisons with similar contexts.

The adopted procedure is pretty standard and it will be shortly described, starting from survey and data interpretation, up to 3D modelling.

Survey activities involved Dense Image Matching (IBM) techniques, based on processes allowing a 3D model of an object to be obtained from a series of images.

Aerial images of the entire area were acquired by UAV, a SWINGLET CAM with a Canon IXUS 220HS mounted on board. Agisoft Photoscan software was used to orientate images and extract a dense point cloud, a 3d model and also an orthophoto (Agisoft Photoscan software, 2015), correctly oriented and scaled through the integration of GPS and total laser station coordinates. The orthophoto allowed understanding immediately the disposition of the elements in the whole area (Fig. 3).

Following a similar approach, but using terrestrial images, the most complex architectural elements, such as altars in bas-relief and statues (today preserved in the local museum) were modelled and integrated in the successive reconstruction work of the site (Fig. 4).

Fig. 3. Aerial orthophoto of the archaeological site of Lucus Feroniae (ground sample distance: 10 cm).

The dense polygon models were optimized using 'sculpting' software (Sculptrix). This software allowed a selective polygon decimation to be performed, reducing the density of the geometry where unnecessary. Normal map generation and texture baking were carried out in 3DS Max software (Fig. 5).

After this preliminary survey and once all the sources were compiled, the 3D modelling process began.

To achieve a reliable reconstruction of the archaeological site and its buildings, several types of archaeological and architectural data were investigated and interpreted, with the support of experts from the Archaeological museum of *Lucus Feroniae* and from the Soprintendenza.

First of all, the information regarding the archaeological remains, such as drawings, pictures of the excavations and materials documentation were organized. Technical data were integrated with archaeological data, such as previous publications, bibliographic sources, hypothetical scientific-based reconstructions, etc.

In order to identify the original parts of each building and define what they should have looked like in the different phases (Tiberian and Trajan ages), the hypothetical reconstructions were drawn up comparing the historical and archaeological data and considering the constructive and aesthetic Roman building rules.

The hypotheses, when not supported by actual historical or archaeological sources, were supported by formal rules, construction techniques and Roman modules, or founded on comparative data identified in other buildings and nearby Roman towns (Gross 2001).

The criteria used for the scientific reconstruction workflow and gained during previous research experiences, were adopted as follows (Pescarin *et al*. 2012), (Dell'Unto *et al*. 2013), (Forte 2008), (Medri 2003):

1. Reconstruction by 'archaeological evidences': the reconstruction was based on archaeological incontrovertible evidence (dimension and plan of the buildings).

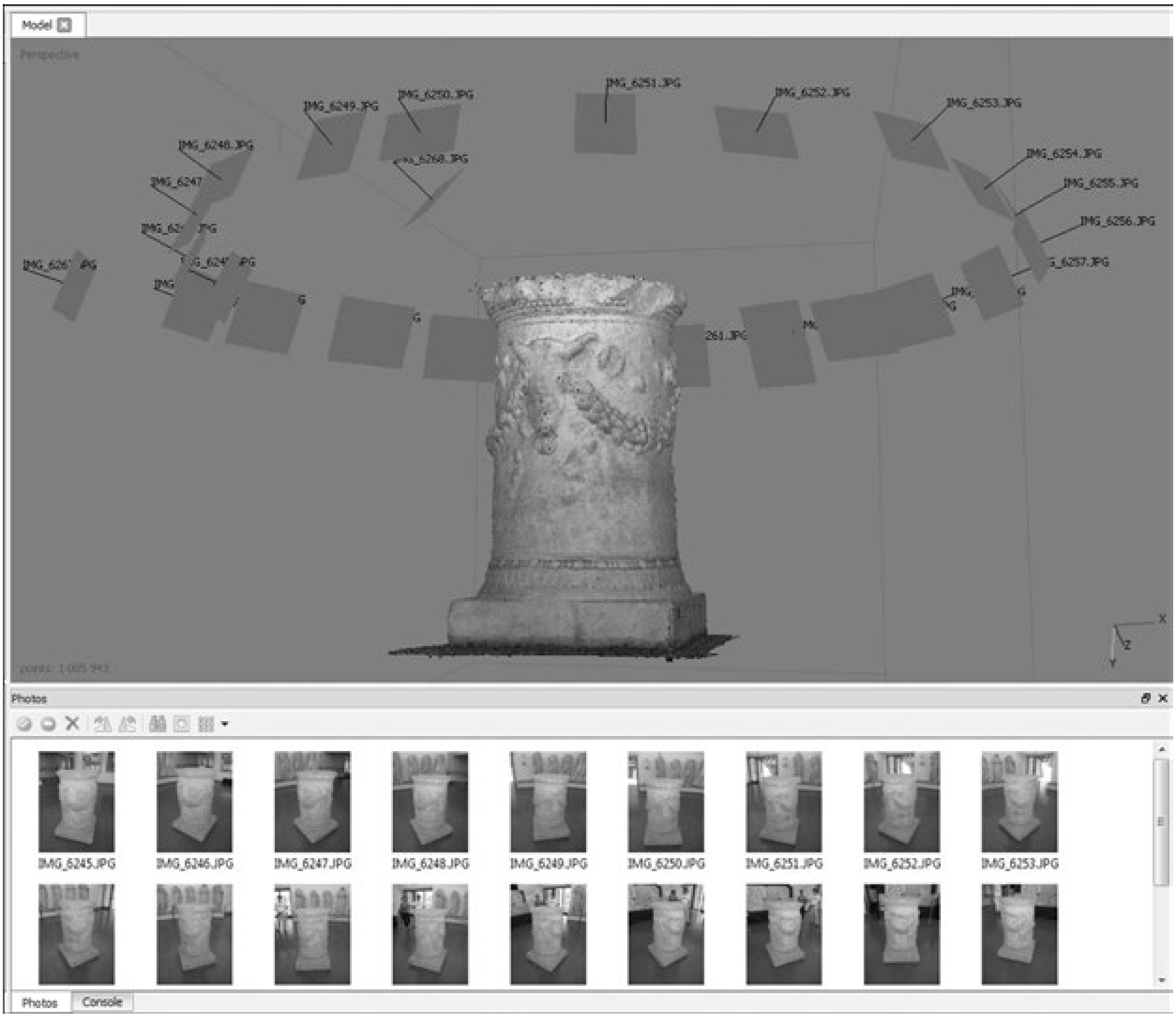

FIG. 4. DENSE POINT CLOUD OF A SURVEYED OBJECT, CREATED USING DIM APPROACH - THE BLUE PANELS REPRESENT THE CAMERA POSITIONS (ABOVE); THE PICTURES USED FOR THE RECONSTRUCTION (BELOW).

2. Reconstruction by 'sources': the reconstruction is based on information found on inscriptions or historical sources (i.e. epigraphs discovered in several altars still present in the *Forum* and the account of foundation made by Plinius in the *Naturalis Historia* (Plinius).

3. Reconstruction by 'analogy': The reconstruction is based on analogy with a well-known and recognizable theoretical model. (i.e. the height of the columns placed in the porch of the *Forum* were calculated based on their diameters according to the canons of Vitruvius).

4. Reconstruction by 'comparisons': The reconstruction is based on direct comparisons with other monuments in the local area in a better state of conservation. For instance for the reconstruction of *tabernae* the most reliable parallels were found in the cities of Minturno, Pompeii and Tivoli. These sites were useful for supplementing historical data, creating a network of comparisons (Ward Perkins, 1974).

5. Reconstruction by 'deduction': although some buildings or architectural elements are incomplete, their complete appearance is deduced by referring to the formal characteristics of the buildings, or to repeated patterns (e.g.: the partial floor of the *Augusteum* was completed by repeating the geometrical pattern of the remaining *opus sectile*; the wooden elements, like doors, were deduced from hinges holes and thresholds).

The computer graphics-based reconstruction was developed using Autodesk 3DStudio Max. 3D modelling work was carried out by using imported 2D plans and profiles derived from archaeological plan and integrated with the ones derived from the aerial orthophoto.

The volumes have been extruded from these construction lines. All the models were unwrapped and mapped with textures designed 'ad hoc', using both an 'in situ' photographic campaign for the existing elements and a 2D digital image processing approach for the missing parts (Fig. 6).

The first 3D drafts were used as a common basis for discussion and analysis of interpretative decisions, and to refine the reconstructive interpretation. This task of the reconstruction

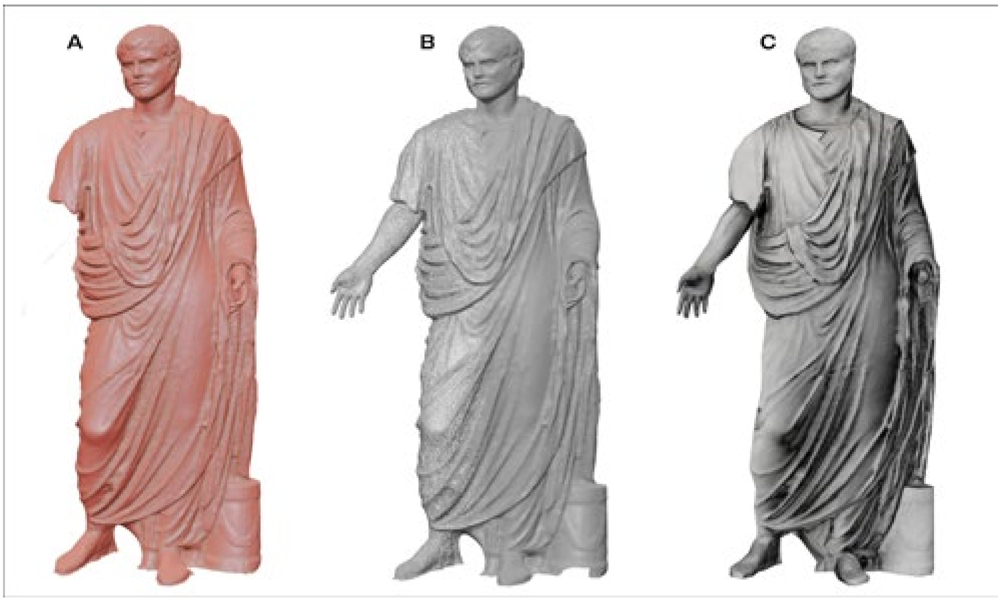

Fig. 5. Optimization workflow - from a scanned model to a RT ready-to-use model: A) scanned model; B) digital restoration of the missing parts; C) polygons decimation and texture baking (diffuse + normal maps).

workflow was crucial in verifying the hypotheses and rejecting those that were proved wrong (Borra 2004).

The 3D models were not only the end result of the work, but also a scientific instrument for interpreting the architectures and understanding better their original shapes. For example, on viewing the first reconstructions of the *Forum*, researchers became aware that the pillars in the south side should have been the basement of the Trajan aqueduct that supplied water to the thermal bath rather than part of a porch. Once the most consistent and reliable hypothesis was established the 3d models were finalised using a low poly modelling approach, particularly useful for the real time output. The small architectural details such as bas reliefs, frieze decoration, roofing, etc., have been described by textures rather than by geometry, allowing better performance in the real time engine, Unity 3D (Fig. 7).

3 Communicative project: design guidelines and implementation (C.R., E.P.)

3.1 Context and condition of implementation: the application in the museum

The consideration of the implementation inside the museum was a fundamental task to help conceive the design of the installation, in order to adapt to visitor experience.

The Virtual reality installation is located in room N31 of the National Etruscan Museum of Villa Giulia, where artefacts related to Faliscans and Capenates are exhibited. These populations lived in the territory north of Rome, along the Tiber River, before the Roman occupation and their stories are told also in the interactive application, thus the integration between museum and virtual contents is quite contextual.

The room has been adapted to host the system; a dedicated, darker, space has been cleared and the installation has been set apart even if, unfortunately, not completely secluded; showcases with artefacts are in the same room.

Visualization extends on three aligned 65-inch screens and contributes to the public's sense of immersion and perceptive involvement; the overall impact is visually very engaging (Fig. 2).

Audio plays a fundamental role in the transmission of storytelling and in the creation, together with visual contents, of a general evocative atmosphere, alternating different registers: emotional, reflective, educational; on occasion the audio style is intimate and contemplative; in other places it is more dynamic because of the multiplication and superimposition of many fragments. Considering the absence of crowding, the compromise to integrate the installation within the surrounding space of the room is perfectly satisfactory.

3.2 Gesture-based interaction design

In the four scenarios of this installation the public has the possibility to explore the 3D space without any traditional input interfaces based on windows, icons, menus and pointing devices (Kurtenbach and Hulteen 1990; Turk 2002). The interaction is possible using simple and natural gestures of the body, standing on a specific 'hotspot' on the floor, in the interactive area in front of the projection.

Mid-air gesture-based interaction constitutes a new paradigm in human-machine interaction; it allows an enhancement of the sense of embodiment and presence inside the virtual world (Featherstone and Burrows, 1995) and this embodiment constitutes a new frontier of the communication and learning processes (Morris *et al*. 2010; Varela *et al*. 1991; Pietroni 2013). In this application gesture-based interaction is implemented through a simple, low cost and standardized sensor, a depth camera, such as Microsoft Kinect (first generation) that that does not require the user to wear any marker and does not

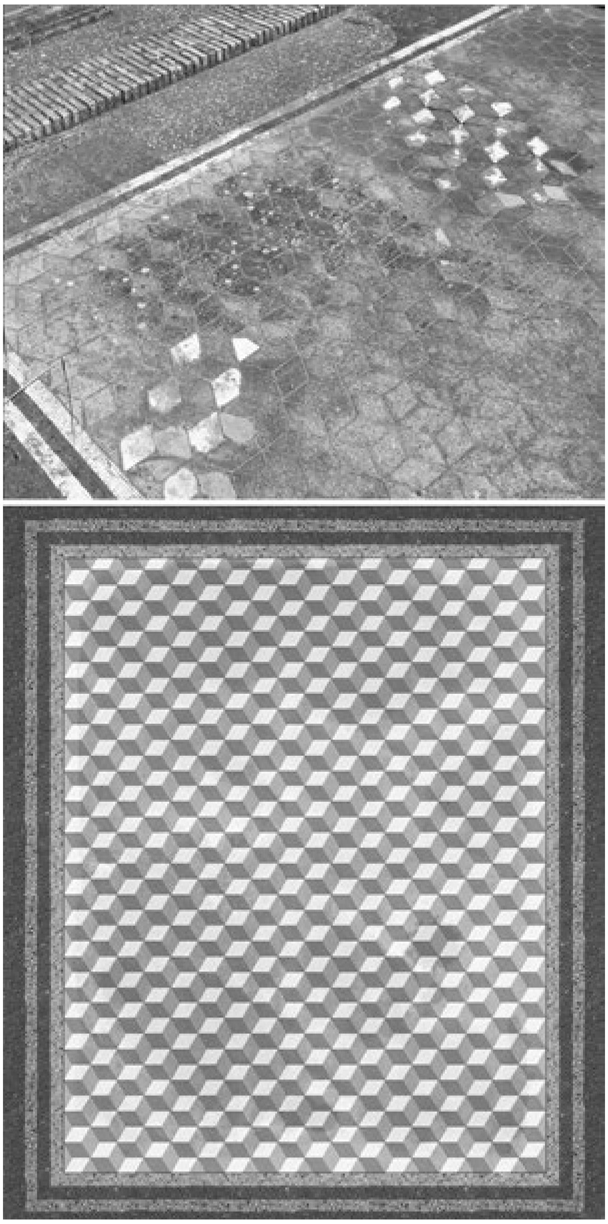

Fig. 6. Remains of the floor of the *Augusteum* characterised by a geometric decoration in *opus sectile* (left) and its digital restoration (right).

Fig. 7. 3D model of the so-called Basilica (solid and textured model).

Fig. 8. VR installation in Villa Giulia Museum, hotspots on the floor and User Graphic Interface, (scene of Volusii's Villa) .

need expensive licenses to operate. Its *frustrum* is about 4.5m (Microsoft Kinect 2015).

The application is single user, this means that one person at a time can enter the interactive area (a space about 3 x 3.5m). Other people can stay in the space all around looking at the virtual contents, the users can alternate continuously in the active role – no calibration is required.

The GUI (graphic user interface) is extremely simple and clear. Four coloured circles on the floor are used to activate the scenarios. The user can change scenario at will, walking and standing on one of these four coloured circles on the floor. Once a scenario is selected, the user is invited to move onto the central yellow circles to perform a range of gestures to explore the 3D environment.

The GUI on the ground is replicated on the screen. Moreover the blue silhouette of a figure is always present bottom right on the central screen, suggesting to the user the gestures available with which to explore the virtual scenario selected (Fig. 8).

The range of gestures is simple (Pescarin *et al*. 2013). In some cases the movements are very natural, like swimming or flying (underwater and aerial scenarios), in some other case, as with *Lucus Feroniae*, we needed to use gestures in a symbolic way, to simulate the action of walking and looking around. In these cases the gesture of the arms simply indicates the direction along which to move. For *Lucus Feroniae*, however, the user is not required to be as interactive. The scenario in fact has a more cinematographic approach and we wanted to keep this delicate balance. Basically the visitor is guided along predefined camera paths and only at specific points are arms used to interact in real time, as with, for example, the scenes of panoramas and crossroads.

3.3 Storytelling (A.P., E.P.)

In this application storytelling does not consist of simple descriptions (as in *Wikipedia* or *Google Earth*), on the contrary it is based on literary quotes, texts from ancient and modern authors, and the use of imaginary but plausible characters whose sequences happen on an historical background, as in the case of the *Lucus Feroniae* scenario.

Here the narrative structure has been carefully designed and implemented according to specific needs.

The user enters the city of *Lucus* as a real wanderer would: the narrative is delivered by common people involved in everyday activities who can be met in the streets, in the *Basilica*, in the shops of the *Forum* or in the baths. Through their personal stories and habits, the historical and cultural background of the site is transmitted, together with the topography of the city and the function of the main buildings.

Such an approach fits well with the specific category of narratives drawn by Umberto Eco in its classification of historical storytelling: '*the past must be recognizable but there is no need of real (famous) personages, as common people make us understand everyday life and their behaviour tells us much more, on their time, than history books can*' (Eco 1983).

For such a purpose a *multi-strand* storytelling structure was created (Truby 2007), in which different independent storylines flow and intersect each other as the traveller gets in contact with them. The characters refer both to common narrative archetypes adapted to the specific context (the countryman, the well-educated person coming from abroad, the shopkeeper, the goddess) or to generic people (men, women, children) who fit a momentary contextual need.

Even if in Tiberian times *Feronia* worship had been discarded, storytelling techniques were adopted to go back in time and evoke Feronia's memory, to whom the deep identity of the place and most of its importance is connected. A more symbolic and evocative stylistic register has been created for this purpose. In our story Feronia reveals herself only to the little child Cesia, who is the only one in the Roman town able to see her. A special relationship is established between the two. Feronia reveals to Cesia her ancient powers and gives her a present: through magic she reveals, just for one day, how the Tiberian city will look in 100 years' time, during the later Trajan age.

Thus, even if the contemporary events happen in the Tiberian age (for which we have more archaeological evidence), the user is brought back and forward in time, experiencing the evolution of the place through a longer timeline.

3.4 Visualization techniques in Unity 3D and general direction (M.F., E.P.)

During the early stages of production in the Unity 3D graphic engine, particular attention has been devoted to the research of graphics solutions capable not only of transmitting historical and scientific information, but also of creating powerful visual moods on several fronts that amplify the degree of usability and involvement for the public. This purpose has been reflected in the management of some major tasks and strategic choices: the creation of a style for camera activity, the distribution of visual digital contents on the three screens, the lighting setup for the 3D environments, the use of effects and filters able to develop the final appearance of the images.

3.4.1 Camera activity and direction

As in the other three scenarios implemented for this installation, the general atmosphere of the virtual reconstruction of the ancient Roman city of *Lucus Feroniae* is very evocative and immersive. The space is quite large, but it is quite patchy in terms of density of information and architectonical detail. For instance we have the *Forum* that is rather empty while information and storytelling are concentrated in specific areas: a shop, the basilica, the *Augusteum*, the thermal baths of the *Forum*.

For this reason we evaluated the opportunity to guide the user along the real time exploration towards those specific targets, and trying not to get the viewer lost or disoriented.

Moreover we needed to limit the duration of the experience inside this scenario to twelve minutes maximum, taking into account the whole context of the application that is composed of four scenarios.

In addition we wanted to strengthen the use of theatrical and cinematographic techniques to experiment their expressive potentiality inside a virtual reality environment. The use of real actors instead of 3D characters follows this approach.

On the contrary, in the other two scenarios, underwater and aerial, the user is completely free to move in every direction without constraints, as in more traditional VR environments. In those cases such freedom is justified by a more de-structured storytelling technique (short poetic fragments randomly flowing, in the case of the underwater scenario) or by the extent of the space and metaphor of interaction (flying, swimming).

Given these premises, for those scenarios characterized by more structured narration (*Lucus Feroniae* is one of the cases), our decision was to make the virtual camera move along predefined paths. The camera simulates the movements of a steadicam, according to a cinematographic style. The user is conducted towards the main contents: he or she only needs to stand on a specific hotspot on the floor to which the function 'move forward' is associated and he is brought along to visit the site. These camera paths head the user along the streets of *Lucus*, the buildings and rooms, up to the narrative areas where he can meet the ancient Roman personages in conversation with each other. A narrative area includes one or two narrative fragments, each one lasting about 20-50 seconds. In the scenario we have four narrative areas (*Forum, Basilica*, shop, thermal baths) and a total of seven narrative fragments.

Users still have two possibilities of free choice:

1. On specific points of the path, they can explore interactive panoramas (see the relevant paragraph below).
2. Along the path they come to some crossroads and can choose a direction: one direction leads to the main characters and the user can listen to their story; in the other direction the user can skip the story and go on, along the exploration path, towards the next narrative point.

3.4.2 Distribution of visual contents on the three screens: an 'augmented' perception

The three aligned screens are used to let the user visualize the archaeological site as it is today and, in parallel, the reconstructed context as seen from the same perspective.

The actual space is presented on the left screen through a sequence of photographs, changing every few seconds. Their flow is synchronized and aligned with the predefined camera paths in the virtual reconstruction of the site that is projected on the central screen. This means that during the movements in real time the images show the site from points of view that have a correspondence also with the animated 3D reconstruction. We could have used animation also in the left screen, making a video in the actual site as well, and using camera tracking techniques to align the two visualizations. However this would have required a large amount of extra work without creating much in the way of added value.

As mentioned above, at specific points along the camera path the user meets interactive panoramas. Here the viewer's eyes can rotate interactively using the arms. In this case the two aligned panoramas, real and virtual, on the two screens, will rotate simultaneously according to this input by the viewer.

In this way the visitor can live an 'augmented' experience of perception and comprehension of the site, continuously comparing the real and virtual on the two screens (Fig. 9).

On the third screen, on the right, the 3D reconstruction of the site is shown through a direction of cameras looking at the site from a greater distance, in perspective view, in order to contextualize the position reached by the user along his exploration: while the two visualizations on the left and on the middle screens are in the first person, this last one, on the right, is in the third person.

When the user is led to the narrative area, the story and performance of the characters of *Lucus* start, and in this case the visualization on the three screens shows no longer three different scenes (as it does during the exploration) but a unique viewport that extends over three screens ('cinema-like' visualization). This solution favours a more powerful sense of presence and immersion for the user within the story.

3.4.3 Lighting the virtual environment

The techniques used to illuminate *Lucus Feroniae* reconstructed in Tiberian and Trajan times have been borrowed from the traditional methods usually employed for 3D rendering. Thanks to the expedient of *LightMapping*, real-time scenarios are pre-processed with the means of lighting typical of conventional global illumination (with marked preference for photorealism), but then drawn to the screen with the same agility of a scenario exempt from the calculation bounces of light. Thanks to this technique we are able to focus on the aspects related to the behaviour of direct light (sunlight) as well as the behaviour of diffused light (mainly by scattering the blue component of sunlight).

The lighting setup and *LightMapping* were aimed at creating a realistic setting, visually rich and deep, because of gradient data from the decays of indirect light but chromatically neutral;

Fig. 9. Augmented experience in *Lucus Feroniae* scenario.

they constitute a base layer for optimal coupling of the third stage of work: the setting of the image effects of the camera.

3.4.4 Image effects

Post production and colour manipulation strategy are largely consolidated in the cinematographic and theatrical domains. *Colour correction* effects, provided in real-time by the graphic engine (Unity 3D), are used to give rich colour tones to the virtual construction, creating an enchanting and evocative atmosphere. Our goal is a powerful visual storytelling. In fact we wanted to evoke rather than merely describe.

Through colour we are able to establish a particular atmosphere for our virtual environment. Colour is meant to tell a story to users even before they hear a single word from the spoken narration.

Another relevant image effect used on the *Lucus Feroniae* scenario is real-time *Tonemapping*. Using *Tonemappin*g we can control the camera exposure and the behaviour of mid-tonal light. In this way we can decide whether to generate generous mid tones for clean air atmosphere, or strong contrast and dense shadows for darker and more mysterious atmospheres. *Vignetting* effect is used to give additional depth to the image; *Bloom* effect is used to produce evocative light halos extending from the borders of bright areas of the objects. *Sun Shaft* filter uses the '*God rays*' effect from sunlight (Fig. 10).

3.5 Virtual set and theatrical paradigms in the* Lucus *storytelling (C.R., E.P.)

Characters in the *Lucus Feroniae* scenario are not in 3D, but they are real actors shot in a virtual set while performing in front of a green screen. The video shoots have been realized in Raw format with a Blackmagic Cinema Camera and have been filtered and balanced in terms of light and colour to be matched within the 3d environment. Then through *chroma key* techniques the green background has been made transparent and the actors have been integrated within virtual space in real time (Fig. 11).

In effect, even if a virtual set is commonly used for cinematographic productions, the final result obtained in the *Lucus* scenario is something closer to theatrical than cinematographic paradigms.

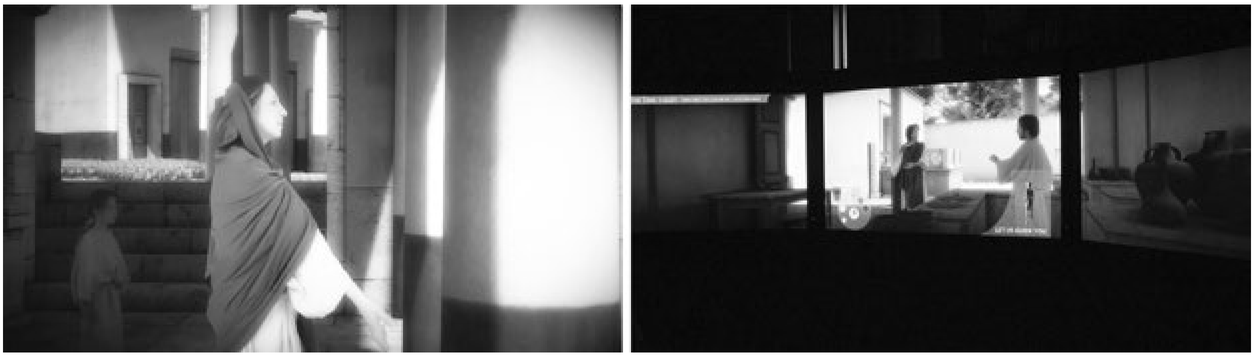

Fig. 10. Virtual reconstruction of *Lucus Feroniae*, final result of the render in Unity 3D.

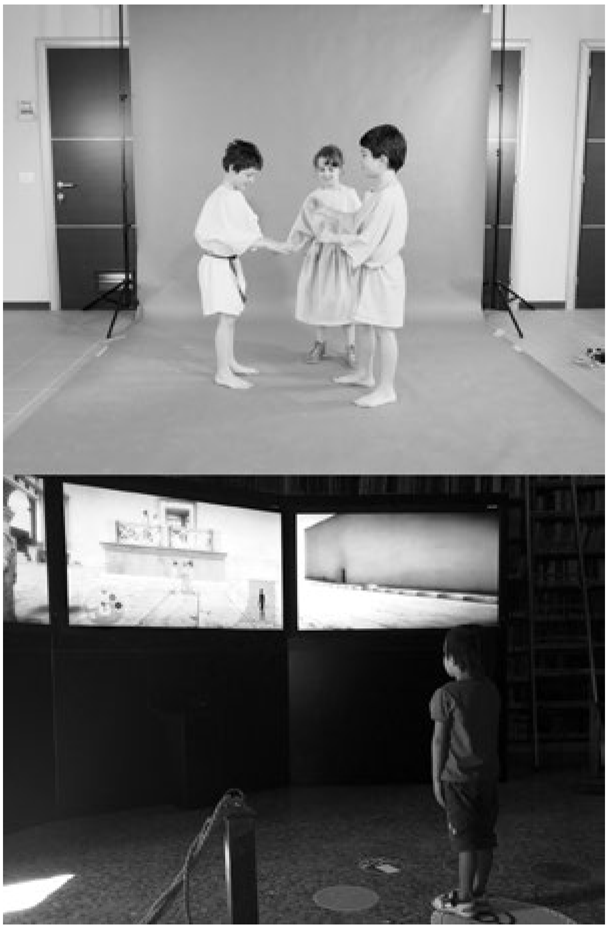

Fig. 11. Virtual set with real actors performing the ancient characters living in *Lucus Feroniae*.

Proximity to theatrical language in this scenario comes from:

1. *Unity of time:* actions develop in a unique moment. The same Goddess Feronia (that was venerated before the Romans, in the archaic period) reveals herself in the Roman age, and when she evokes past time she can only describe it with words, no journey back in time is shown with images. The only time travel that has been represented is the passage from the Tiberian to the Trajan phase (100 years later), and it is made possible by the magic performed of Feronia: in this case part of the 3D model of the city disappears under the floor and new buildings appear, coming up from the same point of the floor. This is a typical theatrical technique.

2. *Use of non photorealistic colours*: the 3D environment, even if very sophisticated in terms of rendering quality, is deliberately false and no realism is attempted. The general grading of the light is red and does not change during the whole experience within the scenario. This condition recalls those theatrical directions where similar lighting effects are very common.

3. *Camera direction during dialogues*: the camera is fixed, looking at the actors, with few and small movements and different from what happens in films. For this reason a small green screen was sufficient to obtain good results. A larger virtual set would have been needed to multiply and vary the perspective during the dialogues.

4. *Recitation style of the physical actors*: their movements, facial expressions, gestures and rhetoric are derived from the theatrical repertoire.

Cinematographic techniques are achieved by camera movements during the exploration of the space, as a virtual steadicam has been created to move from one narrative area to another. The combination of different languages, together with image effects and soundscape, creates something new, never seen before by the public; the results are strange and attractive.

4 Conclusions (E.P.)

The *Tiber Valley Virtual Museum* is an interdisciplinary project aimed at the creation of an effective and involving communication so as to encourage visitors to the region north of Rome and enhance the awareness of its cultural identity (Antinucci 2007). It has been conceived as a digital ecosystem integrating different scenarios and levels of visualization, multi-layered models, storytelling, tools of visualization and interaction, in order to create a performative space where all the information is connected (Varela *et al*. 1991; Cameron and Kenderdine 2007). Every scenario has its own characteristics and atmosphere but together they compose an harmonic ‘whole’.

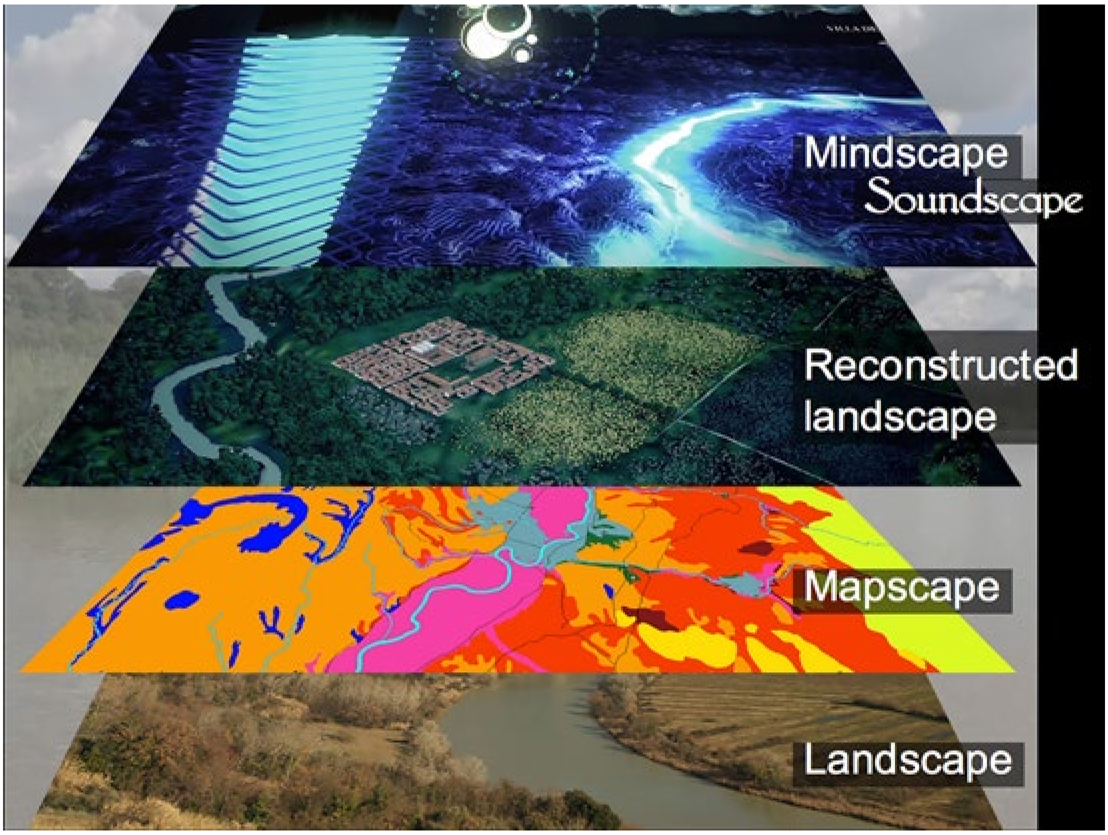

Fig. 12. 'Tiber Valley Virtual Museum', different levels of representation of the cultural landscape.

The integration of b*ottom-up* and *top-down* approaches (Forte, 2008) supported the representation of the territorial context in its diachronic evolution and at different scales of resolution: from the holistic vision of the landscape up to the monographic representation, focusing on specific sites. Among them is included the ancient Roman town of *Lucus Feroniae*, which has been the specific topic of this paper.

The observable archaeological landscape, that was the starting point of documentation and interpretative processes (*map-scape*), continuously alternates with the potential reconstructions of its past phases of life (*reconstructed landscape*) and imaginary dimensions (*mind-scape*) (Fig. 12).

In this way the learning process is greatly fostered by redundancy and variation (Bateson 1979).

A suggestive installation with gesture-based interaction has been developed and presented in the Villa Giulia Museum in Rome, where the user can experience four different scenarios, migrating through different avatars. The design of the *Lucus* scenario has been described in detail to give a clear idea of how the communication has been conceived and developed, depending on the progress made inside the museum.

The *Lucus Feroniae* scenario is a dynamic space that includes not only real objects (3D models of buildings, streets, fountains, trees, etc.) but also stories and relations, where the user can perform activities and create a 'visual drama' beyond what he can see, and thus experience an empathic evaluation of the context.

Both in the general design and in the detailed implementation of the application, great importance has been given to the emotional involvement and aesthetic impact as essential parts of the experience, since they partly determine the sense of presence within the virtual environment. The beauty of the graphics, the music and sounds, the evocative style of the script, the interaction design based on body gestures offer the users the opportunity to feel alive, partakers in the magical dimension taking place. This all immediately translates into an improved educational experience.

The need to create an involving storyline led us towards a new communicative approach, going beyond the traditional paradigms of virtual reality. Narration, in fact, requires a 'direction' that implies script, image effect, atmosphere, camera animations, soundscape (Ryan 2001; Pietroni and Adami 2014). Predefined camera paths have been created to prevent the user from disorientation and to preserve the 'metaphysical' dimensions of the experience; however a certain degree of freedom for the user has been kept in the exploration of the 3D space, as in the 'augmented' panoramas and the choices at the 'crossroads'. This strange convergence of media, the magical atmosphere generated by the image effects and the story itself are immediately perceived by the public (particularly by children) as innovative and highly attractive.

On the occasion of the expo in Laval *Virtual/ReVolution*, where the application was presented in April 2015, the user experience was seen for the first time, although in a very crowded context and far from ideal conditions. A new and closer evaluation was carried out in the Villa Giulia Museum, the final destination of the application, both on active users and observers (120 viewers in total) to verify the attractiveness, usability and educational impact of the system. In both cases the results were very promising and extremely useful in terms of understanding whether the outcome matches the creators' expectations, and what are the strengths and weaknesses of the application. The amounts of data collected are huge and multi-layered and the final reports are near completion and publication.

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Bibliography

AA.VV. 1986. Tevere: un'antica via per il Mediterraneo, Roma.

Antinucci, F. 2011. P*arola e immaginie, storia di due tecnologie.* Roma, Laterza.

Antinucci, F. 2007. *Musei Virtuali.* Roma, Laterza.

Arnoldus-Huyzendveld, A., Di Ioia, M., Ferdani, D., Palombini, A., Sanna, V., Zanni, S., Pietroni, E. 2012. The Virtual Museum of the Tiber Valley Project*.* In *Virtual Archaeology Review* 3, 7: 97-101.

Bateson, G. 1979. *Mind and Nature: A Necessary Unit*, New York, Dutton.

Borra, D. 2004. Sulla verità del modello 3D. Un metodo per comunicare la validità dell'anastilosi virtuale. In *Proceeding of eArcom 04, Tecnologie per comunicare l'architettura, Ancona 20-22 maggio 2004*: 132-7. CLUA edizioni.

Dell'Unto, N., Leander, A. M., Dellepiane, M., Ferdani, D., Callieri, M., Lindgren, S. 2013. Digital reconstruction and visualization in archaeology. Case-study drawn from the work of the Swedish Pompeii Project, in A. C. Edison, G. Guidi, S. Pescarin, L. De Luca (eds.), *Proceeding of the 2013 Digital Heritage International Congress*, Marsiglia 28 ottobre-2 novembre 2013, 1: 621-8. IEEE Computer Society.

Eco, U. 1983. Postille al Nome della Rosa. In *Alfabeta,* 49. Milano, Cooperativa Alfabeta.

Featherstone, M., Burrows, R. 1995. Cultures of technological embodiment: an introduction. In M. Featherstone, R. Burrows (eds.), *Cyberspace, Cyberbodies, Cyberpunk: Cultures of Technological Embodiment*: 1-19. Thousand Oaks (CA), Sage Publications.

Forte, M. (ed.) 2008. *La Villa di Livia. Un percorso di ricerca di archeologia Virtuale*, Rome, L'erma di Bretschneider.

Kurtenbach, G., Hulteen, E. 1990. Gestures in Human-Computer Communications. In B. Laurel (ed.), *The Art of Human Computer Interface Design*: 309-17. Reading (MA), Addison-Wesley.

Medri, M. 2003. *Manuale di rilievo archeologico*. Roma, Laterza.

Moretti Sgubini, A. 1974. *Lucus Feroniae: centro di incontro sul Tevere, in Civiltà arcaica dei Sabini nella valle del Tevere*, Roma.

Morris, M. R., Wobbrock, J. O., Wilson, A. D. 2010. Understanding Users' Preferences for Surface Gestures. In Proceedings of Graphics Interface 2010, Ottawa, Ontario, 31 may – 2 june, 2010: 261-8. Toronto (Ontario), Canadian Information Processing Society.

Pescarin, S., Fanini, B., Ferdani, D., Lucci Baldassari, G. 2012. Archeologia Virtuale a Montegrotto. In M. Bassani, M. Bressan, F. Ghedini (eds.), *Aquae Pataviane. Montegrotto Terme ed il termalismo in Italia. Aggiornamenti e nuove prospettive di valorizzazione*: 309-326. Padova.

Pescarin,, S., Pietroni E., Wallergard, M., Omar, K., Rufa, C., Rescic, L. 2013. NICH: a preliminary theoretical study on Natural Interaction applied to Cultural Heritage contexts. In *Proceedings of Digital Heritage International Congress,* IEEE Advanced Technology of Humanity 1: 355- 62.

Pietroni, E. 2013. Natural Interaction in VR environments for Cultural Heritage: the virtual reconstruction of the Regolini Galassi Tomb in Cerveteri. In *Archeologia e Calcolatori* 24: 231-48. Sesto Fiorentino (FI), All'Insegna del Giglio.

Pietroni, E., Adami, A. 2014. Interacting with virtual reconstructions in museums: the Etruscanning project. In *Journal on Computing and Cultural Heritage* '*Interacting with the past'* 7, 9.1-29. New York, ACM

Pietroni, E., Palombini, A, Di Ioia, M., Sanna, V., Arnoldus-Huyzendveld, A. 2013. Tiber Valley Virtual Museum: 3D landscape reconstruction in the orientalising period, North of Rome: A methodological approach proposal. In *Proceedings of Digital Heritage International Congress, 28 October - 1 November 2013*, 2: 223-30. Doi: 10.1109/DigitalHeritage.2013.6744758

Gross, P. 2001. *L'architettura romana. Dagli inizi del III secolo a. C. alla fine dell'alto impero. I monumenti pubblici*, Milano, Longanesi.

Ryan, M. L. 2001. Narrative as Virtual Reality: Immersion and Interactivity. In *Literature and Electronic Media*. Baltimore and London, Johns Hopkins University press.

Truby, J. 2007. *Anatomy of a story*. London, Faber and Faber.

Turk, M. 2002. Gesture Recognition. In K. M. Stanney (ed.), *Handbook of Virtual Environments*: 223–37. London, Lawrence Erlbaum Associates.

Varela, F., Thompson, E., Rosh, E. 1991. *The embodied Mind. Cognitive Science and Human Experience.* Cambridge, MIT Press.

Ward Perkins, J. B. 1974. *Architettura romana*, Milano, Mondadori Electa.

CHAPTER 2
Modelling the Archaeological Process

Principal Component Analysis of Archaeological Data

Juhana Kammonen

juhana.kammonen@helsinki.fi

Institute of Biotechnology, University of Helsinki, Finland,

Tarja Sundell

tarja.sundell@helsinki.fi

Department of History, Philosophy, Culture and Art Studies, University of Helsinki, Finland

Abstract: Finland has a rich archaeological record that is documented in the Ancient Monuments Register (AMR) and maintained by the National Board of Antiquities (NBA). Archaeological data often contain a large number of multiple features. In a large archaeological database the analysis and visualization of such multi-featured data becomes increasingly difficult, as the raw data points cannot be plotted unambiguously in a human-readable manner. In this paper we show that a computational method called the principal component analysis (PCA) is a valid method for visualizing the data in the AMR and can outline patterns in the data subset difficult to detect otherwise. Moreover, our results indicate that PCA could be a valuable supplement to the general analysis and maintenance of ever-growing archaeological databases. Previously widely used across many fields of science including genetics and computer sciences, PCA is now being used to find and visualize meaningful patterns in archaeological data undetectable by other means.

Keywords: PCA, Archaeological data, Ancient Monuments Register, Finland

Introduction

Studying the prehistory of Finland (Fig. 1) has greatly benefited from the accumulating archaeological record maintained by the Finnish National Board of Antiquities (NBA). One of the most prominent databases organized by the NBA is the Ancient Monuments Register (AMR). The AMR database includes more than 40,000 entries (dwelling and working sites, graves, shipwrecks etc.) each consisting of 50 sub-entries in average, which in turn are comprised of 1-500 single items each, adding up to *c.* two million artefacts altogether (Pesonen and Sundell 2011). The record from the Finnish Neolithic period is characterized by a wide array of stone artefacts, remains of various types of dwelling sites and the appearance of the earliest ceramics spreading into the artefact culture.

The postulated Stone Age population bottleneck in Finland and the consequent fluctuations in prehistoric population size have been studied extensively. The authors of this paper have performed simulation studies investigating these events (Kammonen *et al.* 2012; 2013, Sundell *et al.* 2010; 2013; 2014, Sundell and Kammonen 2015). In many cases, computational methods are the only way to intermittently quantify this kind of past human activity. Moreover, the existence of the population fluctuations is also backed up by our pioneering analysis of the National Stone Artefact Database and provides another example of how the well-documented archeological records in Finland can be utilized (Sundell *et al.* 2014). In addition, the simulation studies have benefited from radiocarbon data (Tallavaara *et al.* 2010) as well as genetic data deriving from population genetic studies of contemporary Finns (Palo *et al.* 2009, Sajantila *et al.* 1996). The authors of this paper continue to refine the existing computational methods and develop new collaboration to assess and quantify these prehistoric population events that are supported by accumulating evidence from multiple disciplines. The newest methodological addition to our simulation pipeline is documented in another paper in these proceedings (Sundell *et al.* submitted), whereas this paper contributes mostly to the database analysis pipeline. We conclude that the methods presented here are potentially applicable to any archaeological data subset where the data points have multiple features.

Fig. 1. Location of Finland in Northern Europe˝.

A computational method called the principal component analysis (PCA) can be used to analyze multidimensional data in order to visualize essential information from the data in two- or three-dimensional surfaces that are more comprehensible to the human eye. PCA is a method of optimization, as it finds in each case the most suitable surface that minimizes the loss of resolution in the data. PCA has been used widely across many fields of science including genetics (Patterson *et al*. 2006, Reich *et al.* 2008, McVean 2009), computer science (e.g. Kim *et al.* 2002) as well as multidisciplinary studies (e.g. Cavalli-Sforza *et al.* 1988). For instance, many web services that contain recommender systems and advertisements often utilize PCA in returning the optimal solution from the service database to the end user as quickly as possible. In archaeology, PCA has been proposed as a viable statistical method for image recovery (Legnaioli *et al.* 2013a; 2013b, Salerno *et al.* 2014). Still, while e.g. many of the studies presented in the CAA conference this year indicate a clear interest towards just this kind of data analysis (Carrer, Cerrillo-Cuenca and Sepúlveda, Kücükdemirci *et al.*), PCA has generally been only limitedly used in computational archaeology. Here, we predispose a set of 10,168 Stone Age dwelling site data points from the AMR to PCA. We find that PCA can outline and quantify patterns in the data that would be difficult to detect from the raw data points alone. Additional ramifications are that PCA could be a valuable supplement to general analysis of any multidimensional features in the ever-growing archaeological databases.

Fig. 2. Reconstruction of a Stone Age dwelling. The Stone Age village at Saarijärvi, Finland. Photo by: Tarja Sundell.

In principle, the PCA method can be used to find and visualize meaningful patterns in numerous types of archaeological data. These could include typological differences in various types of artefacts (for example differences in sizes, shapes and materials in a given artefact group) or archaeological sites and constructions. PCA can separate the researched objects according to given parameters and reveal hidden patterns undetectable by other means.

In this paper, we apply the PCA-method to visualize the geographical distribution of different prehistoric dwelling sites in Finland. Remains of prehistoric dwelling sites found in contemporary Finnish landscape are a prominent indication of localized past human activity. The prehistoric house-pits or semisubterranean house remains currently known from Finland date mainly to the Neolithic Stone Age (*c.* 5100-2000 calBC) (Pesonen 2002). Neolithic houses excavated in Finland and elsewhere in northern Fennoscandia, as well as in northwestern Russia, appear to have been constructed in large pits (hence the term 'pit house' or 'semisubterranean house') (Leskinen 2002). Some of the Neolithic houses have also been found built on a flat surface. The remains of prehistoric dwellings have been studied in Finland since the beginning of the 1920s. At the time Stone Age dwellings were described as hut or tent structures, dwelling pits etc. However, the research of prehistoric houses has been of greater interest since the early 1990s due to the development of new research methods. These include techniques in identifying and excavating the sites as well as recording house remains in structural details. This new research began to reveal an increasing number of remains of semisubterranean houses visible on the ground surface as shallow pits. In many cases excavations revealed that the subsurface structures of the houses were astonishingly well preserved, which have remarkably added to our knowledge of prehistoric houses.

1 Materials and methods

In order to investigate the AMR more closely especially for the Stone Age period, we applied the PCA method for a subset of 10,168 Stone Age dwelling sites documented in the AMR. Usually, the contemporary physical remains of Stone Age dwelling sites in Finland only consist of dwelling depressions of various shapes and sizes. In rare occasions, placements for supporting logs may also be visible, while the actual dwelling structure has since been destroyed by unknown events and, at the very latest, by taphonomic processes. A photo of a reconstruction of one of these dwellings is provided for reference (Fig. 2). The data points of this study were divided into three subtypes directly by their naming in the AMR: 'undefined dwelling sites' (N=9,518), 'dwelling depressions' (N=646) and 'traditional Sami dwelling foundations' (N=4). We grouped the data according to the geographical latitude of the data points into 'South', 'Central' and 'North' groups and executed PCA for both the dwelling site type and elevation from sea surface principal components. The raw data points (Fig. 3 and Fig. 4) consisted of three features: dwelling site type, latitude and elevation from the sea surface.

In preparation for the PCA, we read the target dataset from the AMR into a rectangular matrix with rows indexed by sites and columns indexed by the three features: site type, site elevation and group as explained above. We then labeled the data points so that the longitudinal land area of Finland was split into three roughly even-sized parts. First, the sites that were located more south than the latitude 7,000,000 of the ETRS-TM35FIN coordinate system (about the 63rd parallel north circle of latitude) were designated as 'South' data points. Second, the sites that were located between the latitudes 7,000,000 and 7,300,000 of the coordinate system (about the 66th parallel north circle of latitude) were designated as 'Central'. Finally, the sites that were located more north than the 7,300,000 latitude of the coordinate system were designated as 'North' data points.

The basic workflow for PCA is simple (Patterson *et al.* 2006). Characteristic values and respective characteristic vectors known as eigenvectors are computed for the features that were predisposed to PCA. When normalized, the unit vectors for the eigenvectors represent the axes of a linear transformation of the original data. This transformation is an optimal surface where variation in the original multidimensional data is maximally visualized on the two or three first axes. As an end-result, the algorithm returns a topological space where the principal component that explains most of the variance in the data is located on the first coordinate, the second principal component on the second coordinate and so on. In the case of our two

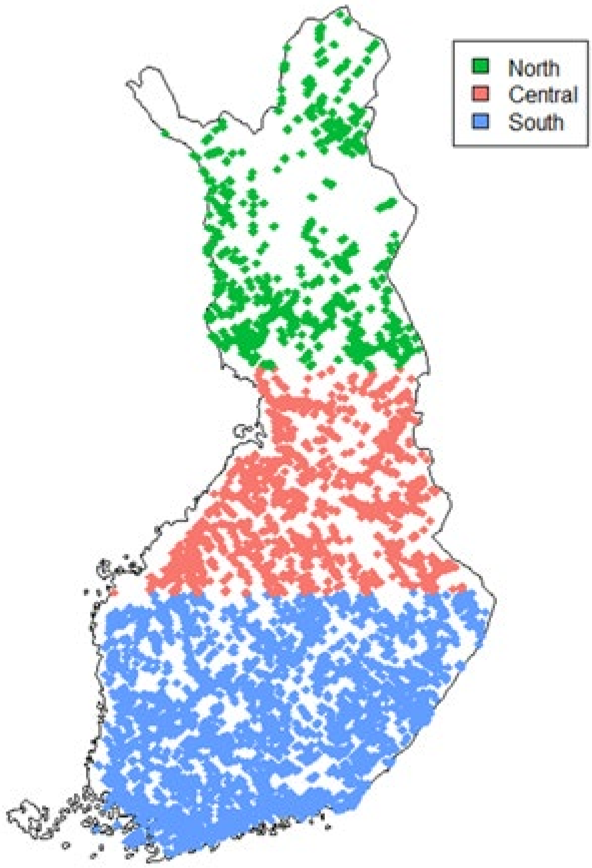

Fig. 3. Raw data points (*N*=10,168) plotted on top of geographical map of Finland.

features, the result space was two-dimensional and the two axes that span this space were represented by the elevation from sea level component and the site type component (Fig. 5). The result space contains all original data points.

For multi-featured data, the ordering of the features as principal components is automated in PCA. This means that e.g. the first two principal components will always be those two that account for most of the variance in the overall data. The data preprocessing as well as the eigenvalue decomposition of the two target features in the dataset were executed in the R-environment (R-project). We used the prcomp() function of the standard R packages (R-project) which implements the PCA algorithm in the manner explained above. The PCA result plot (Fig. 5) was visualized with the ggbiplot() utility of the ggbiplot R package (Ggbiplot). All analyses were performed in a desktop computer running Windows 8 operating system with a single AMD A6-5200 64-bit processor and 8 gigabytes of Random Access Memory.

2 Results

The raw data points can be presented as a three-dimensional scatterplot where each feature can be visualized on its own axis (Fig. 4). After grouping the data according to latitude and

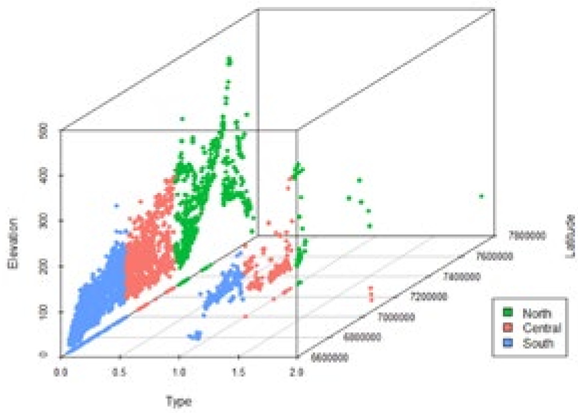

Fig. 4. Three-dimensional scatterplot of the raw data points (*N*=10,168).

running PCA on the site type and elevation from sea surface features, patterns emerge from the data: The northern dwelling sites are clustered more strongly on elevation, whereas the other groups are clustered more strongly by site type (Fig. 5). Moreover, the within-type variation becomes apparent. The undefined dwelling sites in the 'North' group tend to have higher elevation in general and the 'North' group apparently is the most abundant group in this dwelling site type (Fig. 5). Interestingly, sites identified as dwelling depressions seem to be more abundant in the 'Central' and 'South' groups in comparison to those located in the north (Fig. 4).

3 Discussion and conclusions

Apparently, the northern dwelling sites in our dataset were clustered more strongly by site elevation. This is best explained by the geography of Finland, where the overall highest elevations from sea surface are located in the northern part of the country. In addition, land rise has been rapid in North Ostrobothnia, where many of the house-pits are located, and the dwellings had to be rebuilt closer to the beach every few decades. This produced more dwelling remains than would be found at a locality where the waterline did not shift and the same site could be used for a long time (Pesonen 2002).

The sites defined as dwelling depressions were found to be more abundant in the 'Central' and 'South' groups. This may indicate that the dwelling sites in these latitudes have been more identifiable in general. Whether dwellings built into these depressions have actually been more infrequent in the northern latitudes during the Stone Age is a reasonable question that could be further investigated. Indeed, remains of Stone Age dwellings have been found as far north as on the northern coast of Arctic Ocean in Norway and within the Petsamo province in the extreme north of Murmansk Oblast, Russia (Pesonen 2002).

The existence of multi-featured data points is ubiquitous in archaeological databases. Here we have shown that PCA is a valid method for visualizing the data in the AMR and that it can outline patterns in the data subset that may be difficult to detect otherwise. While being suitable to datasets where the

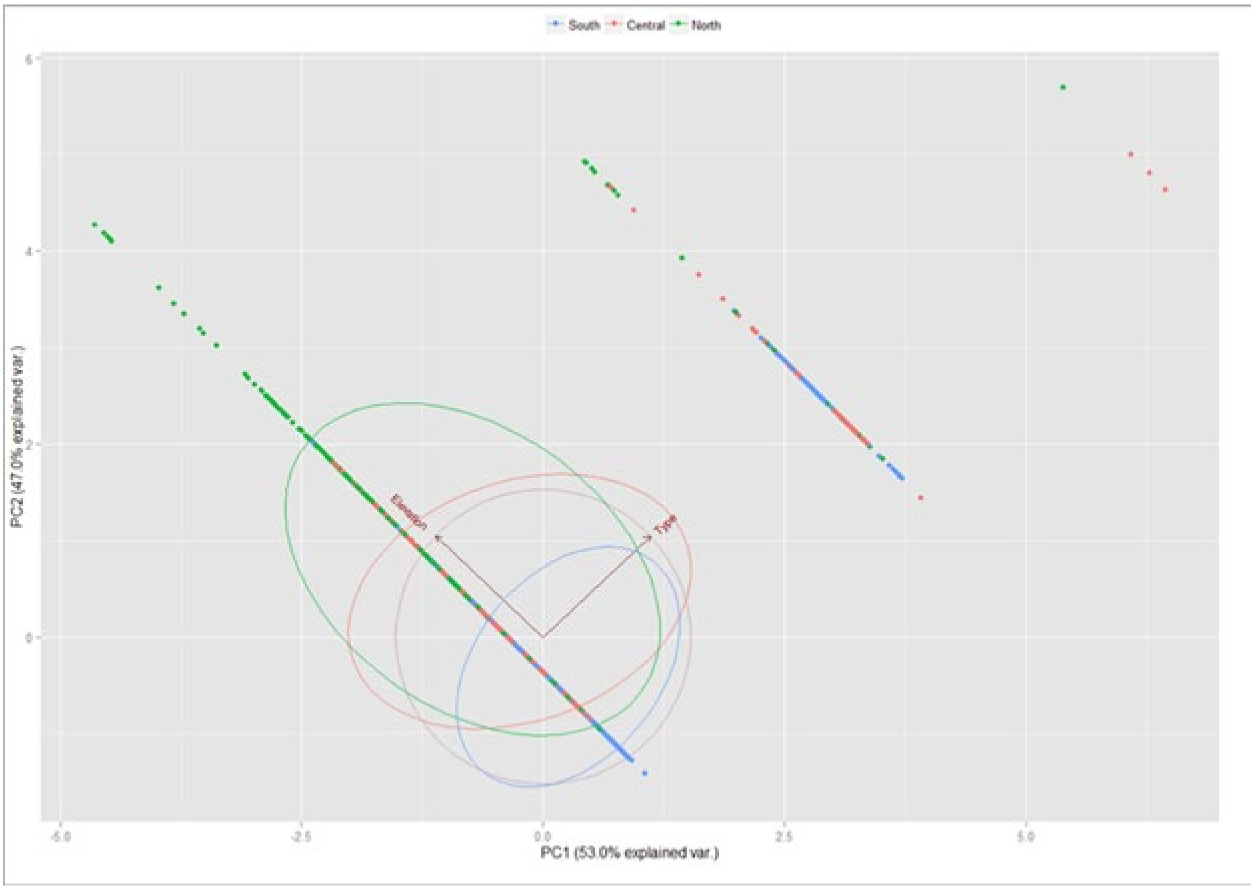

Fig. 5. Two-dimensional PCA result plot for the dwelling site type and elevation from sea surface principal components. The cluster ellipses contain 68% of the within-group observations and the reference circle contains 69% of the total observations.

data points have even more than three features, our results indicate that PCA could be a valuable supplement to the general analysis and maintenance of ever-growing archaeological databases. Next such database may well be the National Stone Artefact Database that earlier proved its usability in the sheer quantity of the artefacts currently recorded in the database (Sundell *et al.* 2014). It is worth mentioning that our analysis was performed for more than 10,000 multi-featured data points in a reasonable time in a rather modest computing environment and without the need for supercomputer power. Indeed, most of the modern desktop computers and even tablets do meet the system requirements of the computations presented in this study. The results presented in this paper further contribute to the extensive multidisciplinary effort of investigating and quantifying prehistoric population events in Finland.

Bibliography

AMR. Ancient Monuments Register, National Board of Antiquities, Finland. Available at: http://kulttuuriymparisto.nba.fi/netsovellus/rekisteriportaali/mjreki/read/asp/r_default.aspx Accessed: 18 june 2015.

Cavalli-Sforza, L. L., Piazza, A., Menozzi, P., Mountain, J. 1988. Reconstruction of human evolution: bringing together genetic, archaeological, and linguistic data. *Proceedings of the National Academy of Science U S A.* 85, 16: 6002-6.

GGBIPLOT . A biplot based on ggplot2. Open access. Available at: http://github.com/vqv/ggbiplot . Accessed: 18 jun 2015.

Kammonen, J., Sundell, T., Moltchanova, E., Pesonen, P., Oinonen, M., Heger, M., Haimila, M., Onkamo, P. 2012. Bayesian Spatial Analysis of Archaeological Finds and Radiocarbon Dates: An example from Finland 4000-3500 cal BC. In Zhou, M., Romanowska, I. Wu, Z., Xu, P., Verhagen, P. (eds.), *Revive the Past: Proceedings of the 39th Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Beijing, 12-16 april 2011*: 318-25. Amsterdam, Pallas

Kammonen, J., Sundell, T., Pesonen, P., Oinonen and Onkamo, P. 2013. Bayesian Spatial Modelling of Radiocarbon Dated Archaeological Artefacts Using R-INLA. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 414-9. Amsterdam, Amsterdam University Press.

Kammonen, J. 2013. *Improving the throughput of the forward population genetic simulation environment simuPOP*. Unpublished MSc thesis, Department of Computer Science, University of Helsinki.

Kim, K. I., Jung, K., and Kim, H. J. 2002. Face recognition using kernel principal component analysis. *Signal Processing Letters, IEEE*. 9, 2: 40-2.

Legnaioli, S., Grifoni, E., Lorenzetti, G., Marras, L., Pardini, L., Palleschi, V., Salerno, E. and Tonazzini, A. 2013. Enhancement of hidden patterns in paintings using statistical analysis. *Journal of Cultural Heritage*, 14S: 66-70.

Legnaioli, S., Lorenzetti, G., Cavalcanti, G. H., Grifoni, E., Marras, L., Tonazzini, A., Salerno, E., Pallecchi, P., Giachi, G. and Palleschi, V. 2013. Recovery of archaeological wall paintings using novel multispectral imaging approaches. *Heritage Science* 1: 33.

Leskinen, S. 2002. The late Neolithic House at Rusavierto, in H. Ranta (ed.), *Huts and Houses. Stone Age and Early Metal Age Buildings in Finland*: 147-69. Helsinki, National Board of Antiquities.

Mcvean, G. 2009. A Genealogical Interpretation of Principal Components Analysis. *PLoS Genetics* 10, 5: e1000686.

Novembre, J. and Stephens, M. 2008. Interpreting principal component analyses of spatial population genetic variation. *Nature Genetics* 40, 5: 646-49.

Palo, J.U., Ulmanen, I., Lukka, M., Ellonen, P. and Sajantila, A. 2009. Genetic markers and population history: Finland revisited. *European Journal of Human Genetics* 17, 10: 1336-46.

Pesonen, P. 2002. Semisubterranean Houses in Finland – a Review, in H. Ranta (ed.), *Huts and Houses. Stone Age and Early Metal Age Buildings in Finland*: 53-64. Helsinki, National Board of Antiquities.

Pesonen, P. and Sundell, T. 2011. Argeopop-projektin arkeologiset tietokannat. *Muinaistutkija* 4/2011: 11-8.

Patterson, N., Price, A. L. and Reich, D. 2006. Population Structure and Eigenanalysis. *PLoS Genetics* 12(2): e190.

R-PROJECT. The R Project for Statistical Computing. Retrieved from: http://www.r-project.org/ Accessed: 23 june 2013.

Reich, D., Price, A. L. and Patterson, N. 2008. Principal component analysis of genetic data. *Nature genetics* 40, 5: 491-2.

Sajantila, A., Salem, A. H., Savolainen, P., Bauer, K., Gierig, C. and Pääbo, S. 1996. Paternal and maternal DNA lineages reveal a bottleneck in the founding of the Finnish population. *Proceedings of the National Academy of Science U.S.A.* 93, 21: 12035-9.

Salerno, E., Tonazzini, A., Grifoni, E., Lorenzetti, G., Legnaioli, S., Lezzerini, M., Marras, L., Pagnotta, S. and Palleschi, V. 2014. Analysis of multispectral images in cultural heritage and archaeology. *Journal of Applied and Laser Spectroscopy*, 1, 1: 22-7.

Sundell, T., Heger, M., Kammonen, J. and Onkamo, P. 2010. Modelling a Neolithic Population Bottleneck in Finland: A Genetic Simulation. *Fennoscandia Archaeologica* XXVII: 3-19.

Sundell, T., Kammonen, J., Heger, M., Palo, J. and Onkamo, P. 2013. Retracing Prehistoric Population Events in Finland Using Simulation. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*: 93-104.

Sundell, T., Kammonen, J., Halinen, P., Pesonen, P and Onkamo, P. 2014. Archaeology, genetics and a population bottleneck in prehistoric Finland. *Antiquity* 88: 1132-47.

Sundell, T. and Kammonen, J. 2015. A Density-Based Simulation Approach for Evaluating Prehistoric Population Fluctuations in Finland. In Giligny, F., Djindjian, F., Costa, L., Moscati, P. and Robert, S. (eds.), *CAA 2014, 21st Century Archaeology. Concepts, Methods and Tools: Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*: 605-10.

Sundell, T., Heger, M., and Kammonen, J. (Submitted). Reconstructing the Boom of Prehistoric Hunter-Gatherer Population Size in Finland by Agent and Equation-Based Modelling. *CAA 2015, Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology. Siena, Italy.*

Sundell, T. 2014. *The past hidden in our genes. Combining archaeological and genetic methodology: Prehistoric population bottlenecks in Finland*. Unpublished PhD thesis, University of Helsinki.

Tallavaara, M., Pesonen, P. and Oinonen, M. 2010. Prehistoric population history in eastern Fennoscandia. *Journal of Archaeological Science* 37, 2: 251-60.

IT-assisted Exploration of Excavation Reports. Using Natural Language Processing in the Archaeological Research Process

Christian Chiarcos
chiarcos@informatik.uni-frankfurt.de
Applied Computational Linguistics, Goethe-University Frankfurt am Main, Germany

Matthias Lang
matthias.lang@uni-tuebingen.de
eScience-Center, University of Tübingen

Philip Verhagen
j.w.h.p.verhagen@vu.nl
VU University Amsterdam

Abstract: In this paper we summarize recent experiments conducted on what has become known as 'Machine Reading' of scientific literature from different fields of archaeology, i.e., the extraction of machine readable, semantic information out of plain text. We describe a processing pipeline to extract semantic concepts and relations, the representation of extracted information by means of Semantic Web standards, its linking with background knowledge from both domain vocabularies and general lexical/conceptual knowledge sources and possible user interfaces that provide access to the extracted information.

These experiments represent early steps in the development of an elaborate system that will allow to analyse excavation reports, access/search them on a semantic, rather than a textual basis, and augmenting them with background information specific to the field of archaeology.

Keywords: Natural Language Processing, Semantic Web, Linked Open Data (LOD), Archaeological grey literature

1 Motivation

Archaeology as a scientific discipline was established during the 19th century, and with almost two centuries of scientific publications, one of the most time-consuming challenges to nearly every researcher nowadays consists in the task to assess this huge amount of knowledge created by earlier generations of scholars on a particular phenomenon, region or artefact type currently under consideration. Over time, many of them worked in different countries, with different methodological and ideological backgrounds, using different terminologies in different languages. Accordingly, an exhaustive overview over, say, the distribution of Roman coins in Celtic contexts, requires not only to cover an enormous wealth of literature, but also, a wealth of literature of extreme heterogeneity. In addition, great parts of this information may be available only as 'grey literature', as technical reports, in-house publications of different universities, thesis papers or mere manuscripts. In the digital age, this body of sparsely accessible knowledge grows even more drastically than the number of traditional print publications.

Machine reading represents itself as a way to improve the accessibility of this wealth (or, in parts, this mess) of information: the extraction of machine-readable, formalized knowledge out of written text, and ways to make this information accessible to scholars in the field in a way that it can be used without or with minimal technical expertise.

We describe one selected case study in this regard, focusing on retrieving and querying semantic relations between entities in archaeological literature. These experiments are still in an early stage of development, but they represent an important extension of existing approaches on grey literature in archaeology, which focus on identifying and classifying archaeologically relevant entities rather than relations between them. In the longer perspective they will thus have a profound impact on the way scientific literature is accessed in archaeology and other branches of Digital Humanities.

So far, our experiments have been conducted on English texts only. But this is only because of the availability of Natural Language Processing resources for this particular language, which makes it a promising candidate for initial experiments and for determining which technologies to choose for our specific task. With information extraction experiments successfully conducted on that basis, analogous processing pipelines for other languages can be created.

2 Use Case and Technological Background

In the scenario detailed in this paper, we imagine an archaeologist interested in objects that are described as having been *'found'* in the course of an excavation. We would like to emphasize that the example use case is different from the state of the art in Natural Language Processing as currently conducted on scientific publications and grey literature from archaeology which is represented by Named Entity Recognition and Entity Linking (Binding, Tudhope and May 2008, Byrne and Klein 2010). We go beyond detecting and classifying archeologically relevant terms in isolation, a task which we consider to be solvable by existing initiatives and their technologies. Instead, we are interested in recovering semantic relations connecting such terms.

For reasons of space, we cannot provide an exhaustive introduction for the technologies described here, which fall under the broad scope of Natural Language Processing (NLP), Human Language Technologies (HLT) in its specific application to Digital Humanities (DH), as well as the Semantic Web (SW) resp. Linked Open Data (LOD)[1]. We see our activities within the more general scope of *Machine Reading* (Etzioni, Bank and Cafarella 2006) in its application to scientific publications and grey literature from the field of archaeology.

Following Barker (2007), Deep Machine Reading aims to provide a formal representation of a given text, say, a text book, as exhaustively as possible. It is related to concepts like traditional *Information Extraction* and *Text Mining*, but goes beyond these in that we aim to process not only information defined in pre-existing vocabularies or registries, but also evaluate *free text*. Unlike general-purpose *Open Information Extraction*, however, we formalize the output of our system in line with standards, technologies and logics developed in the context of the Semantic Web, thereby establishing not only machine-readable representation of the semantics of scientific publications, but also a representation with well-defined formal semantics, i.e., the Resource Description Framework RDF (W3C-RDF, 2014) and the Web Ontology Language OWL (W3C-OWL, 2012).

Using this representation, we aim to answer a query directly run against (the automatically extracted RDF representation of) a PDF document for a natural language question like *'What did they find?'*

3 Open Information Extraction: From PDF to RDF

For our first experiments we choose digital-born PDFs including selected publications of the Römisch-Germanische Kommision since 2004 (*Germania*, *Bericht der Römisch-Germanischen Kommission*), and FASTI Online (Fasti Online 2015).

Out of this pool of data we currently focus on Imperial Rome. The technology is, however, not specific to such data but may be applied to other strands of archaeology (and beyond). Below, we use Muccigrosso (2011) as an example text for the analysis.

3.1 Text Extraction

Extracting text from a digital publication designated for print is not a trivial issue. We extract text using PDF2XML (PDF2XML, 2015) and a set of tailored XSLT scripts which heuristically detect and classify textual content (titles, author, headlines and paragraphs), de-hyphenate line breaks and merge paragraphs across page breaks.

3.2 Natural Language Processing

The actual NLP pipeline takes the resulting text as its input and uses existing NLP tools for linguistic analysis of the text, including steps of sentence splitting, tokenization, part-of-speech tagging, lemmatization, syntactic parsing and named entity recognition. Particularly relevant for our example is the sub-task of *Semantic Role Labeling* (SRL, Palmer, Gildea, Kingsbury 2010): Semantic roles, or theta-roles, describe the semantic relationship between a predicate (say, a verb) and its arguments (say, subject and object), often formalized in terms of frame semantics. In this context, any particular frame consists of a number of semantically defined 'slots' for predicate and argument, but in addition, it is defined as being in a particular ontological relation with other frames, e.g., in terms of inheritance. Semantic Role Labeling, the task of automatically identifying predicates (both verbal and nominal), their arguments (e.g., prepositional phrases) and the semantic role between them, thus represents a major component in our approach.

The result of the NLP analysis for the example sentence marked blue in the figure above is shown below.

Here, the first column (coloured in an ascending red-green scale) is the number of the word in the sentence, the second column is the actual word, followed by lemma, parts of speech, named entities, shallow syntax (chunking) and a phrase structure parse. The 8th and 9th columns provide a dependency representation of this parse with links to the respective head of a given word (colours match the colours of the first column) and the respective dependency labels. Then, semantic role labelling follows with the list of predicates. The arguments of the first predicate (*basing*) are shown in the following column, those of the second in the one after, etc.

3.3 Target Format: Resource Description Framework (RDF)

For representing the information to be extracted from the text, we adopt the Resource Description Framework (RDF, W3C-RDF 2014) as a modelling toolkit: The fundamental data structure of RDF is a *triple*, i.e., a pair of two *nodes* (RDF resources) connected by a labelled edge (RDF property/predicate). Edges in this graph structure are *directed*, with the source node being conventionally referred to as the '*subject*' and the target node the '*object*' of a particular triple. Subject, object and predicate are by themselves RDF resources, and can be identified with a Uniform Resource Identifier (URI). As a result, any RDF resource is uniquely addressable in the web (of data), e.g., in the form of a HTTP link. An example triple conveying the information that *We (continue to) find a relatively large number of coins* (Muccigrosso 2011) may thus have the following form:

:we :find : coins.

Additional triples then may further describe*:coins*, etc., e.g., as having the string representation *'a relatively large number of coins*'.

:coins rdfs:label 'a relatively large number of coins'^^xsd:string.

If URIs are resolvable (i.e., if a HTTP link opened in a browser or crawler points to a resource than can be accessed via HTTP

[1] For general introductions into these areas, we recommend Jurafsky (2008) for Natural Language Processing, Schreibman (2004) for Digital Humanities, Hitzler (2009) for Semantic Web technologies and Berners-Lee (2009) for Linked Data. Unless an explicit reference is given, the technical terms used below are used as defined in these works.

1	Neverthele:	neverthele:	RB	O	S-ADVP	(S1(S(ADVP	2	ADV	-	O	O	O	O
2	in	in	IN	O	S-PP	(PP*	0	ROOT	-	O	O	O	O
3	1938	@card@	CD	O	S-NP	(NP*))	2	PMOD	-	O	O	O	O
4	,	,	,	O	O	*	2	P	-	O	O	O	O
5	partly	partly	RB	O	B-VP	(S(VP(ADVI	6	ADV	-	S-AM-MNR	O	O	B-AM-ADV
6	basing	base	VBG	O	E-VP	*	2	COORD	basing	S-V	O	O	I-AM-ADV
7	his	his	PRP$	O	B-NP	(NP*	8	NMOD	-	B-A1	O	O	I-AM-ADV
8	hypothesis	hypothesis	NN	O	E-NP	*)	6	OBJ	-	E-A1	O	O	I-AM-ADV
9	on	on	IN	O	S-PP	(PP*	6	ADV	-	B-A2	O	O	I-AM-ADV
10	several	several	JJ	O	B-NP	(NP(NP*	11	NMOD	-	I-A2	B-A0	O	I-AM-ADV
11	inscriptions	inscription	NNS	O	E-NP	*)	9	PMOD	-	I-A2	E-A0	O	I-AM-ADV
12	found	find	VBN	O	S-VP	(VP*	11	APPO	found	I-A2	S-V	O	I-AM-ADV
13	in	in	IN	O	S-PP	(PP*	12	ADV	-	I-A2	B-AM-LOC	O	I-AM-ADV
14	the	the	DT	O	B-NP	(NP*	15	NMOD	-	I-A2	I-AM-LOC	O	I-AM-ADV
15	area	area	NN	O	E-NP	*)))))))	13	PMOD	-	E-A2	E-AM-LOC	O	E-AM-ADV
16	,	,	,	O	O	*	6	P	-	O	O	O	O
17	Giovanni	Giovanni	NNP	B-PER	B-NP	(S(NP*	18	NAME	-	O	O	B-A0	O
18	Becatti	Becatti	NNP	E-PER	E-NP	*)	19	DEP	-	O	O	E-A0	O
19	proposed	propose	VBD	O	S-VP	(VP*	6	COORD	proposed	O	O	S-V	O
20	this	this	DT	O	B-NP	(NP*	21	NMOD	-	O	O	B-A1	O
21	location	location	NN	O	E-NP	*)	19	OBJ	-	O	O	I-A1	O
22	for	for	IN	O	S-PP	(PP*	19	ADV	-	O	O	I-A1	O
23	the	the	DT	O	B-NP	(NP*	24	NMOD	-	O	O	I-A1	O
24	vicus	vicus	NN	O	E-NP	*))))	22	PMOD	-	O	O	E-A1	O
25	,	,	,	O	O	*	19	P	-	O	O	O	O
26	and	and	CC	O	O	*	19	COORD	-	O	O	O	O
27	subsequen	subsequen	RB	O	S-ADVP	(ADVP*)	2	ADV	-	O	O	O	S-AM-TMP
28	several	several	JJ	O	B-NP	(S(NP*	31	NMOD	-	O	O	O	B-A0
29	other	other	JJ	O	I-NP	*	31	NMOD	-	O	O	O	I-A0
30	confirmator	confirmator	JJ	O	I-NP	*	31	NMOD	-	O	O	O	I-A0
31	inscriptions	inscription	NNS	O	E-NP	*)	32	DEP	-	O	O	O	E-A0
32	have	have	VBP	O	B-VP	(VP*	26	CONJ	-	O	O	O	O
33	emerged	emerge	VBN	O	E-VP	(VP*)))	32	VC	emerged	O	O	O	S-V
34	.	.	.	O	O	*))	2	P	-	O	O	O	O

Fig.1.

and that provides information about the resource), then data sets on different remote servers share identifiers for, e.g., terminology, and provide cross-links with each other, a concept conventionally known as 'Linked (Open) Data' (Berners-Lee, Bizer and Heath 2009). With the concept of *federation*, SPARQL 1.1 (W3C-SPARQL 2013) allows to query such links across distributed resources, so that the set of interlinked resources accessible in this way and available under an open license forms the 'Linked Open Data (LOD) cloud'. This is an interesting feature when it comes to combining different knowledge sources (Section 5).

We don't use the RDF-toolkit to represent the domain by itself, but the lexical semantics of the text. Aggregating multiple texts will, however, approximate a domain model in that we can extrapolate typical properties and their likelihood to connect (instances of) specific classes. Our presentation featured such a concept graph bootstrapped from analysing raw text, omitted here caused by the format of the paper. While such an automatically constructed domain model is from a quite different quality than a formal ontology, it can be used to infer additional information (Penas and Hovy 2010).

3.4 Triple Extraction

To construct RDF triples out of plain text, we ground most of our triple extraction on 'Semantic Role Labeling**'** a la PropBank (Palmer, Gildea and Kingsbury 2005). Unlike other representation formalisms for semantic roles, PropBank limits itself to a *minimal set* of semantic roles and aims for a high degree of genericity. For every verbal predicate, it distinguishes 6 classes of direct arguments, the most important being A0 (AGENT, prototypical subject), A1 (PATIENT, prototypical direct object), and A2 (THEME, prototypical indirect object), whereas the other classes are predicate-specific. In addition, several classes of oblique arguments are supported, including AM-NEG (negative modifier), AM-LOC (locative modifier) and AM-TMP (temporal modifier).

For every transitive verb, then, a triple is formed connecting its main arguments (A0 and A1) with a relation that carries the lemma of the verbal predicate, resulting in the *:proposes* relation in Figure 2. Other semantic roles are then connected to A0 and A1 arguments with relations composed of the generic relation identifier *:do* combined with a placeholder for the respective semantic role, e.g. *at* for AM-LOC and *during* for AM-TMP. Hence, we establish the relation *:do-at* between A0 arguments and locative modifiers, etc.

Figure 2 gives a full example analysis of the sentence '*Nevertheless in 1938, partly basing his hypothesis on several inscriptions found in the area, Giovanni Becatti proposed this location for the vicus , and subsequently several other confirmatory inscriptions have emerged*' in graphical form. (Note that here, rdfs:labels replace the actual URIs and cardinality properties have been omitted.)

This fragment captures roughly the following semantics:

Giovanni Becatti proposes 'the vicus'

someone (_:n5) bases 'his hypothesis' on inscriptions found by someone (_:n4) in 'the area'

'confirmatory inscriptions' emerged

An obvious limitation of this representation is that context-dependencies get not resolved. Of course, the blank node *_:n5* is to be resolved to Giovanni Becatti, who also occurs to possess 'his hypothesis'. But in addition, *the vicus* and *the area* need to be identified with areas or vici mentioned before, and the relational nature of the adjective *confirmatory* (which

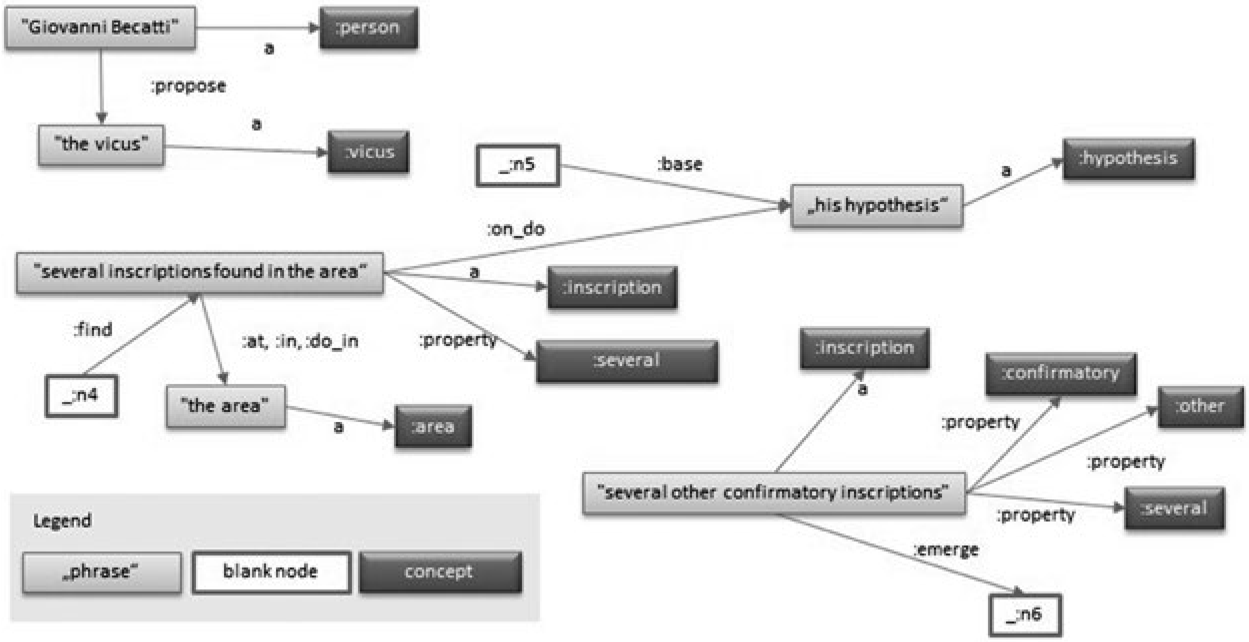

FIG. 2.

presupposes a hypothesis to be confirmed) is not recognized. Partially, these problems can be handled through anaphor resolution systems. At the moment, the development or domain adaptation of such a system is beyond the scope of our initial experiments, but future refinement of the extracted information will include the support for co-reference.

4 Querying RDF

The extracted data can be directly queried using the SPARQL (W3C-SPARQL 2013), the standard query language for RDF data. However, as this may be inconvenient to archaeologists, we also provide a simple (though limited) natural language query interface to the extracted data. The general idea is appealingly simple: Given a user query, run the NLP pipeline and triple extraction procedure above and convert the output into a SPARQL query by replacing object and subject URIs by variables.

As an example, the analysis of the query *What did they find?* is shown below, together with its SPARQL version.

The resulting query is just a minor, and fully automated modification of the triples generated from the NLP analysis: SELECT and WHERE statements are added as obligatory components of the query, the arguments of *:find* are transformed from URIs to variables (marked by *?*) and the string values of their labels are replaced by variables, as well. For the result, SELECT requires that only these label variables are returned.

This trivial transformation works already well, and it returns matches for phrases like *X found Y*, *Y has been found by X,* or *X, the finder of Y*. With this naive approach, however, it is not possible to query for optional arguments (unless every variable is set to optional by default), and hence, the result set is limited to instances of *:find* that come with an explicit A0 argument. To query for objects of *:find*, only one can, however, ask *What was found?*

So far, this system remains bound to lemma matches with the text. While *What did they find?* generates the same SPARQL query as *Who found what?*, the system is not capable yet to capture the generalization to *X discovered Y*.

5 Background Knowledge and Inference

To unleash the potential of semantic technologies, inference beyond plain lemma matches as described above is a key requirement. This involves augmenting the extracted data with semantic information both for general world knowledge and for domain-specific vocabulary. As we are interested in verbal predicates here, we describe linking with an existing resource for verbal semantics. Other lexical-conceptual resources, however, can be processed analogously[2].

Similar to concepts during Named Entity Recognition, resp. Entity Linking, properties can be linked, inferred and queried. As we do not preserve their property labels during triple extraction, though, we rely on *URI match* during linking, i.e., the use of identical predicates. VerbNet (Kipper *et al.* 2006) is an extension of the verbal lexicon which provides a taxonomy of verb senses, with leaves representing sets of (English) verbs, as it takes the syntactic realization of arguments into account, we used this resource to generalize over predicates.

However, VerbNet identifiers are partially abstract. Accordingly, we chose not to query for them directly, but to assume that all verbs associated with the same concept are (to a certain extent)

[2] In addition to the experiment described in the text, we created and experimented with two small domain vocabularies, i.e., a minimal Dutch-English-German SKOS vocabulary of archeological features and periods (29 concepts), and a German thesaurus of 4552 concepts for classical archeology covering general excavation terminology (265 concepts), Greek/Roman mythology, toponyms and ethnonyms (1430 concepts), artifacts (1192 concepts) and materials (242 concepts), architecture (457 concepts), as well as anthropology, botanics and zoology (561 concepts).

TAB. 1.

```
#What did they find ?
      data:n0_000_what        rdfs:label      "What"^^xsd:string.
      data:n0_002_they        :find           data:n0_000_what.
      data:n0_002_they        rdfs:label      "they"^^xsd:string.
```

```
SELECT DISTINCT ?n0_000_what_label ?n0_002_they_label
WHERE {
      ?n0_000_what            rdfs:label      ?n0_000_what_label .
      ?n0_002_they            :find           ?n0_000_what .
      ?n0_002_they            rdfs:label      ?n0_002_they_label .
}
```

TAB. 2.

```
PREFIX terms: <http://purl.org/acoli/open-ie/>
...
SELECT DISTINCT ?n0_000_what_label ?do0
WHERE {
        _:n2 :declare-29.4|:discover-84|:get-13.5.1  ?n0_000_what .      # superproperties of :find
        _:n2 ?do0 ?n0_000_what .                                         # which predicate is actually used ?
        FILTER regex(str(?do0), "^http://purl.org/acoli/open-ie/[^0-9]*$")# limit to terms predicates
        ?n0_000_what rdfs:label ?n0_000_what_label .
}
```

n0_000_what_label	do0
"no new inscriptions naming the site"	<http://purl.org/acoli/open-ie/discover>
"The second tomb discovered in 2010"	<http://purl.org/acoli/open-ie/discover>
"several classes of object which indicate the presence of fairly elaborate buildings at the site"	<http://purl.org/acoli/open-ie/find>
"the fragment found last year from the factory of Suriscus"	<http://purl.org/acoli/open-ie/find>
"a relatively large number of coins"	<http://purl.org/acoli/open-ie/find>
"a deposit of what we believe to be mortar , which may have come from the now missing upper ...	<http://purl.org/acoli/open-ie/find>
"several drainage trenches running EW across the site , cutting through ancient walls and other features"	<http://purl.org/acoli/open-ie/discover>
"Their location along the Via Flaminia just 3.5 km from our site makes plausible their use by the ...	<http://purl.org/acoli/open-ie/find>

FIG. 3.

semantically similar, and broadened the query to all sibling verbs of the actual verb queried. Sibling verbs, as defined here, are children of the immediate parent node(s) of the verb we queried for. An example query explicitly addressing the sibling concepts is shown below. According to VerbNet, the verb 'find' is found in the verbal senses *:declare-29.4*, *:discover-84* and *:get-13.5.1*. Using this generalization, however, we lose information about the actual verb used, so that we add an additional variable to the query, limit its values to URIs from the *terms* namespace in which our extracted properties and those of VerbNet reside and include it in the result.

If we allow the query generation engine to access the VerbNet hierarchy, the SPARQL example below can be generated for *What has been found?*

Now, this query not only retrieves results for *find*, but also for, e.g., *discover*:

Note that this query requires RDFS reasoning and thus require enabling the corresponding entailment regime in the database. As an alternative, direct querying in native RDF is possible by means of SPARQL 1.1 property paths: Assuming that the property *:find* is defined as an *rdfs:subPropertyOf :declare-29.4* etc. (in accordance with its lexeme information in VerbNet), the following query is equivalent to the one given above.

Here, we use the original predicate *:find* as an anchor, we go one step up to its VerbNet generalization(s) (defined with using *rdfs:subPropertyOf*) and one step down to its sibling concepts (using the inverse property path *^rdfs:subPropertyOf*). The relation between superproperties and properties created from the text (i.e., verbal lemmas) is drawn from VerbNet, and as here, only the lowest level in the VerbNet hierarchy is addressed, it is not necessary to limit the result to the *term:* namespace anymore. At this level, the only sub-properties must have come from the text, i.e., the *term:* namespace. The result of the query, however, remains the same, but with the inference (i.e., access to the VerbNet hierarchy) handled internally by the RDF data base rather than an explicit VerbNet lookup. Like the query in Sect. 4, this query can thus be *automatically* generated from the analysis of a natural language question.

Similar semantic generalizations are possible when concepts are addressed and a terminological resource with hierarchical structure is employed, e.g., WordNet-RDF (2015).

This experiment shows that semantically supported access to archaeological publications is possible and promising, and that

Tab. 3.

```
PREFIX : <http://purl.org/acoli/open-ie/>
PREFIX terms: <http://purl.org/acoli/open-ie/>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX skos: <http://www.w3.org/2004/02/skos/core#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT DISTINCT ?n0_000_what_label ?do0
WHERE {
        :find rdfs:subPropertyOf/^rdfs:subPropertyOf ?do0 .       # ?do0 is a sibling property of :find
        _:n2 ?do0 ?n0_000_what .                                   # the triple in the data
        ?n0_000_what rdfs:label ?n0_000_what_label .
}
```

it can be supported with existing resources for, e.g., the general semantics of verbs. Both observation are, however, merely subjective impressions at the moment and require a more in-depth evaluation within a concrete application scenario.

6 Conclusions and Prospects

Our experiments show that the application of state-of-the-art semantic technologies from both NLP and Semantic Web is both possible and potentially fruitful for developing innovative applications of methodological value to archaeologists as well as other fields of (Digital) Humanities that are at least in parts concerned with scanning and accessing existing collections of heterogeneous scientific text.

The NLP analysis and triple generation is implemented as described. On this basis, we conducted additional experiments using off-the-shelf technology. None of this is integrated into a toolkit tailored towards end users, but it requires a minimal level of technical background to be replicated. Our point is to show how easily these experiments could be conducted with minimal knowledge of SPARQL on the side of the user, and this is a basis for developing concrete tools.

Core functionalities such as basic query interfaces and subsumption inferences are already available or can be easily developed. Also, general lexical resources seem applicable to the domain of archaeology. Nevertheless, the development of domain vocabularies, or the development of bootstrapping domain vocabularies from the existing body of text is a desideratum of great importance

A fundamental problem here is that ontological resources for the archaeology which are (or are supposed to be) developed at or by larger initiatives (e.g., Ariadne) are rarely publicly available. The freely accessible ontologies we are aware of are highly domain-specific (e.g., http://nomisma.org for Roman numismatics, http://data.archaeologydataservice.ac.uk/page/ for datasets and publications) or provide only TBox information (http://www.heritagedata.org/crmeh/crmeh_current.rdf) for documenting excavations. We do not have an ontology of find-spots, named entities, archaeological features, cultures, etc. which could be used for this purpose in a sufficient way.

So far we did not tackle the problem of multilinguism. Ontology localization has been a major topic in the Semantic Web community, e.g., in the context of the OntoLex and Multilingual Semantic Web workshops or in the OntoLex W3C community group founded in 2012 (OntoLex 2015). A simple solution that maintains queriability (at the expense of a non-minimal and possibly incorrect representation) would be to use bilingual word lists to 'translate' concept and property names created from one foreign-language text to the target language (say, English), with all possible translations generated out. A more advanced solution would be context-aware statistical machine translation, an idea currently pursued in the above-mentioned community efforts.

Additionally, our NLP components need to be extended to other languages. Thinking about German and French, this is a relatively easy task for languages with such richly developed research landscapes in the field of NLP, for other European (and even worse, non-European) languages, however, the situation is more problematic. This already includes Dutch (for which we possess neither Semantic Role Labelling nor an anaphor resolution system), but for other European languages, the situation is even worse (META-NET 2015). A technical problem in this regard is that NLP technology has a traditional focus on English whose lack of morphology is particularly suitable for the development of statistical NLP tools. The development of elementary tools for morphology-rich languages (say, Slavic, Greek, Latin, Finnish, Hungarian, Turkish, or Arabic) is still an active area of research. For the immediate future, we thus focus on selected languages with substantial NLP support (English, German, possibly French). In addition, we aim to experiment with a mid-resourced language, Dutch in our example, to assess the potential and the efforts required to extend the coverage of languages beyond this immediate core group.

Another aspect is that additional NLP techniques need to be integrated. In particular, an anaphor resolution system to facilitate information aggregation across sentence boundaries. As anaphor resolution benefits from rich semantic information, we aim to adapt an existing anaphor resolution system to take domain-specific information into account. While such efforts are beyond the scope of the pilot studies described here, they should be a major component of any more dedicated project.

To conclude, we developed and described prototypical core components of a system for machine reading scientific texts, illustrated here with a novel application in the field of archaeology, and sketched their application to search for relations in this body of text. Using formal background knowledge (VerbNet in the example), we were able to answer a natural language query in a way that not only literal matches for the verb *find* could be retrieved, but also matches from related verbal concepts like *discover*. Although no archaeology-specific resources were employed in this example, we have demonstrated the principal applicability of our technologies to this domain. At the same time, major technical problems (coreference, performance optimization, modal and contextual information, multilingualism) remain to be addressed, these are to be addressed within the scope of a dedicated research project that combines an original research problem from archaeology with this kind of technology to demonstrate its benefits and potential and to facilitate its adaptation by the scientific community. At the same time, any such project should provide expert knowledge from archaeologists for the automatically assisted creation, curation and extension of terminology resources.

Bibliography

Barker, K., Agashe, B. *et al.* 2007. Learning by reading: A prototype system, performance baseline and lessons learned. In *Proceedings of the Twenty-Second National Conference on Artificial Intelligence (AAAI 2007, Vancouver, British Columbia)*: 280-6.

Binding, C., May K., Tudhope D. 2008. Semantic Interoperability in Archaeological Datasets: Data Mapping and Extraction via the CIDOC CRM. *In Proceedings of European Conference on Digital Libraries* (ECDL08), no. 5173 (Aarhus, Denmark, Springer): 280–90.

Berners-Lee, T., Bizer C., and Heath, T. 2009. *Linked data – The story so far*. International Journal on Semantic Web and Information Systems 5, 3: 1-22.

Byrne, K. and Klein, E. 2010. Automatic Extraction of Archaeological Events from Text, in Frischer, B., Webb Craford, J., and Koller, D. (eds.), *Making History Interactive. Computer Applications and Quantitative Methods in Archaeology* (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, March 22-26 (BAR International Series S 2079): 48-56. Archaeopress, Oxford.

Etzioni, O., Banko, M., and Cafarella, M. 2006. Machine Reading. In *Proceedings of the 21st Conference on Artificial Intelligence (AAAI-2006, Boston)*: 1517-9.

Fasti Online 2015. A database of archaeological excavations since the year 2000 [online] http://www.fastionline.org/index.php [Accessed: 29th June 2015].

Hitzler, P., Krötzsch M. and Rudolph S. 2009. Foundations of Semantic Web technologies. Boca Raton, CRC Press.

Jurafsky, D. and Martin, J. 2008. Speech and language processing. Upper Saddle River, Prentice Hall.

Kipper, K., Korhonen A., Ryant A. and Palmer, M. 2006. Extending VerbNet with novel verb classes. In *Proceedings of the 5th International Conference on Language Resources and Evaluation, LREC-2006*, Genoa.

Muccigrosso, J. D. 2011. The 2010 Excavation Season at the Site of the Vicus ad Martis Tudertium *(PG)*, *The Journal of Fasti Online, Associazione Internazionale di Archeologia Classica*, http://www.fastionline.org/docs/FOLDER-it-2011-227.pdf [Accessed: 29 june 2015].

META-NET 2015. A Network of Excellence forging the Multilingual Europe Technology Alliance [online] http://www.meta-net.eu/whitepapers/key-results-and-cross-language-comparison [Accessed: 29 june 2015].

ONTOLEX 2015. Ontology-Lexica community group [online] https://www.w3.org/community/ontolex/ [Accessed: 29 june 2015].

Palmer, M., Gildea, D. and Kingsbury, P. 2005. The Proposition Bank: An annotated corpus of semantic roles. *Computational Linguistics* 31(1): 71-106.

Penas, A. and Hovy, E. 2010. Semantic Enrichment of Text with Background Knowledge

http://www.aclweb.org/anthology/W10-0903.pdf [Accessed: 15 november 2015].

Palmer, M., Gildea D. and Xue, N. (2010) Semantic role labelling. Synthesis Lectures on Human Language Technologies 3(1): 1-103. San Rafael, Morgan and Claypool.

PDF2XML 2015. Pdf2xml converter based on Xpdf library [online] http://sourceforge.net/projects/pdf2xml [Accessed: 29 june 2015].

Schreibman, S., Siemens, R. Unsworth, J. 2004. A Companion to Digital Humanities. Oxford, Blackwell.

W3C-OWL 2012. OWL 2 Web Ontology Language (Second Edition), W3C Recommendation 11 December 2012 [online] http://www.w3.org/TR/owl2-overview [Accessed: 29 june 2015].

W3C-RDF 2014. RDF 1.1 Concepts and Abstract Syntax, W3C Recommendation 25 February 2014 http://www.w3.org/TR/rdf11-concepts [Accessed: 29 june 2015].

W3C-SPARQL 2013. SPARQL 1.1 Overview, W3C Recommendation 21 March 2013 http://www.w3.org/TR/sparql11-overview/ [Accessed: 29 june 2015].

WORDNET-RDF 2015. WordNet RDF http://wordnet-rdf.princeton.edu/ [Accessed: 29 june 2015].

A 3d Visual and Geometrical Approach to Epigraphic Studies. The Soli (Cyprus) Inscription as a Case Study

Valentina Vassallo
(v.vassallo@cyi.ac.cy),

Elena Christophorou
(e.cristophorou@cyi.ac.cy),

Sorin Hermon
(s.hermon@cyi.ac.cy),

Lola Vico
(l.vico@cyi.ac.cy),

Giancarlo Iannone
(g.iannone@cyi.ac.cy)

The Cyprus Institute – STARC

Abstract: The paper focuses on a multidisciplinary study carried out on an inscription from Soli (Cyprus) within the framework of the on-going EAGLE and AKGDC projects, aimed at developing a research pipeline for the 3D digital study and digital long-term preservation of ancient inscriptions. The pipeline includes the definition of most suitable 3D data acquisition methodology (technique, level of detail, lightening, etc.), description of a comprehensive metadata structure for digital archiving and information retrieval and visual analysis using selected filters and views. Particularly, this paper focuses on the 3D visual and geometrical approach applied to epigraphic studies. The chosen case-study is a highly and fragmented inscription and scholars debate on its interpretation. Our analysis, performed on the 3D model acquired and based on computer vision methods wants to help scholars to analyse, interpret and reconstruct damaged inscriptions, where the letters' interpretation cannot be firmly based solely on the geometry of the carved surface, as well as investigate through 3D methodology the production of the inscriptions.

Keywords: Digital epigraphy, 3D data capture, 3D analysis

Introduction

A part of our research is based on the 3D documentation of archaeological artefacts, museum items, heritage buildings and archaeological excavations. Particularly, we have standardized a procedure for 3D documentation of Cultural Heritage assets that describes all the steps, from the 3D data acquisition of the real world object, the post processing of raw data and digital recording, to documentation and digital preservation of the 3D data (Athanasiou *et al.* 2013; Ronzino *et al.* 2012; Vassallo *et al.* 2013).

Within the framework of EAGLE - Europeana Network of Greek and Latin Epigraphy (http://www.eagle-network.eu/), an EU funded project that aims at creating and providing multimedia digital content to the wide public through the Europeana portal (www.europeana.eu), we have developed a 3D visual and geometrical approach applicable to the study of epigraphy. The European project will give access to digital texts, images, and 3D models related to the Ancient Cypriot inscriptions (Voskos 1995), parts of which are available online in the Archaia Kypriaki Grammateia Digital Corpus project (http://akg.cyi.ac.cy/) (Pitzalis *et al.* 2012).

Regarding the 3D material, some experiments were carried out in order to document the inscriptions three-dimensionally and to study and analyse them through the use of this technique. In particular, in this paper we focus on an Ancient Greek inscription, damaged and therefore object of controversies among scholars on its full interpretation, in order to apply our methodology for performing attempts to improve the reading with 3D measurements and visual investigations.

1 Research aims

The scopes of our research are finalized to shed light in the reading of the inscription, especially where damages or time wear are preventing the visibility and interpretation. Furthermore, our interest is aimed at providing rich description of the letters, in order to identify possible production patterns, techniques of engraving and the technologies involved.

Our assumption is that by applying various visual filters and rendering options we could be able to enhance the reading of the inscription, particularly by enhancing the edges of the letters and their 'separation' from the damaged area. For the second aim, we instead propose to use metrical analyses within a CAD and 3D environment for accurate measurements and geometry comparisons.

Our research is therefore aimed at clarifying matters related to:

- methods of inscription
- techniques of inscription
- the assessment of the usefulness of a 3D methodology for understanding how inscriptions were produced.

2 Work methodology

The reading and interpretation of an inscription present several difficulties. One of the epigraphist's task is to reconstruct the text of the inscription by suggesting the completion of the missing parts.[1] Some of the traditional methodologies and techniques that help to read an inscription are, for example, the use of oblique light and casts (Di Stefano Manzella 1987). The first technique helps to accentuate all the defects and surface details and to individuate possible incisions and decorations,[2] leading to the identification of areas not visible with naked eye. The casts can be made of plaster or resin, but the easier and cheaper way is the use of paper towel, water and brush: the wet paper is beaten with the brush on the surface so to adhere perfectly; when the paper is dry it is possible to get as a result the negative of the inscription. The technique of the cast can be useful and accurate for small and in good condition objects, but it is an invasive technique that could cause problems with inscriptions not well preserved. In the same way, the direct and indirect drawing, as well as the 2D reproduction (e.g. photography), even if it is not an invasive procedure, it is 'subjective' and non measurable, and depends on the capacity and accuracy of the operator (Buonopane *et al.* 2005).

The use of the laser scanner for the survey and documentation of cultural heritage assets is an approach that can solve the problems of subjectivity and give a measurable outcome with high level of accuracy in terms of geometry measures and level of details. Last but not less important, it gives the possibility to enhance the visibility of the details with specific filters and procedures.

The work methodology developed for our 3D visual and geometrical approach to epigraphic studies is based on three fundamental steps:

- Gathering of the historical and archaeological information about the inscription

This step is fundamental because it is the base of all the following processes of interpretation and communication. It is in fact necessary to begin from a first phase of data gathering, consisting of texts, archives, as well as previous studies or study cases morphologically and temporarily comparable (Vassallo *et al.* 2006).

- 3D data capture and post-processing of the inscription

The data acquisition allows us to have at disposal measurable information about the archaeological artefacts that we are going to study and analyse. Moreover, the digital data acquisition and the digital restitution permit to perform analyses and tests otherwise not possible on the real object or with the same millimetric precision.

- 3D analysis of the inscription

The final 3D model, is a digital object with exactly the same shape, size, form and texture as the real artefact. Through visualization software it is possible to perform a direct interaction and simulations with the 3D model (Athanasiou *et al.* 2013). Particularly, for what concerns our approach to the study of epigraphy, following are some of the analyses taken into consideration:

- visibility and lighting simulations
- extraction of letters
- complementation of 'missing parts'
- measurements of letters
- surface analysis
- comparison between letters
- analysis of spatial location of letters
- archaeological implications of the geometric analysis
- production techniques
- identification of engraving tools

2.1 The case study: the Soli epigram

The severely damaged inscription object of our study was found at the archaeological site of Soli, in the Morphou bay, Cyprus. Soli (Σόλοι) was a flourishing city until 498 BC, when it was conquered by the Persians following a long siege. It became independent and flourished again at the beginning of the 4th century BC.[3] Soli was one of the ten city-kingdoms into which Cyprus was divided. It is attested that the last kings of Soli were supporters of Alexander the Great and thereafter of Ptolemy Soter (Mitford 1961). The inscription from Soli (AKGDC E16 and E16 in Voskos 1995) is the only significant inscription of that period to survive; it has been discovered and published for the first time in 1908 (Φωνὴ τῆς Κύπρου newspaper, no. 1158 of 18 April / 1 May 1909).

The Soli epigram is inscribed on a limestone slab; it is damaged on its right side and thus incomplete. Its dimensions are: 0,53 m (width), 0,50 m (height) and 0,26 m (thick). The left edge is both vertical and undamaged. Mitford (Mitford, 1961: 133) remarks that the slab was not a statue base and it is uncertain whether it was incorporated into the funerary monument of the man it concerns. Peristianis (Peristianis 1995) mentions that it

[1] This task can be easy if the fragment of the frame allows to identify with certainty the beginning or the end of missing lines. A piece that does not retain any of the original margins, or an inscription written in a rough and uneven way, may prevent seriously the reconstruction of the text. The use of repetitive formulas in the epigraphic language and abbreviations help the reading and interpretation of an inscription as well as the comparison with other similar inscriptions. In the case of inscriptions in verse, the reconstruction of the text can be based on the metre.

[2] http://www.opificiodellepietredure.it/index.php?it/204/ripresa-in-luce-radente. Accessed on the 9th November 2015.

[3] For the history of Soli, see Mitford 1961: 133.

FIG. 1. AN OLD IMAGE OF THE SOLI INSCRIPTION (E16, VOSKOS 1995).

[*Τόνδε ἀρετὴν ἀσκοῦ*]*ντα βίωι παίδων τε τ*[*υχόντα*]
[*κλειτῶν, Πασικράτεα,*] *γῆς Σολίωμ βασιλέ*[*α,*]
[*ζῶντα μέγα θνητῶν πε*]*ριώσιον ἠδὲ θανόντ̣*[*α*]
[*χθὼν κεύθει ἥδε, ξεῖνε,*] *τάφωι γεραρῶι.*

FIG. 2. RECONSTRUCTION OF THE TEXT BY A. VOSKOS (VOSKOS, 1995, E16; AKGDC PROJECT, E16).

was found at *Palaia Chora* on the site of ancient Soli in 1908 and it was thereafter acquired by the Cyprus Museum (now in its storerooms, inventory number: IG 189). The letters of the inscription are from 0,031 m to 0,042 m high and they are boldly cut with incisions and slightly angular in section, blobs or serifs at the end of haste.

Different scholars gave their contribution in interpreting and translating the inscription, according also to the reading of the visible letters and the integration of the missing ones. The different interpretations bring of course to different datations and historical context for the epigram.

It is, though, clear that it is related to a king of Soli (l. 2): γῆς Σολίωμ βασιλέ[α,] (Mitford 1961: 133-134).

The inscription and the latest attempt to reconstruct the fragmented funerary epigram which is engraved on it, as well as an extensive commentary, the critical apparatus and its translation into Modern Greek have been published in Voskos (1995: 86-7, 265-70).

The digital version of the inscription and its translation is published in the *Archaia Kypriaki Grammateia* Digital Corpus project (AKGDC), a searchable digital library of Ancient Cypriot Literature which contains Ancient Greek and Latin texts of various genres (Pitzalis *et al*. 2012). Along with the epigram on the Soli inscription, there are 73 other epigrams, mostly funerary, featured in the AKGDC, consisting of the entire corpus of ancient inscriptions found in Cyprus.

2.2 3D data capture

The inscription of Soli is currently in the storeroom of the Cyprus Museum. Because of the object's dimensions and its position, it was decided to acquire the 3D points of the artefact with a time of flight laser scanner in order to document with precision all its possible features. The test on this particular inscription aimed at the 3D visualization of the inscribed text with the application of specific tools and filters, in order to facilitate its reading and provide a base for a further interpretation.

The 3D recording of the Soli inscription was carried out with a phase-shift laser scanner (*Surphaser 2HSX i*) in about 45 minutes. Three medium-resolution scans were needed to acquire all the visible sides of the object and to have enough overlap of the scans.[4]

The data obtained were then processed from the original C3D format (the proprietary format of the laser scanner) in PTX format and were then imported into the JRC Reconstructor software, where they were treated and processed for the creation of the final mesh and the application of the textures. Specifically, all the point clouds were first cleaned from the background noise produced during the acquisition and then

[4] The position of the inscription in the Museum on top and behind of other objects and the impossibility to move the Soli inscription, did not allow us to perform a complete 3D scan of the object. The study focused, therefore, on the front and on the sides of the inscription in order to three-dimensionally analyse the parts of the inscribed text.

aligned by taking three common points between each scan, with a final error of 0,0008 m. The next step consisted of the creation of a triangulated surface at high density which served to further analyse the hollows' letters and to facilitate a more clear reading of the damaged letters that are in the corner of the object and are not easily visible. Finally, the textures were aligned and placed on the stele by taking about 20 common points, in order to have a more precise correction. Table 1.

	Soli inscription
Equipment	Phase-shift laser scanner
Acquisition time (minutes)	45
Number of scans	3
Number of images	20
Alignment and post-processing (minutes)	120

Tab. 1. Synoptic table of the 3D data capture process

The final 3D model was exported to the .ply format for the elaboration in MeshLab.[5] This is a format compatible with Meshlab: the meshes keep the texture and the files are more manageable.

At this point it is possible to further proceed with 3D analyses of the object.

2.3 3D analysis

The analyses that can be performed on a 3D model of an inscription, can be grouped in two major sets:

- Metrical analysis (e.g. measurements, micro-topography)
- Visual analysis (e.g. application of filters, changeable light sources and intensity)

The metrical analysis permits to extract many information. For example, for what concerns the geometry and position, it is possible to analyse:

- the letters' alignment
- the highest number of shared points along a line
- the level of parallelism
- the letters' geometry
- the identification of geometry shapes
- the position along the score.

Or regarding the symmetry and orientation, it is possible to study:

- the orientation in a xyz space
- the ratio among letters.

The visual analysis allows to extract other kind of information. For example, through the depth maps is possible to:

- identify depth of letters carved
- compare erosion / degrade scale
- map damages on the inscription surface.

2.3.1 Metrical analysis

As a result of the 3D scan, it was possible to get the exact measurement of the Soli inscription, with millimetre precision: 0,4980 m (height), 0,5282 m (width) and 0,2450 (thick). It was, moreover, possible to measure small and other details of the inscription, such as the measurement of the letters and the depth of the incisions. The 3D scans have shown diversions from the measurement of the letters as cited in the publications of the Soli inscription. The size of the letters are from a minimum of 0,027 to a maximum of 0,030 m. with an average space of 0,010 m between them.

Due to the particular precision of the size and the shape of the letters, a further analysis regarding their comparison has been elaborated on the 3D model. This is to verify the possible use of tools or stencils that could facilitate writing.[6] A geometrical analysis was conducted.

On the measurable 3D model the letters which have the same or similar shape have been analysed (all the O, Θ; and all the Δ, Α, Λ) in order to study the engraving procedure with the use of the geometric design (circumferences, ellipses, triangles). The first test was on the letter Δ. The dimension and analysis of the letter suggested that the length of the sides and the measure of the angles are the same in all the Δ of the inscription. Moreover, the superimposition of the Δ on top of similar letters, such as Λ and Α, shows a total overlap of the basic shape (sides length and angle). In the same way, a second test was done on the letter O. Also in this case, the superimposition of this shape on all the circular letters (O and Θ) of the inscription shows that there is a complete overlap of the shapes.[7]

A further ongoing analysis was done on other letters. The Ωs, for example, do not have all the same dimension and shape.

5 MeshLab is an open source software that allows to post-process the mesh produced by the laser scanner and also to perform further analysis on the 3D models. The open source software is developed at the Visual Computing Lab of ISTI - CNR. http://meshlab.sourceforge.net/.

6 There is no archaeological evidence on the use of alphabetical stencils in antiquity. It is, though, possible that they used them in the making of colossal epigraphs (Di Stefano Manzella 1987).

7 Higgins and Kendrick Pritchett (Higgins and Kendrick Pritchett, 1965) state that the techniques to draw these letters consisted of a circular or rotatory drill. They report that Raubitschek (Raubitschek 1951) has already thought about the problem of engraving letters with curved segments, with particular attention to the introduction of a specific tool as the circular drill for making *omicron* and *theta* (Higgins and Kendrick Pritchett, 1965). Moreover, they write that the center dot of the Θ was generally chipped out with a punch until the introduction of the rotatory drill. The simple incision compass was used by the early Archaic sculptors and probably also by the painters of Geometric and Cypriot vases.

FIG. 3. METRICAL ANALYSIS OF THE LETTERS AND THE SPACES.

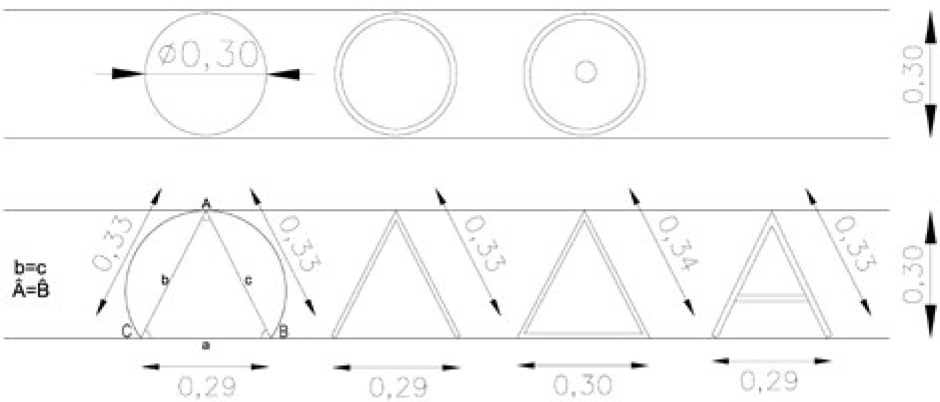

FIG. 4. METRICAL AND GEOMETRIC ANALYSIS OF THE LETTERS' SHAPES.

It is clear a tool was used (compass with three legs?) for the elaboration of the upper semicircle. In the same way, the Φ, even if not comparable with another letter in the inscription, it demonstrates the use of a tool for the elaboration of a precise and measurable ellipses.

On top of the orthogonal picture extracted from the 3D model, a further test has been carried out: after the metrical and geometrical analysis of the letters, their basic shape has been overlapped on the image itself in order to experiment the correctness of the calculation. The result is a perfect match of the calculated shapes and the engraved ones. Moreover, the regular dimension of the letters and the horizontality of the lines confirm the use of guidelines (probably drawn but not incised since no lines are visible with oblique illumination), as it can be demonstrated by the simulation of the pattern designed. Even if it is not possible to confirm the use of stencils for inscribing the letters on an inscription, the way the Soli inscription was engraved, may suggest that the engraver probably used perishable signs, instruments and/or drawings that helped the engraving procedure.

2.3.1 Visual analysis

Through the Meshlab tools some filters for an enhanced visualization were applied. The status of conservation of the inscription's text and the fragmentary nature on its both sides, required analysis of the text through modern techniques which show in greater detail elements of the object.

Through the 3D visualization it is possible to analyze the inscription in detail. For the Soli inscription it is visible that the left side of the support presents a cut, probably due to a later reuse of its support. Evidently the reuse of the support, in addition to the loss of part of the inscription, has caused the damage of its corners and half of its text. On the first line of the inscription, on the left, the letters and their shape are clear. They are smooth and partly destroyed because of a lacuna (a deep incision), probably the result from the cutting of the stone for reuse (or from a damage during its discovery). On the right part of the inscription it is possible to analyse the cut of the stone and the fracture: the cut must have been done in the past, as it is smooth and deteriorated.

Fig. 5. Overlap of the measured letters shape on top of the orthogonal picture extracted from the 3D model.

Fig. 6. Radiance render (in Meshlab) to perform lighting simulations.

Fig. 7. The presence of a circular sign detected with the change of the light direction.

After the post-processing and the 3D restitution of the object, some other tests were performed on the 3D representation of the inscription. Through the application of filters, e.g. the exaggeration of the z value, the changing of lights (Radiance render) and the colorization of the curvature (Colorize curvature – APSS[8]), the visibility of the details was enhanced. With this technique, it is possible to detect and visualize features, elements and details which are not visible with a naked eye and are only revealed after the application and elaboration of the 3D modelling and texture filtering.

As in the traditional methods, by varying the orientation of the oblique light beam on the engraved surface, it is possible to highlight grooves and guidelines otherwise invisible (Di Stefano Manzella 1987). As a result of the change of the lights direction, it has been possible, for example, to detect the presence of a circular shape (probably an O or a Θ) below the text, maybe drawn as incision test and then not properly erased.

[8] The Colorize curvature (APSS) colorize the vertices of a mesh or point set using the curvature of the underlying surface. This is the algebraic point surface (APSS) variant which is based on the local fitting of algebraic spheres. It requires points equipped with oriented normals.

The analysis of the shape demonstrates that even if it is slightly bigger than the other circular signs of the inscription, it is a measurable perfect circle (diameter 0.0356 m).

The study through digital filters has allowed us to perform the analysis of the inscribed characters of the inscription. In this way, it is possible to improve the reading of the engraved text thanks to the enhancement of the engraving depth and to the movement of the light position in order to create an oblique illumination and to get the best view of the text on the three-dimensional model directly. So far, the application of the filters gave as a result the reliable reading of the letters on the left of the inscription and confirmed the reading by Mitford (1961: 133) and Voskos (1995: 86). Further analyses are planned in collaboration with epigraphers in order to study and test our hypotheses.

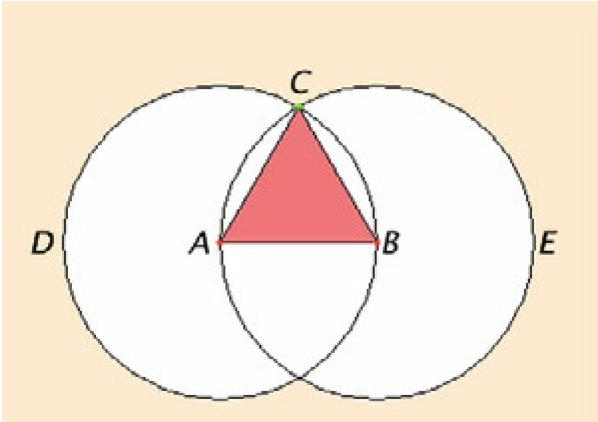

FIG. 8. THE EUCLIDEAN KNOWLEDGE APPLIED TO THE LETTERS OF THE SOLI INSCRIPTION.

3 Conclusions

The three-dimensional data acquisition through laser scanner has produced a representation of the artefact that is objective and complete of all its features (a complete and measurable acquisition of the geometry and of the texture). Moreover, this acquisition is not invasive and does not cause any problems to the archaeological object. It is also possible to intervene on the object digitally, both through the application of filters and analysis and through the digital reconstruction and restoration. Furthermore, the digital representation gives the possibility to the users to interact with the artefact three-dimensionally.

The results of the digital analysis at the moment confirms that the reading of the surviving letters on the inscription by some scholars is correct, but a further analysis is needed. For this reason, a multidisciplinary analysis with leading experts in epigraphy is currently ongoing, in order to confirm, reject or integrate our hypotheses about the presence of specific letters and their consequent interpretation.

3D documentation and visualization can help scholars to study the text and the letters of the inscription with great precision and safety far from any misinterpretations. In other cases, 3D documentation can bring to surface details that are not visible with naked eye and change significantly or totally the reading and interpretation of the text of an inscription by scholars. The high precision of the 3D outcomes allows the scholars to perform further analysis, such as the study of the inscription itself and its engraving procedure, giving the possibility to hypothesize the techniques, the tools used and the eventual presence and identification of the same distinctive 'hands' (Higgins and Kendrick Pritchett 1965), also through the comparisons of similar chronological inscriptions.

For the Soli inscription, the 3D analysis revealed that the letters were most probably carved according to drawings along a score, drawn but not incised. There is in fact no trace of any visible incised lines using oblique illumination on the 3D model, but the letters present a precise horizontality. The analysis of the inscription says also about the possible use of a compass, used to keep constant the measures of the letters and the precision in drawing them. The use of the compass seems to be applied not only to the creation of rounded letters, but also to the construction of the equilateral triangle ones. Particularly, this tells us about the importance of the aesthetics and symmetry of letters' aspect, but also that the inscription was probably made by a person with knowledge on geometry and symmetry, at a time when the Euclidean 'Elements' was already applied in daily life.

Most probably, the care for details can confirm the importance of the inscription and the relation with the king of Soli (γῆς Σολίωμ βασιλέ[α,]).

The 3D analysis on the Soli epigram added new information on the inscription, previously not addressed. Many are still the questions to be further investigated, from the interpretation of the text to the analysis of the support, as well as the study of the production within the island also in comparison with coeval inscriptions. This research will eventually lead to diachronically describe the engraving process and possibly identify scribes, workshops, etc.

For this reason, the research team plans to digitally acquire, analyze, reconstruct, restore and preserve the whole AKGDC collection of inscriptions within the ongoing EAGLE and AKGDC projects. This procedure is a formalized scientific pipeline that will enable the access to the raw and processed data for a holistic and multidisciplinary study of Cypriot inscriptions.

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Bibliography

Athanasiou E., Faka M., Hermon S., Vassallo V., Yiakoupi K. 2013. 3D documentation pipeline of Cultural Heritage artifacts: a cross-disciplinary implementation, in Addison A. C., De Luca L., Guidi G., Pescarin S. (eds), *Digital Heritage International Congress (DigitalHeritage), 28 October – 1 November 2013 Marseille, France*, IEEE, Vol.1: 142-52.

Buonopane A., Grossi P., Guarnieri A., Pirotti F. 2005. L'impiego del laser scanner nel rilievo delle iscrizioni sui miliari. In Angeli Bertinelli M. G. and Donati A. (eds), *Atti del Convegno Internazionale di Epigrafia 'Misurare il tempo, misurare lo spazio'*, Bertinoro (Forlì-Cesena), 20-23 ottobre 2005: 373-88.

Di Stefano Manzella I. 1987. *Mestiere di epigrafista. Guida alla schedatura del materiale epigrafico lapideo*. Roma, Edizioni Quasar: 21-31.

Higgins C. G., Kendrick Pritchett W. 1965. Engraving techniques in Attic epigraphy. *American Journal of Archaeology* 69: 367-71.

Pitzalis D., Christophorou E., Kyriacou N., Georgiadou A., Niccolucci F. 2012. Building Scholar e-communities using a Semantically Aware Framework: Archaia Kypriaki Grammateia Digital Corpus. In *VAST. International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*: 89-95.

Mitford T. B. 1961. Further Contributions to the Epigraphy of Cyprus. *American Journal of Archaeology* 65, 2: 93-151.

Peristianis I. 1995. *General History of the island of Cyprus, Nicosia* [Περιστιάνης, Ι. 1995. Γενική Ιστορία της νήσου Κύπρου, Λευκωσία].

Raubitschek E. 1951. The mechanical Engraving of Circular Letters. *American Journal of Archaeology* 55: 343-44.

Ronzino, P., Niccolucci, F., Hermon, S. 2012. *A Metadata schema for Cultural Heritage documentation*. In V. Capellini, Electronic Imaging and Visual Arts: 36-41. Firenze, Firenze University Press.

Vassallo V., Moro A., Vico L. 2006. The importance of the relief and the sources to interpret and communicate the Cultural Heritage. In Campana S. and Forte M. (eds.), *From Space to Place: 2nd International Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4-7*. Archeopress, British Archaeological Reports International series.

Vassallo, V., Christophorou, E., Hermon, S., Niccolucci, F., 2013, Revealing cross-disciplinary information through formal knowledge representation – a proposed Metadata for ancient Cypriot inscriptions. In Addison A. C., De Luca L., Guidi G., Pescarin S. (eds.), *Digital Heritage International Congress (DigitalHeritage), 28 October – 1 November 2013 Marseille, France*, IEEE 2: 79–82.

Voskos, A. 1995. Αρχαία Κυπριακή Γραμματεία, τόμ. 2: Επίγραμμα, Λευκωσία.

Modelling the Archaeological Record: a Look from the Levant. Past and Future Approaches

Sveta Matskevich
svetlana.matskevich@mail.huji.ac.il
Ilan Sharon
ilan.sharon@mail.huji.ac.il
Institute of Archaeology, The Hebrew University of Jerusalem, Israel

Abstract: The history of Levantine archaeology is a story of establishing methodological traditions from borrowed as well as locally developed techniques of excavation and recording. Today Near Eastern archaeologists use several relatively standardized recording systems that reflect different and, on first glance, incompatible approaches. Yet, analysis of these systems on a conceptual level shows that they use two basic entities, a spatial unit and a find, and two different narrative styles, a diary model and a form system.

In this paper we present a radically new model of recording systems, based on two principles. First, a recording system reflects our interpretations of what is found, and not the site or the objects. This implies that the bottom-level entity of our model is the interpretation event. Second, we claim that since relations lie in the foundation of archaeological reasoning, they should be treated equally to entities. We also introduce several types of high-level entities—sets of spatial units (e.g. a stratum, an excavation-area); finds (e.g. an assemblage, a type), and relations there-between.

We claim that using this model of the archaeological workflow allows the mapping of seemingly incompatible recording systems to one reference model. Moreover, the same reference model can be used for on-site recording and post-excavation analysis, upto and including the final site report. Such inclusive models are critical for the development of meta-databases, such as national archaeological archives, and for evolution towards interactive electronic site-reports.

Keywords: Recording systems, Conceptual modelling, Levant

1 Recording Levantine archaeology

1.1 Background

Levantine archaeology today, and in particular its recording methods, emerged as a result of a long tradition that started with the first excavations in the Near East at the end of the 19th century. It was strongly influenced by British, German, French and American archaeology during the first part of the 20th century. The British and the Americans brought rivalling field methods to the large multi-layered sites (*tells*) with Biblical-period remains. French archaeologists established their standards for excavating prehistoric sites; while the German legacy is most influential in the sphere of architecture and graphic recording, particularly for the study of durable monuments of the Classical or later periods. From the 1950s onward, with the second generation of local archaeologists, field methods in the Levant evolved independently. Looking today at both contemporary practice and legacy data we have an extremely eclectic picture, which we will try to outline here.

Another factor to be considered is the role of technology: the first generation of scientific explorers of the Holy Land brought with them an impressive array of new recording equipment—theodolites, cameras, typewriters, blueprint copy technology etc. Indeed, this ability to record accurately and 'objectively' constituted an important part of their claim to being 'scientific' vis-à-vis earlier travellers and pilgrims—or indeed the locals. After that, however, came a long hiatus. The technology for field-recording available in 1980 was virtually the same as that of 1900! As of the mid-80s, however, this began to change in ever-quickening pace. Photocopying, Word-processing, computerized data bases, EDM's—later to be replaced by Total Stations, CAD-based plans, digital photography, PTM imaging and 3D scanning of artefacts, stereophotogrammetry for field recording—the list just goes on and on.

1.2 Recording systems in Levantine archaeology: concepts, documents, theory

1.2.1 Definition of excavation recording systems

A *Recording system* is a scheme that includes all record types and their relationships, all documents that carry these data, and a workflow for producing these records and documents during the excavation. The recording system creates a paper (or cyber-) *model* of the excavation. We, in turn, are trying to construct a *meta*-model, i.e. model different recording methods. This presentation is limited to systems that are in common use in the archaeology of the Levant, which we are most familiar with, but we contend that the meta-model we constructed should be applicable, with minimal changes, to other archaeologies as well. Recording systems can be grouped according to the stratigraphic unit in focus, type of documents used, and theoretical approach.

1.2.2 Concepts

On the conceptual level, almost all recording systems work with two basic entities: a basic *spatial* (locational) unit and a *find*. The conceptual dissimilarity between the two seems intuitively clear. Archaeologists are in the business of dealing with 'stuff', which comes from some 'context', and archaeological sites are complexly-structured 'loci' studded with 'goodies'. In practice the differentiation is not always trivial.

For example, is an olive press (Fig. 1) an architectural element, a spatial unit or a find? When the working surface of a press is uncovered during the dig, it is usually (esp. if it is large enough) defined as a discrete unit of the excavation area and a context of finds (e.g. olive pits in it). If the olive press is cut into the rock, then this surface (its interface with the sediment above it) is the only part of the installation which can be observed and

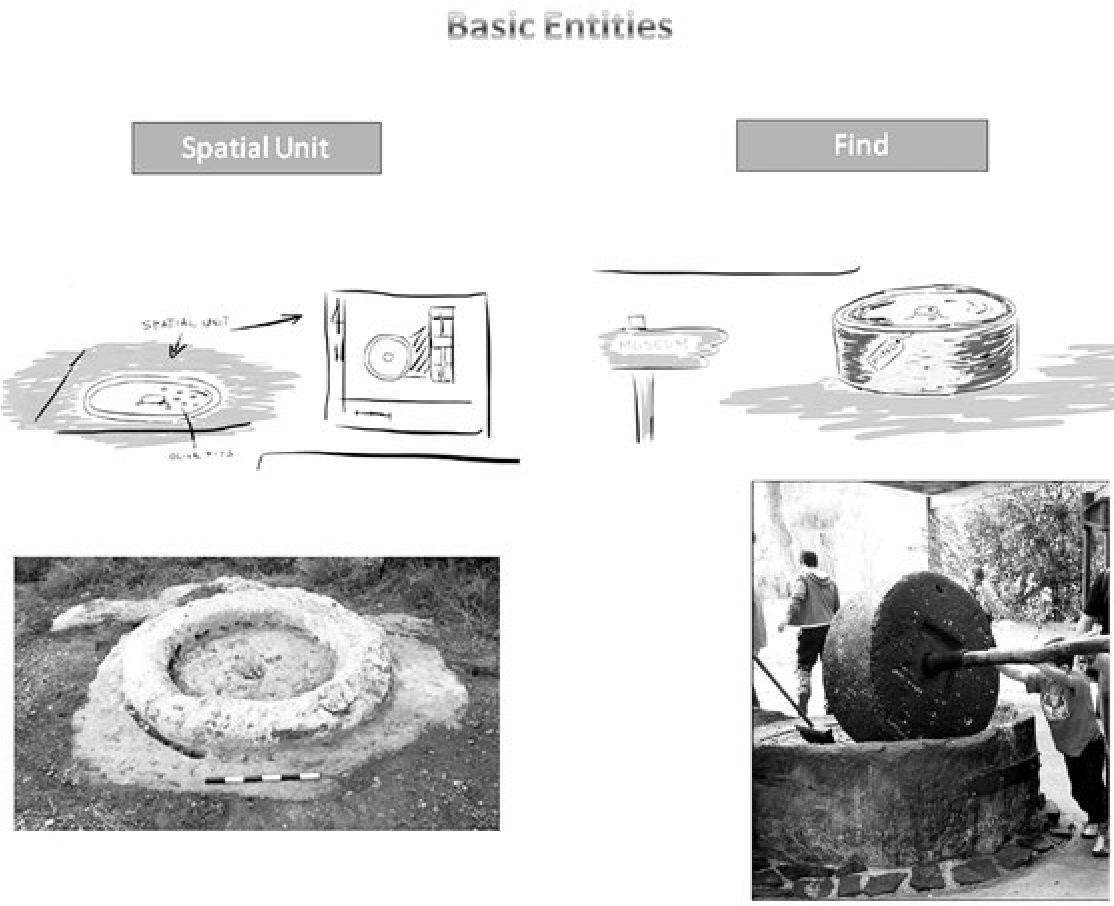

Fig. 1. Recording an olive press installation.

recorded, and it is likely to only be preserved for posterity in the guise of [part of] a locational unit. The excavators would most likely leave it *in situ* and treat it as an architectural feature (a wall): it would be drawn on the area plans, a locus/installation card, would be opened for it, etc. If, on the other hand, the press is a smaller, detachable installation, especially if it is a single stone and the excavator does not consider it to be *in situ,* it may well be treated as a *find*, and recorded accordingly—e.g. be hauled to the museum, issued a find ID, drawn by the standards of artefact-drawing etc.

Similar dilemmas are evident at the other end of the 'artefactual' scale. Most archaeologists would consider the dirt that they are digging-in as part of the locational unit. E.g. 'matrix description' is usually found as a field within a locus card rather than an attribute of an artefact (except as part of a ceramic fabric description). But if we take a soil sample, we would tend to give it an artefact (or ecofact) ID, i.e. treat it as a 'find'.

Many registration systems also distinguish units consisting of aggregates of finds. A case in point is the 'basket' in many Levantine excavations (a quaint archaism from a time where finds were actually stored in wicker baskets). Many consider these merely units-of-convenience. Rather than measure independent x-y-z coordinates for each of 23 bits of debitage in the same excavation spit (see definition below), and then repeat the same shared attributes (date, excavation unit etc.) for each, we put them in the same bag and record the attributes only once (with a calculated loss of resolution of the locational values). Arguably, the 'basket' is not an independent entity but a shortcut. It can be broken down to 23 independent records for 23 artefacts.

To make things more difficult, some excavations regard the 'basket' as a sub-division of the 'locus' i.e. as a locational unit rather than an aggregate of finds (Fig. 2). There is no unique locational ID that defines the spit from which they originate.

But what of the case of the restorable pot in Fig. 3? The person doing artifact typology would probably want to regard the pot as a single find, and open a single 'find card' for it; while the stamp-impressions catalog should have two, related but nevertheless distinct, records. If the petrographer is interested in comparing different samples from the same vessel, she, too, would consider sample 2 a different entity from 1.

Should we treat all these, and similar problems as 'technical' and find ad-hoc solutions? Or do these difficulties hint at real ambiguities in the definition of the entity 'find'? We contend that whether we define an entity (or a set of) as a 'find' or a 'locus'—or as single or aggregate is a situational, rather than an essentialist decision. i.e. it is influenced more by what we intend to do with the object[s] than by what the object is in and of itself.

The terminology used to describe the concept of *locational unit* is diverse: *layer* (Kenyon 1961), *feature* (Barker 1982), *locus*

Fig. 2. Consider a bucket of potsherds, a bag of bones, and a coin—all collected from the same 10 cm. spit of the same locus in one day. If they are called "1232.1P" "1232.1B" and "1232.1.C" then "1232.1" is essentially a locational unit. If they are labelled "B13453 (L1232) – pottery", "B13454 (L1232) – bones" and "Reg. #: Coin.53; x: 2.35, y: 3.15, z: 116.16 (L1232)" then B13453 and 13454 are find-aggregates.

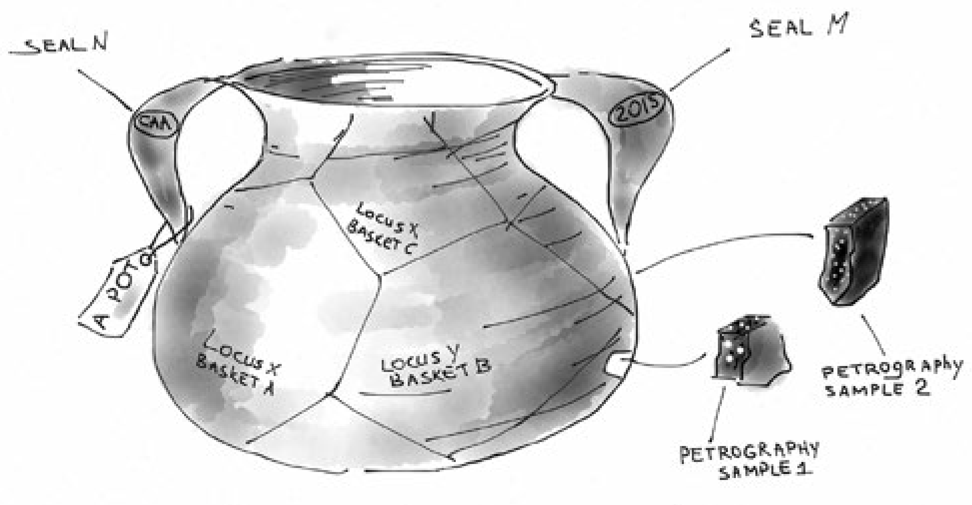

Fig. 3. A pot, reconstructed from potsherds found in different "baskets" in different loci; with two [different] stamp impressions on two of its handles; that was repeatedly sampled for petrography.

(eds. Dever and Lance 1978), spit – arbitrary unit (Hole and Heizer 1969), context (MoLAS 1994), etc. Most excavations in the Levant nowadays use *Locus*—a term that has the advantage of neutrality—it has no connotations besides 'a locational unit' and the disadvantage that the same term can mean different things in different projects (see below). In rare, but not unknown cases, the concept was not defined explicitly at all or locational units have no IDs (e.g. the Joint Expedition to Samaria, Crowfoot, Kenyon and Sukenik 1942).

The concepts behind these numerous terms can be grouped into three categories: arbitrary, depositional and behavioural.

Arbitrary units are usually horizontal slices of [sub-]grid squares. We shall refer to such as *spits* (Fig. 4a). Spits are used mainly (but not exclusively) on prehistoric excavations, where there are few or no architectural elements, and layers are hard to recognize. Individual finds can be identified by their spit ID + a registration number (though hybrid systems using spits as locational units and baskets/find nos. for individual finds and aggregates do exist (Garfinkel and Davidzon 2008).

The term *Locus*, was introduced on the Oriental Institute of Chicago's Megiddo excavations during the 1920s (Guy 1938), where it was used to refer to an architectural space.

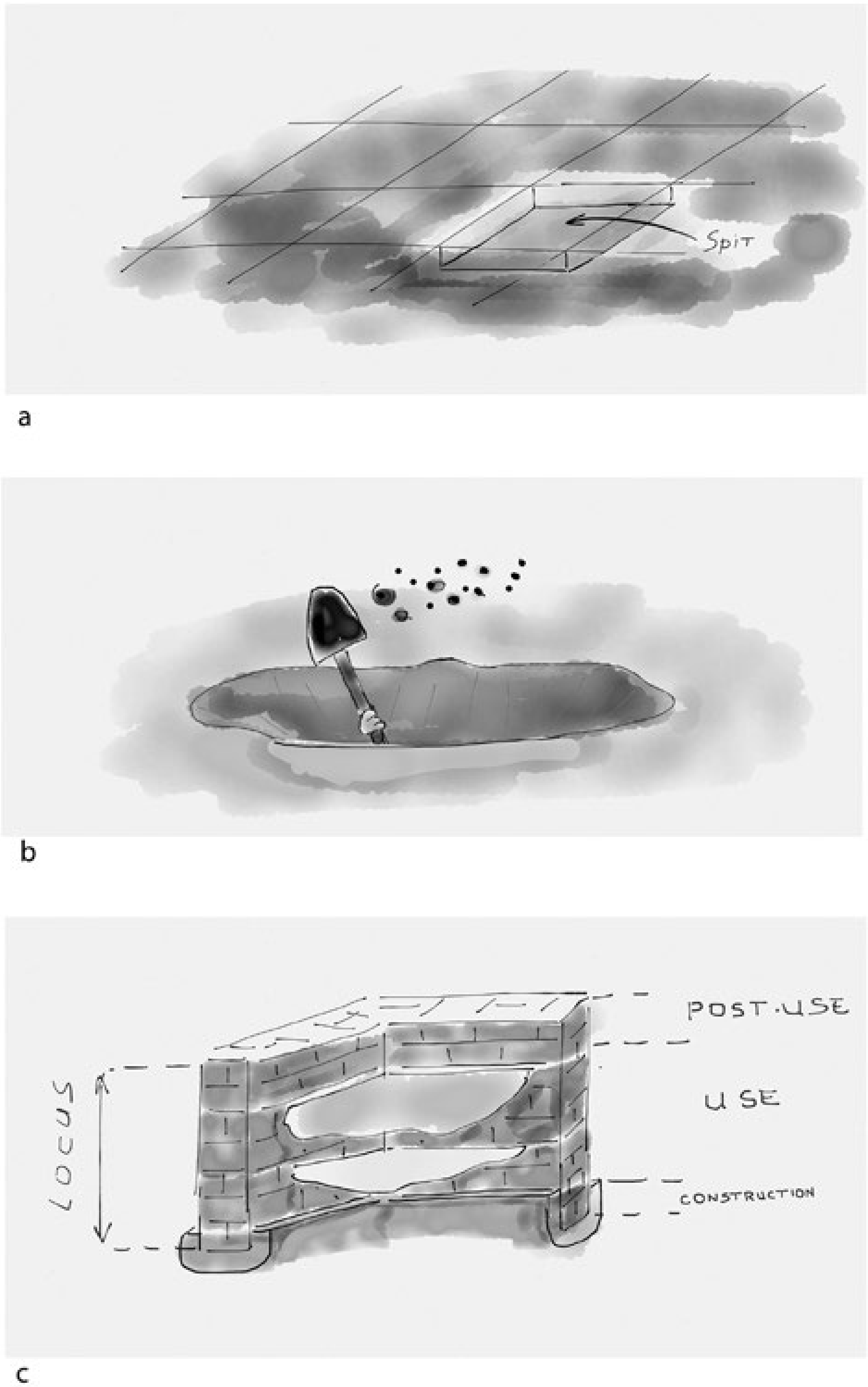

FIG. 4. SPATIAL UNITS.

This was defined as the excavated volume from the top of the walls to the bottom (or until a lower set of walls began to appear), and hence may include deposits (and therefore, finds) of construction, occupation and post-occupation stages of the feature. In later excavations which inherited this system (e.g. Yadin's excavations at Hazor, in the 1950s [Yadin *et al*. 1958]) finer divisions could be made by the use of 'baskets' as explained above (though there was no unique ID by which such smaller features could be identified).

This architectural definition of the prime locational unit is an example of what we call here a 'behavioral' definition (Fig. 4c). The primary locational unit is modeled after what the excavator supposes was a distinct activity area within the site.

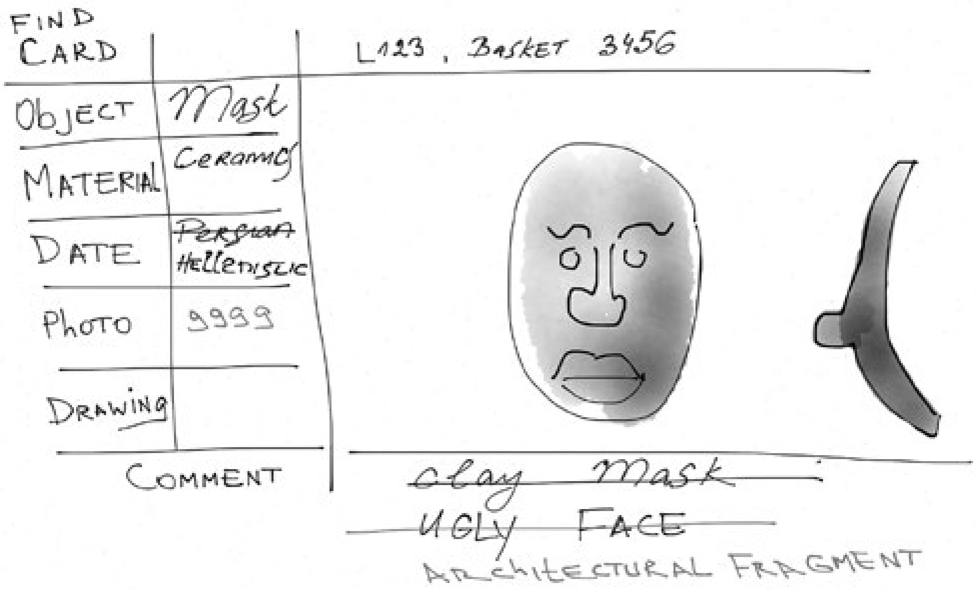

Fig. 5. By looking at the handwriting on legacy find-cards, we might guess that different people contributed to the compilation of a catalogue, but we would not know who, when or why.

The 'feature', common in New World archaeology, is a similar type of unit. In as much as it is used in Levantine prehistory (usually as a secondary unit—see below) the 'locus' is still defined as an activity area.

A depositional primary location unit (Fig. 4b) was introduced in the Levant in the 1950s with the definition of the *layer* in K. Kenyon's excavation at Jericho (Kenyon 1961). In such a system the primary units to conform to what the excavator thinks were individual depositional episodes in the formation of the site.

Most excavators of the so-called 'American School' in the Levant, in the 60s-70s employed a depositional definition for their primary locational units, but, confusingly, kept the term 'locus' as the name for them (Dever 1973). The equally-dubiously-named 'Israeli' school disavowed any influence of the 'British' methods (Aharoni 1973; Bar-Yosef and Mazar 1982), and indeed most excavations in the 60s and 70s kept the architectural definition of the locus. By the late 70s, however, a quiet process of defection began (Kletter 2015); and nowadays most *tell* excavations in the Levant (no matter how they define their scholarly genealogy) designate their loci as depositional units, as do some Classical / later projects, though an architectural / behavioral definition can still be found in this sub-discipline. The ambiguity of the term 'locus' is exacerbated by the fact that few projects explicitly define their primary units. What type of entity exactly is meant by the bland designation 'locus' often needs to be guessed-at on a case by case basis.

1.2.3 Documents

In terms of genre of documentation, a differentiation can be made between unstructured (based on a diary narrative) and structured recording systems, based on a set of forms.

The first method was inherited by the first archaeologists of the Levant in the 19th century from *travelogues* and *itineraria* – journals of European travellers to the Holy Land. Written in the chronological sequence of work on the site, the diary allows for writing the story of the excavation (as seen through the eyes of a specific recorder). It is less useful for telling the story of the site (i.e. writing the narrative of the site-report) because observations relating to the same entities might be scattered throughout the text. A straightforward diary, or 'excavation notebook' lacks even a mechanism to ensure that each entity is described once.

Forms were introduced gradually, starting from the 1920s, and became almost standard as the main framework for written records during the 1970s. The idea behind splitting the record into atomic units is the ability to sort them according to various attributes, i.e. type, excavation areas, stratigraphical sequence, etc., which is essential for analysing and writing a story of the site. At the same time, breaking the stream of interpretation to discrete and interchangeable forms tends to strip out the identity of the participants, the time and circumstances of the recording act, and renders static the workflow by which [current] understanding of the entity was reached (Fig. 5). The earliest forms were index-cards used to construct collection catalogues and typologies of finds, only later augmented by stratigraphic forms (locus cards). Last to appear were pre-printed forms with prescribed fields.

The advent of computer databases consolidated the stranglehold that form-based systems had over archaeological recording, since early database management systems were mostly of the tabular kind—arranging data in tables of identically-structured records and manipulating it using table-algebra languages such as SQL. This is no longer necessarily the case.

1.2.4 Theoretical approaches

We submit that recording systems can be classified, at the level of their theoretical pre-assumptions, to two types: *positivistic* or *non-deterministic*.

The positivistic approach implies the belief that excavation reveals evidence for historical facts. This is usually coupled with acceptance of the 'dogma of immaculate perception'—that a qualified observer should be able to 'read' these facts with no bias or ambiguity (Kaplan 1964: 131); and sometimes of the Sherlock Holmes Principle. A registration system built under such premises fails to distinguish between 'entities', 'data' and 'record'—where 'data' is the reduction of the actual entity to pieces of information, and 'record' is a document containing a particular observation of a datum by a particular observer under particular circumstances.

In practical terms, a positivistic recording system will accept only one record per individual entity, only one value for each attribute in the record, and allow no equivocation or qualification of these values. At the documentation level, this approach is expressed in one-to-one relations between attributes of one entity and between instances of one entity (Fig. 6).

In contrast, the relativistic model, assumes that archaeological investigation is fundamentally hermeneutical. The archaeologist does not 'read the archaeological record' but engages with it. She confronts (and directly manipulates) it consonant with her current understanding of the actions and behaviour of the people who occupied the site and the depositional processes which operated on it. Moreover the 'record' does not consist of archaeological—much less historical—'facts'. The archaeologist records her interpretation of [a portion of] the site as she plunges into it. The physical 'stuff' of archaeology can always be interpreted in multiple ways.

Relations in such a model will be defined as 'one-to-many' or 'many-to-many', so that each attribute could have multiple values (e.g., type, stratigraphical attribution, etc.) and/or will be equivocal and open to qualification.

Unstructured recording is a more-fitting vessel for a relativistic theoretical stance than a form-based system, especially one where fields are strictly prescribed and accept only certain forms of input. It is not surprising that the first archaeologists of the Levant in the 19th century adopted a romantic / religious *genre* for the production of their texts, nor that form-based systems became prevalent as archaeology sought scientific pretensions. What is remarkable is that little thought seems to have been accorded to field recording following the rise of post-processual archaeology. Indeed the debate between the processual and post-processual schools was disputed mainly in the realm of 'high' theory (how perceived patterns in material culture are explained in terms of human actions) rather than 'low' (how 'data' is acquired and coded, and how patterns are perceived). This is all the more surprising as the demise of positivism in the 'hard' sciences has as much to do with the failure of its conceptual models in the realm of 'low' theory as in the formulation of universal 'laws'.

2 A New meta-model for archaeological data management

Taking into account all of the above is it possible to accommodate all, or virtually all these recording systems and link them, within an archiving or publication platform in such a way that the data will be interoperable?

Numerous integrated systems for archaeological data management exist today: the Archaeological Data Service (ADS 2015), tDAR (tDAR 2013) and Open Context (OpenContext 2015; Kansa, Kansa and Arbuckle 2014), OCHRE Data Service (OCHRE 2015; Schloen and Schloen 2012) to mention a few. Most of these are archival platforms that require a lower level of integration and lesser interoperability. A user of such an archive can query several data sets simultaneously but can't build her own interpretation of the resulted data set within the framework of the system.

A solution we propose is a conceptual meta-model that may be used as a core of systems for archaeological data recording, dissemination and archiving (Fig. 7). Our basic assumption is the *interpretative character* of the archaeological process at all its stages, from initial field recording to report writing. This implies that the subject of our records is not contexts or finds, but our interpretations of such. Recording can be best described as an *event* of the transformation of what was seen and/or thought, by a particular participant at a given time and under specific circumstances, and recorded into a *document*.

Why the choice of this particular theoretical stance for a meta-model meant to subsume all kinds of registration systems (positivistic ones included)? Quite apart from the fact that that this stance happens to reflect the writers' convictions, as should be clear by now, we submit that whereas a non-determinist theoretical agenda can be incommensurable with a positivist recording system, the opposite is not the case. A positivist recording system can be seen as a particular case of the generic one. This is because a one-to-one relationship is a subset of the one-to-many (and that is a subset of the many-to-many) relation. A positivist archaeologist can use the more-general non-determinist registration system—with the added proviso that each entity must have but a single record, that certain relationships must be one-to-one, that qualifiers not be used, and that time-, place- and participant-stamps attached to the records are ignored.

2.1 Basic entities and attributes

We argue that the basic entity of archaeological registration systems is the *recording event* that follows any engagement between the archaeologist and the site (whether this engagement consists of the removal of sediment, the collection of a find, taking a photo, or gaining a new insight). Two intrinsic attributes of any recording event are a person producing the record and the time of the event. Other attributes of an event can be, for instance, qualifiers (important—not important / dead certain—guess so) that prioritize interpretations for subsequent analysis. Thus records (of any kind) are collections of individual interpretations (or recording-events).

On excavation, an individual recording might pertain to a single spatial unit, or to a single find, or to a *relation* between units (see below), between finds (i.e. samples), or between a find and a spatial unit.

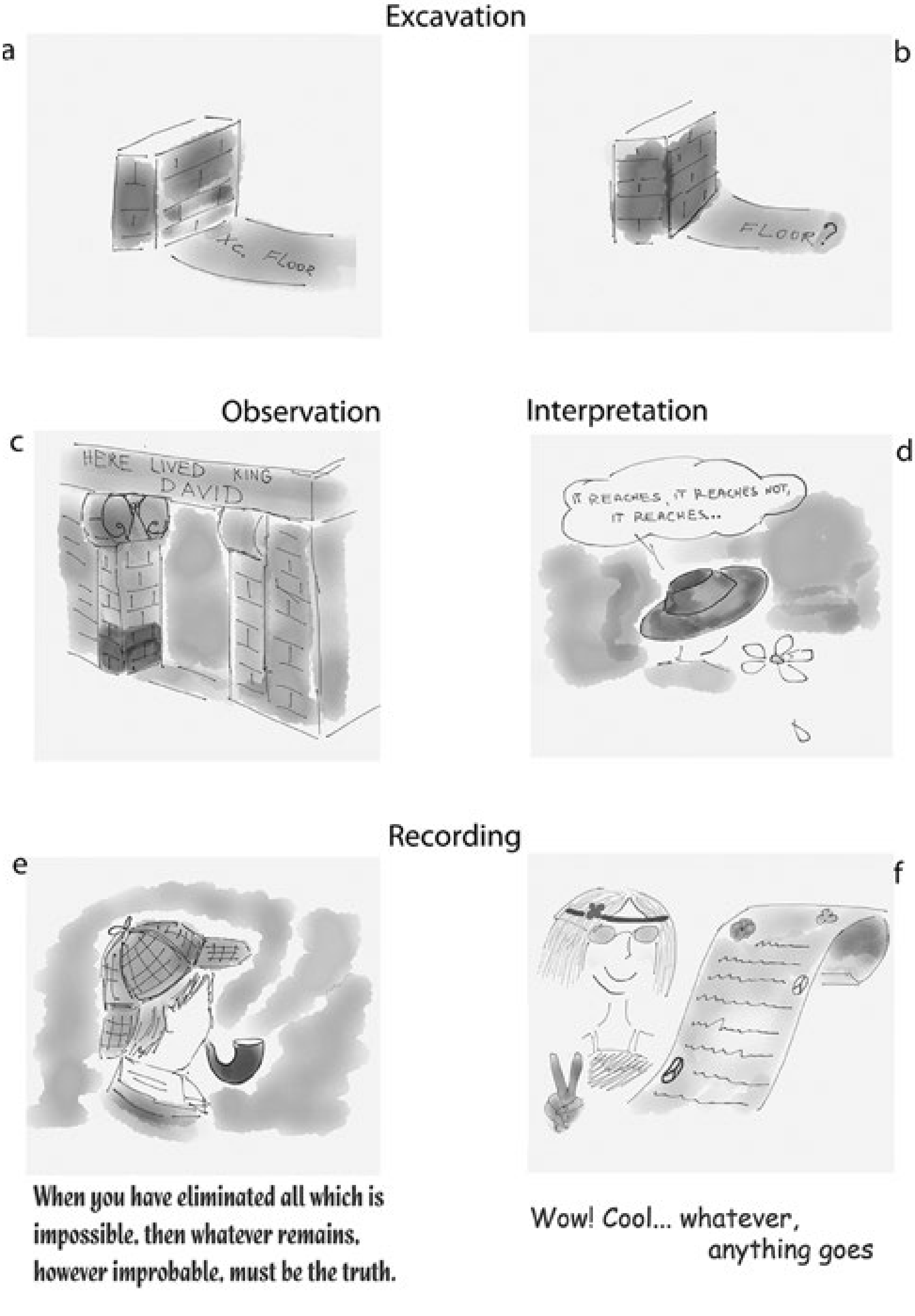

FIG. 6. THEORETICAL APPROACHES TO EXCAVATION AND RECORDING.

The basic entities of most archaeological registration systems form the second tier in ours. In keeping with the dynamic, event-driven nature of the proposed model, we switch the 'find' entity for a *sampling event*. The removal of any object from its current context (except that of dirt to the dump) is a sampling event. We avoid the difficulty of the essentialist definition of the 'find' by opting for a procedural one—a find is whatever we have chosen to sample and tag. Note that both 'finds' and 'baskets' are samples, and that the splitting of a sample (or the amalgamation of several samples) are sampling events. Even change-of-placement for a sample can be defined as a sampling event—facilitating the tracking of objects during excavation and analysis workflow within the same registration system.

We call the basic locational entity in our meta-model by the nonbinding term *spatial unit* (SU). Since we are not defining what this entity represents, the only constraints on it are geometric. Each SU must be a closed polyhedron, and the complete set of SU's must form a partition of the [excavated] space—i.e. each point in space must belong to one SU and only one (unless it is on the surface of the polyhedron).

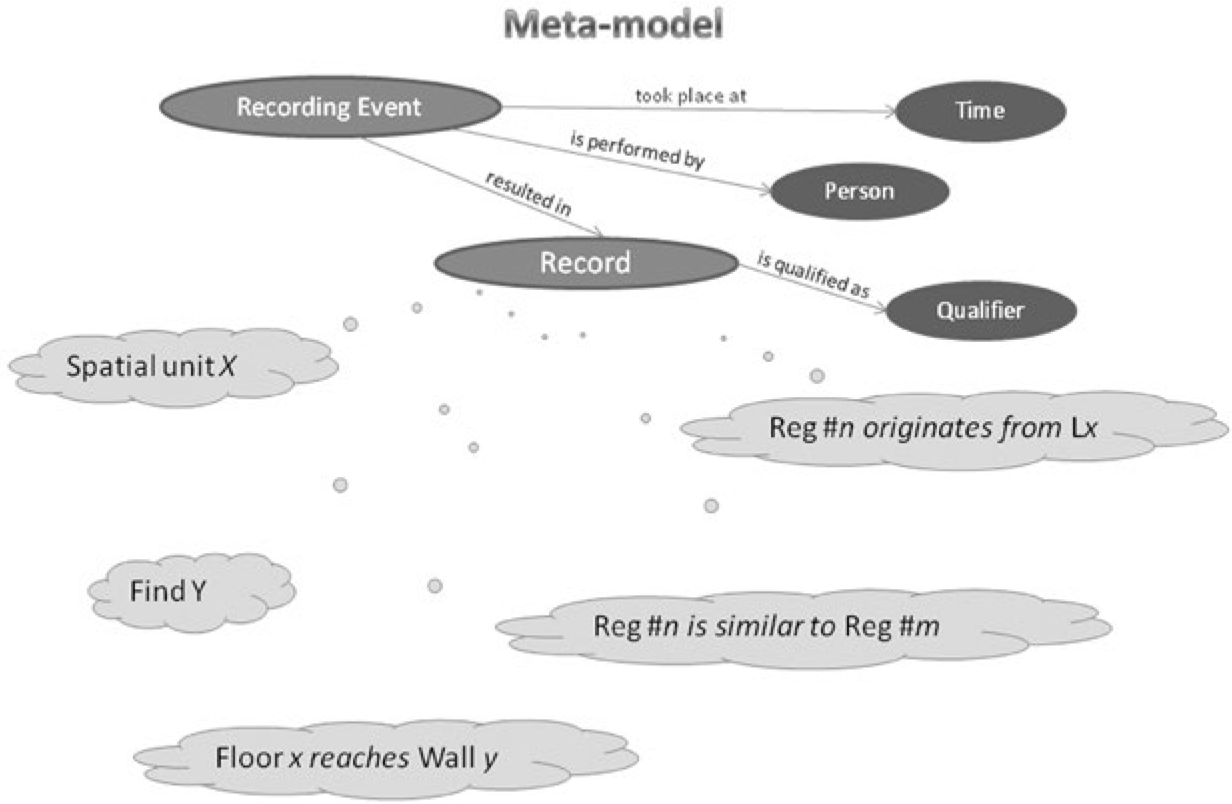

Fig. 7. Recording meta-model - basic entities.

Two actions are defined on the SU in our event-driven model, and these are the opening (at the beginning of excavation of the SU, or when it is first defined) and the closing of an SU (when it has been excavated out and removed).

Each of the second-tier entities may participate in any number of recording events, and multiple instances of the same record can be supported. The possibility of more than one value for an attribute renders the entire system multi-vocal and [at least potentially] equivocal. Two participants in an event may record *different* interpretations of it, as may a single participant who is not sure (Fig. 6d).

2.2 Relations

The third tier of our model consists of *relations*. Archaeological inference is first and foremost contextual in as much as one explains individual 'factoids' by reference to the context in which they are embedded (Fig. 9). Archaeological reasoning is based on explicit or, more often, implicit statements like the ones in Figure 7.

The importance of relations is often underplayed in archaeological recording systems. In printed form-based systems they were entered as attributes of the relevant entities, and were usually kept this way after conversion to computer databases. An attempt to give priority to the relation as an entity was made in some Harris matrix-based systems (e.g. IADB at Silchester Roman Town project, Clarke *et al*. 2001), where the hub of relations between spatial units was used as a starting point for exploring the data set.

Technically, setting the relation as a separate entity has the merit of lowering redundancy and thus saving space and enhancing database integrity. Consider the wall and floor in Figure 6: if the wall *cuts* the floor, than perforce the floor *is cut by* the wall. In a form-based system this might be recorded as an attribute of the wall, or of the floor, or in the forms of both (without necessarily checking that the two attributions conform) or not at all. In data-processing formulation, whether relations are considered attributes or independent entities is what sets apart the tabular data model (Fig. 8) from the *graph* data model (Figs 7, 9 – 13 are drawn from a graph perspective, with relations represented as lines between entities).

Stratigraphic relations naturally come to mind when discussing relations in archaeology. But no less important are inclusion / attribution / identification relations (Fig. 10). Representing group inclusion as an attribute of the entity (such as 'Type' or 'Body Part') perforce implies categorization. Categorization *can* be enforced in a model where inclusion is represented by a relation between an entity and a group (about which, see below), but more fluid attributions (such as overlapping groupings or qualified inclusion ('object x *might be of* Type A') can also be supported.

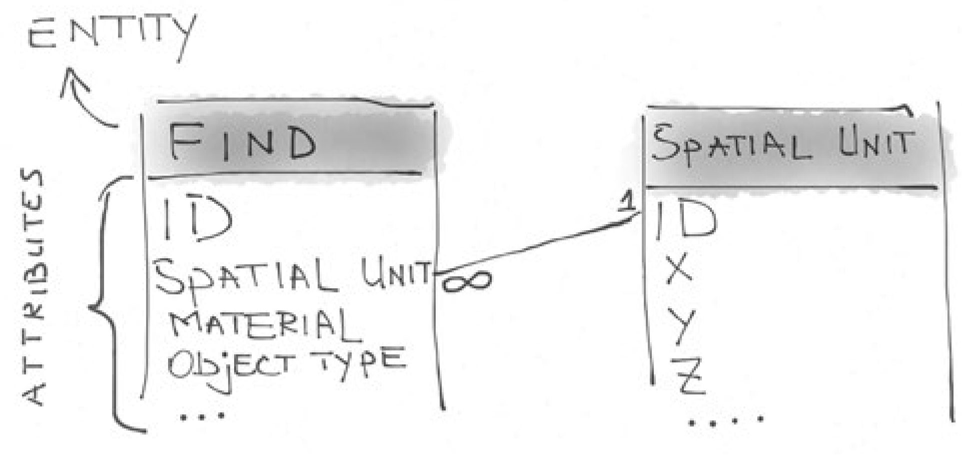

FIG. 8. 'RELATIONS' IN RELATIONAL DATABASE.

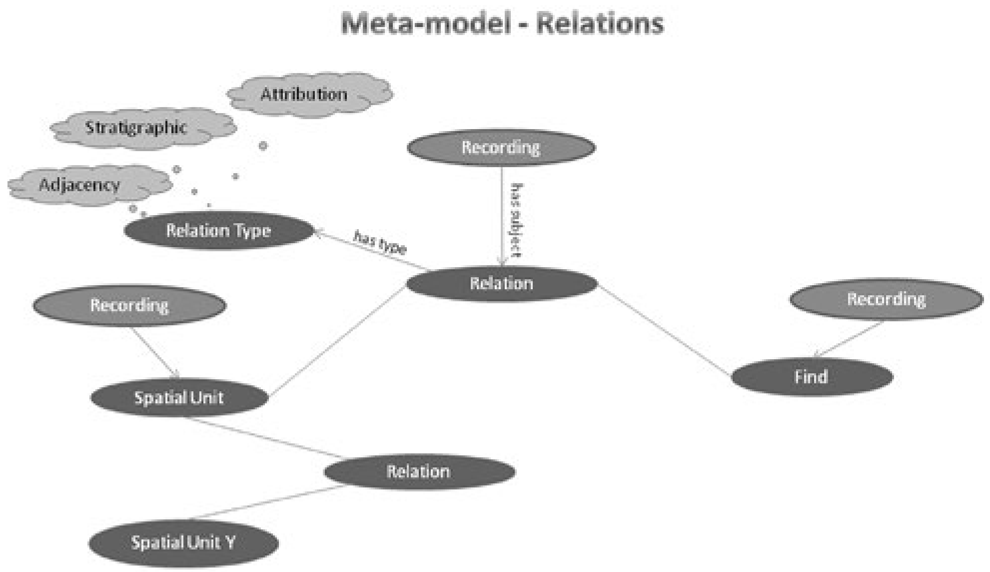

FIG. 9. THE RECORDING MODEL – RELATIONS.

2.3 Composite entities

Above these tiers we define two *set* entities.

A *spatial composite* is a set of SU's. A room, a structure, a stratigraphic phase are all *composites*, but so is an excavation area, a plan or a locus genealogy.

Similarly, a 'type' or a 'petrographic group' or even 'a pottery plate' are *collections*—groups of finds. Composites and collections can be defined by enumerating the loci/finds in them, but also by grouping of other contexts/collections (Fig. 11). These sets can have recording events linked to them, as well as relations between them (over and above the records of and relations between the primary units of which they are made up).

2.4 Scenarios

In the highest tier of the model, a *scenario* is any string of recordings on different composites and/or collections accompanied by appropriate connecting texts. Any 'story of the site', including the most comprehensive one—a site report—can be defined as a scenario.

Within the model, scenarios provide charted 'routes' of moving through the system. Since a scenario is a composite entity of a higher level, one needs to group other entities in a narrative order to create it. The act of grouping is not exclusive, i.e. members of a group may belong to other groups too. This allows the presentation of conflicting scenarios, for example alternate site stratigraphies, qualified by the authors as more or less preferable.

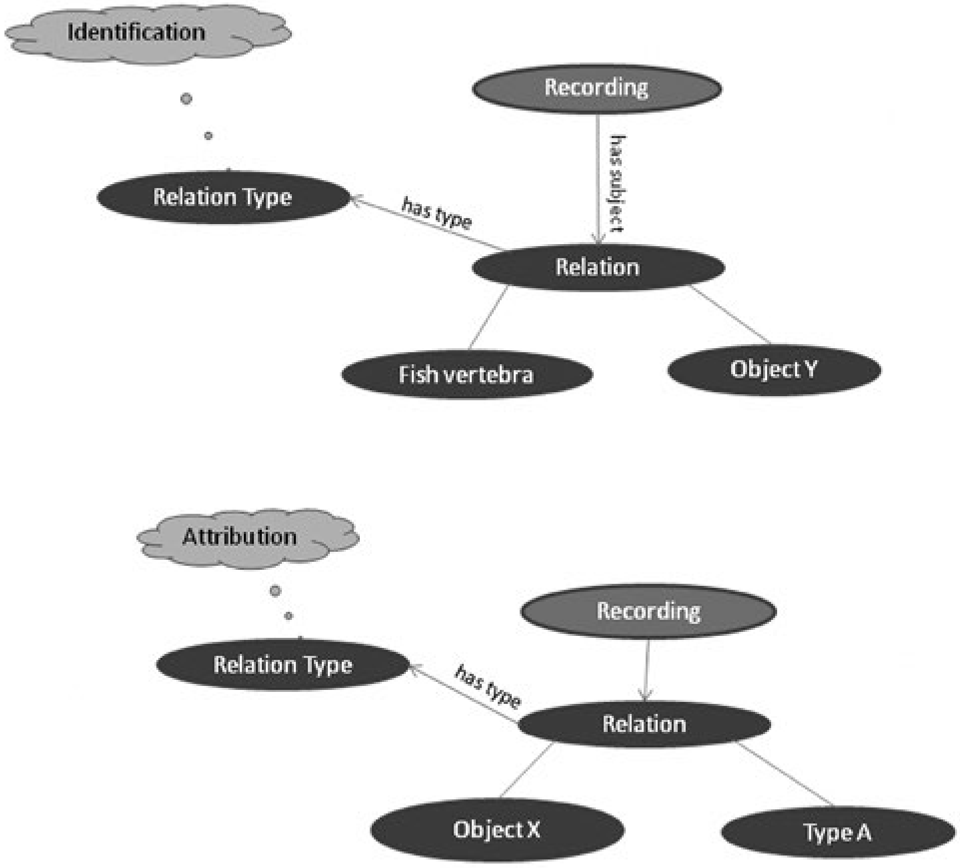

FIG. 10. ATTRIBUTION AND IDENTIFICATION RELATIONS.

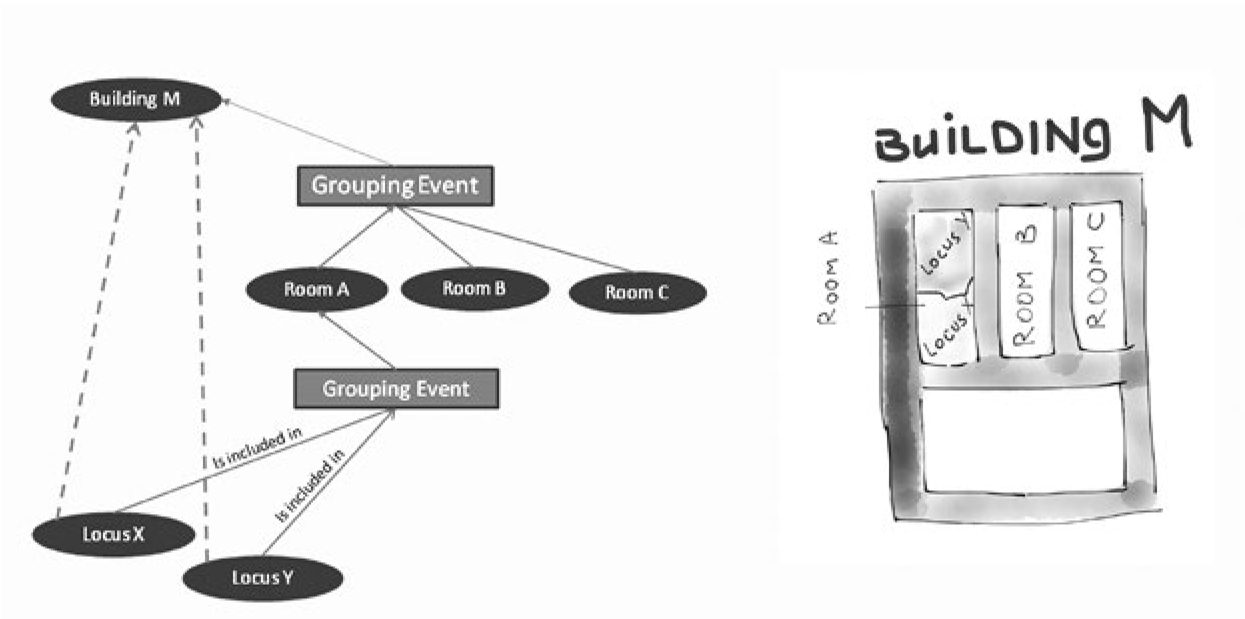

FIG. 11. DEFINING A COMPOSITE.

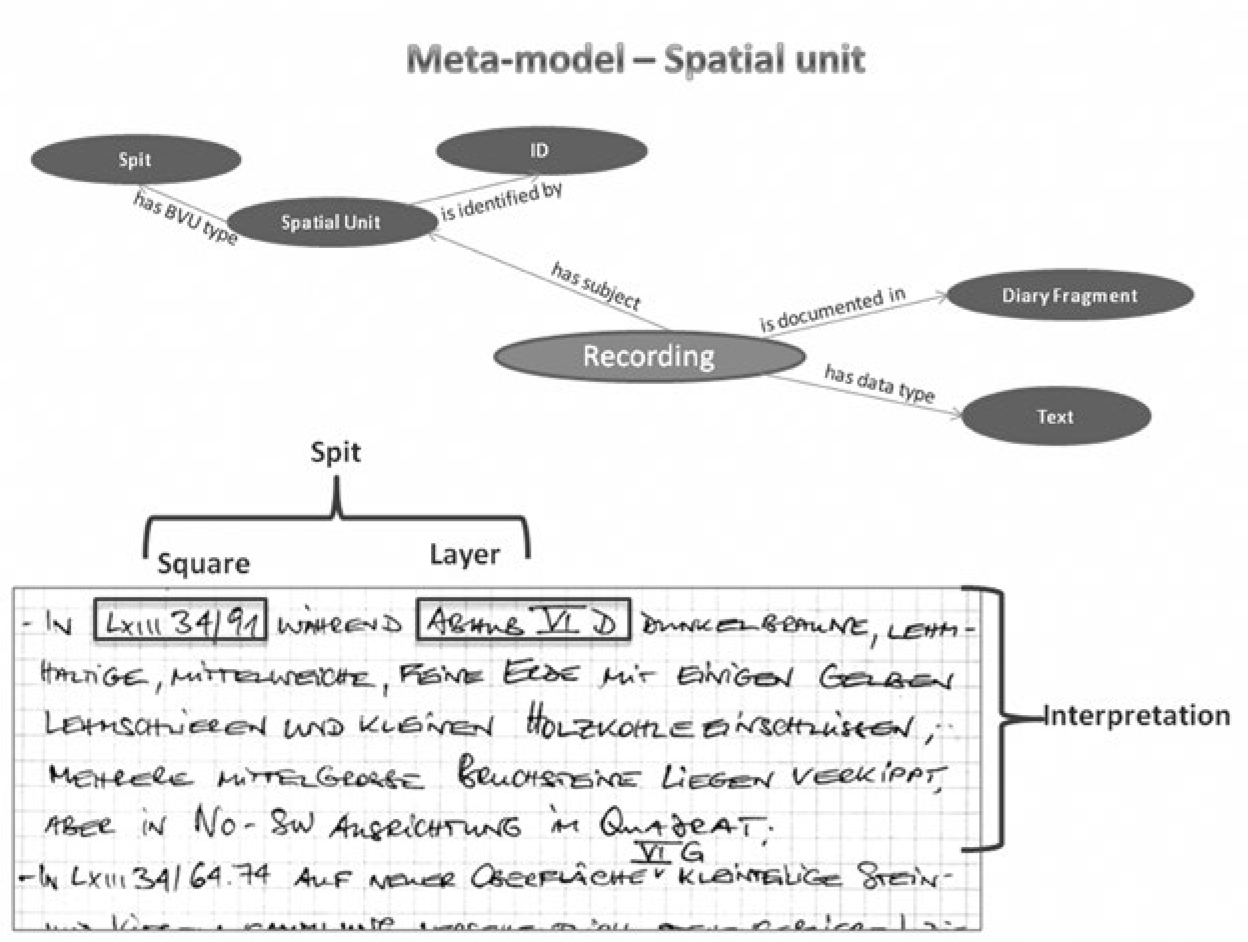

Fig. 12. Mapping a diary entry to the meta-model.

2.5 Documents and the 'interpretative meta-model'

At the level of record types, a recording event may be expressed in a form of a text, or an image, or a 3D model, or any other human- or machine-readable medium. There is also no limitation on introducing new media of recording (e.g. video or audio clips, or the output of some analytic machine).

In terms of documents, both journal-based and form-based registration systems can be mapped onto this meta-model. For example, an excavation diary entry can be defined as 'a recording of a spatial unit made by one person at a specific day and represented by a textual record'. A 'Description' field of a spatial unit form would have the same definition, which means that both can be 'mapped' to the 'interpretation model' (Figs 12, 13).

3 Conclusions

In Levantine archaeology today, the combination of basic excavation unit and the type of documentation usually correspond to the studied periods: Prehistoric archaeologists tend to use arbitrary excavation units (spits) and diaries, while Biblical and Classical excavations most often work with loci and forms. At the same time, as showed a survey of archaeological records in Israel (Matskevich 2015), almost all combinations of excavation units and documentation coexist in different recording systems, both today and even more so in the past. Theoretical agenda, on the other hand, are rarely reflected in excavation and recording methods of 21-century archaeologists: while heading to the field archaeologists usually leave their processual or post-processual beliefs behind them in the offices and classrooms.

The conceptual construct presented here may solve the problem of incompatibility of archaeological recording systems via mapping various systems to one meta-model. The concepts of the model comprise the very basics of archaeological field recording, while its structure allows for maximal flexibility in the relations between the concepts. These two qualities guarantee that any data set, even ones as different as the ones produced by prehistorians and classical archaeologists in the Levant or the 'single-context' records popular in Europe , will be *map-able* to this format. The uniqueness of this meta-model is in its ability to bridge between recording systems that differ on several levels, concepts, documents and theoretical approaches.

If applied to a recording system, the model will support implementation of relativistic principles in field practice. The model will perfectly suit a post-processual recording system but can accommodate a positivistic one too, if the user interface allows only one-to-one relations between entities and one value for attributes.

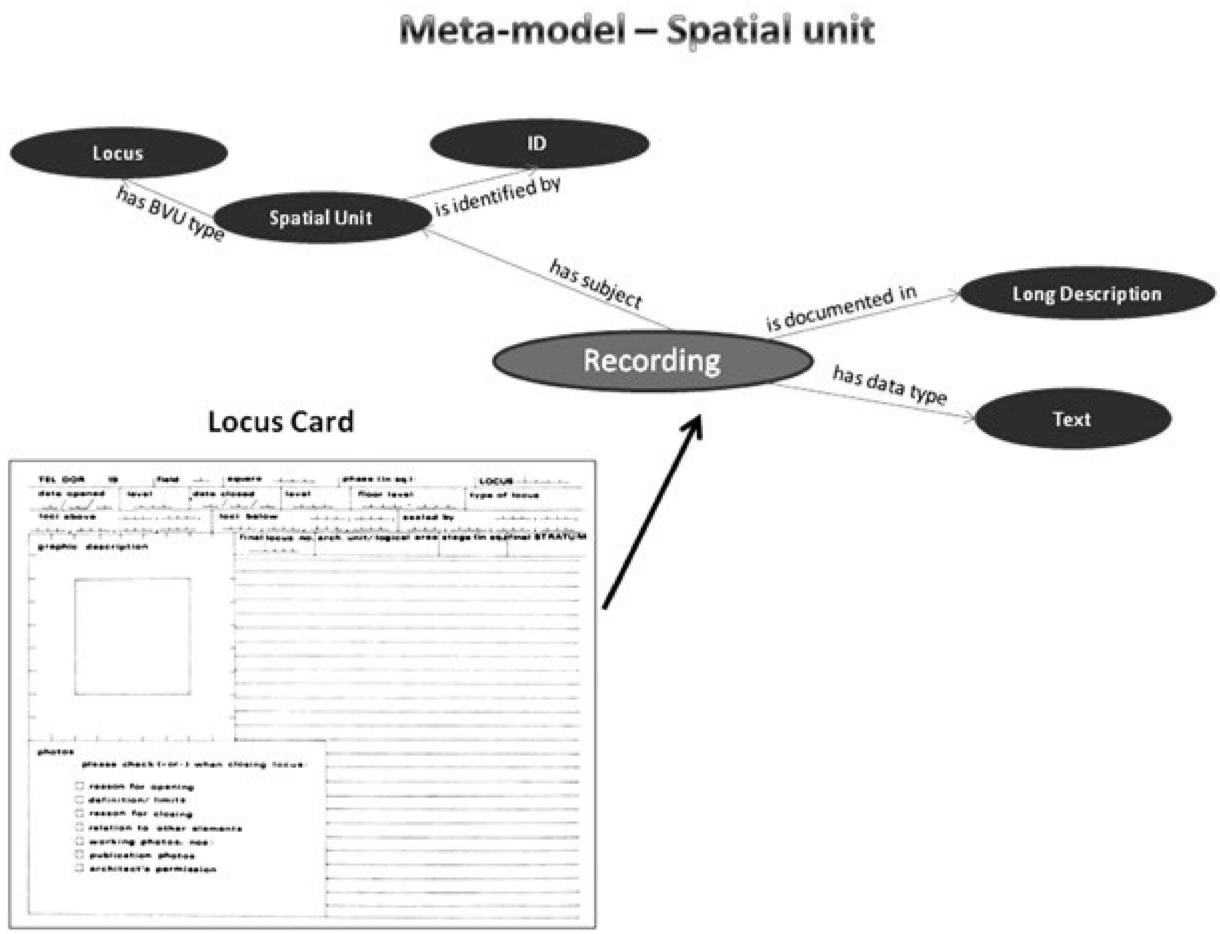

Fig. 13. Mapping a Locus Card field to the meta-model.

A publication platform based on this meta-model would benefit from built-in hypertextuality and let a reader to evaluate the presented scenario(s) while getting to the bottom of the excavation database, and to construct their own scenarios within the platform.

Bibliography

Aharoni, Y. 1973. Remarks on the 'Israeli' Method of Excavation. *Eretz Israel* 11: 48-53 (Hebrew).

ADS (2015) *Archaeology Data Service*. [Online] Available at http://archaeologydataservice.ac.uk/. [Accessed: 21st June 2015].

Bar-yosef, O. and Mazar, A. 1982. Israeli Archaeology. *World Archaeology* 13(3): 310-25.

Barker, P. 1982. *Techniques of Archaeological Excavation*. 2nd ed. London, B.T. Batsford Ltd.

Clarke, A. *et al.* 2001. *The Victorian Excavations of 1893 Silchester Roman Town - The Insula IX Town Life Project.*[Online]. Available at: http://www.silchester.reading.ac.uk/victorians. [Accessed: 6th june 2015].

Crowfoot, J. W., Kenyon, K. M., and Sukenik, E. L. 1942. *Samaria-Sebaste II. The Buildings at Samaria*. London, Palestine Exploration Fund.

Dever, W. G. 1973. Two approaches to archaeological method – the architectural and the stratigraphic. *Eretz-Israel* 11: 1-8.

Dever, W. G. and Lance, D. (eds.) 1978. *A Manual of field excavation: handbook for field archaeologists*. Cincinnati, Hebrew Union College.

Garfinkel, Y. and Davidzon, A. 2008. Expedition Organization and Excavation Methods. In Garfinkel, Y. and Dag, D. *Neolithic Ashkelon*. Qedem 47. Jerusalem, Hebrew University of Jerusalem.

Guy, P. L. O. 1938. *Megiddo Tombs*. Chicago: The University of Chicago Press.

Harris, 1979. *Principles of Archaeological Stratigraphy*. Studies in Archaeological Science. London, Academic Press.

Hole, F. and Heizer, R. F. 1969. *An Introduction to Prehistoric Archeology,* 2nd ed. New York, Holt, Rinehart and Winston.

Kansa, E. C., Kansa, S. W. and Arbuckle, B. 2014. Publishing and Pushing: Mixing Models for Communicating Research Data in Archaeology. *International Journal of Digital Curation* 9, 1: 57-70.

Kaplan, A. 1964. *The conduct of inquiry; methodology for behavioral science*. San Francisco, Chandler Pub. Co.

Kenyon, K. M. 1961. *Beginning in Archaeology,* 2nd revised ed. London, Phoenix House Ltd.

Kenyon, K. M. 1981. *Excavations at Jericho III: The Architecture and Stratigraphy of the Tell. Plates.* London, The British School of Archaeology in Jerusalem.

Kletter, R. 2015. In Search of the Israeli Method of Excavation". *Palestine Exploration Quarterly* 147: 146-59.

Lamon, R. S. and Shipton, G. M. 1939. *Megiddo I*. Chicago: The University of Chicago Press.

Matskevich, S. 2015. *'Off the Record'. Recording Systems for Archaeological Excavations in the Levant: Past and Future.* A Thesis Submitted in partial fulfillment of the Requirements of the Hebrew University of Jerusalem for the Degree of Doctor of Philosophy. Jerusalem, the Hebrew University of Jerusalem.

Molas 1994. *Archaeological Manual*, 3rd ed. London, Museum of London.

Ochre 2015. *OCHRE Data Service.* [Online] Available at http://ochre.uchicago.edu/. [Accessed: 21st June 2015].

Open Context 2015. *Open Context*. [Online] Available at http://opencontext.org/. [Accessed: 21st June 2015].

Schloen, J. D. and Shloen, S. R. 2012. *OCHRE. An Online Cultural and Historical Research Environment*. [Online] Winona Lake, Eisenbrauns. Available at: http://ochre.uchicago.edu/sites/ochre.uchicago.edu/files/uploads/OCHRE%20Manual.pdf. [Accessed 6th June 2015].

tDAR 2013. *The Digital Archaeological Record.* [Online] Available from http://www.tdar.org/. [Accessed: 21st June 2015].

Yadin, Y., Aharoni, Y., Dunayevski, E., Dothan, T., Amiran, R. and perrot, J. (eds.) 1958. *Hazor I: An Account of the First Season of Excavations, 1955*. Jerusalem, Israel Exploration Society.

3D Reconstitution of the Loyola Sugar Plantation and Virtual Reality Applications

Barreau J.B.(1, 6), Petit Q.(2), Bernard Y.(1), Auger R.(3), Le Roux Y.(4), Gaugne R.(5), Gouranton V.(6)

[1] CNRS, CReAAH UMR 6566, France - {jean-baptiste.barreau;yann.bernard}@univ-rennes1.fr
[2] CNRS, IRISA/Inria UMR 6074, France - quentin.petit@irisa.fr
[3] CELAT - Université Laval, Canada - reginald.auger@celat.ulaval.ca
[4] AAPPAG - Université Laval, French Guiana - rorota@wanadoo.fr
[5] Université de Rennes 1, IRISA/Inria UMR 6074, France - ronan.gaugne@irisa.fr
[6] Insa de Rennes, IRISA/Inria UMR 6074, France - valerie.gouranton@irisa.fr

Abstract: Discovered in 1988, the Loyola sugar plantation, owned by the Jesuits in French Guiana, is a major plantation of colonial history and slavery. Ongoing archaeological excavations have uncovered the Jesuit's house and the outbuildings usually associated with a plantation such as a chapel and its cemetery, a blacksmith shop, a pottery, the remains of the entire sugar production (a windmill, a boiler and a dryer), coffee and indigo warehouses etc. Based on our findings and our network with 3D graphic designers and researchers in virtual reality, a 3D restitution integrated within a virtual reality platform was initiated to develop a better understanding of the plantation and its surrounding landscape. Also, our work on the interactive changes of sunlight and animal sounds aims to reconstruct a coherent evolution during one day of the site's environment.

Keywords: Sugar plantation, Slavery, 3D modeling, Virtual Reality, Digital Heritage

Introduction and context

The Loyola sugar plantation has a real archaeological value because of its exceptional nature and because it represents the colonial economy of the 17th century (Croteau 2004). Concerning virtual reality research, the integration of a 3D restitution of this site (Koller 2010), within a dedicated platform, provides a good basis for the development of generic virtual reality tools (Christou 2006) (Arnaldi 2006) to analyse (Forte 2011) (Barreau 2014) and understand (Pujol Tost 2007) (Vergnieux 2011) wide and complex archaeological sites.

The Loyola Habitation is located in the municipality of Remire-Montjoly, French Guiana (Fig. 1). It disappeared from the Guyanese landscape until the discovery of the ruins (Fig. 1) in 1988 by Patrick Huard. It was over 1,000 hectares wide, with 500 slaves, and produced half of the cocoa and coffee in the colony. This singular establishment, both religious and slaver, began in 1668 and ended nearly a century later with the expulsion of the Jesuits from French Guiana in 1763. Its foundation aimed to get regular and substantial earnings to fund evangelical missions for the Indians. Since 1674, the Jesuits reorganized the place to turn it into a sugar plantation (Le Roux 2006).

We have focused our work on this period. Indeed, this plantation included a wide spectrum of buildings (main house, chapel, blacksmith shop, pottery, windmill (Bigot 2006), boiler, dryer, cemetery, coffee and indigo warehouses etc) and a considerable variety of vegetation.

1 Objectives and Contributions

Archaeologists specialised in this site have done research since 1996. The needs of virtual reconstruction for an evaluation of the results, but also for an understanding, were identified in November 2013 during exchanges with computer scientists. These first needs resulted in a series of more detailed objectives.

The first goal was the creation of a 1:1 reconstruction of the 18th century sugar plantation. The 3D reconstruction was feasible thanks to the following elements:

- Documents provided by archaeologists who know the site perfectly (Fig. 2).
- One drawing (Fig. 2) among these documents made by a contemporary of the Habitation and others from a French comic book whose author had reflected upstream on the arrangement of the site (Pellerin 2001).
- The West Digital Conservatory of Archaeological Heritage (Barreau 2013), which allows 3D modeling of archaeological sites based on the information provided progressively by archaeologists.
- The possibility of integrating such reconstructions within the Immersia virtual reality platform (Gaugne 2014).

Besides reconstructing the appearance of the building at 1:1 scale, our next objective was to reconstitute the natural environment of the site. We wanted to provide a geographically, ethologically and botanically coherent restitution. To do that, we planned to work on sky positioning, spatial and time localized birdsong and vegetation coherency.

The last step involved the exploration of possibilities for the user to interact with the environment. From these new possibilities of interaction and beyond visualization and immersion, the final objective was the creation of new tools for the work of archaeologists and historians.

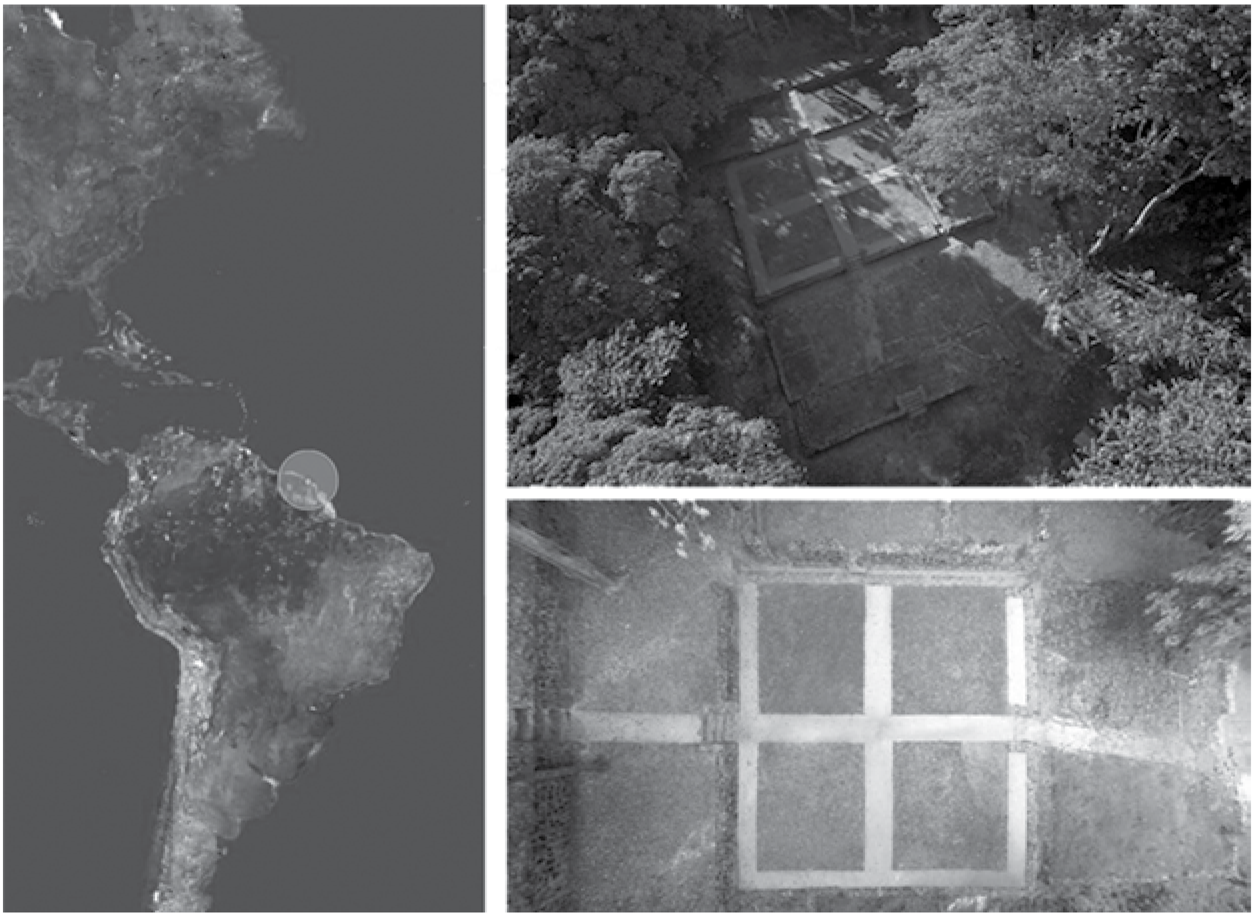

Fig. 1. Location of the site / Ruins of the habitation.

2 Work Description

2.1 Environmental restitution

2.1.1 3D restitutions

Documents provided by archaeologists to make the reconstruction were extremely diverse. Firstly there was a very detailed book with many illustrations, including those mentioned above (Le Roux 2009). A considerable amount of descriptive information was also available thanks to an excavation report, photos and videos made with a tablet. In the videos, the site is explained in situ by the archaeologist. More technically, we also had site and lines of communication maps, altitude surveys (Fig. 3), 3D animated renderings of similar buildings and a low-resolution point-cloud from an aerial photogrammetry. The 3D models, positioned and textured buildings were as follows: blacksmith shop, main house, sugar refinery, chapel, hospital, terraces, small houses of the quarter of the slaves and a windmill (Fig. 4). Modeling was done at 1:1 scale and the 'System Unit Setup' in 3DsMax was set to 1m. As in the software development process, we follow a top-down approach to have a first global understanding of the system. Thus we first focused on the outside of buildings.

For example, the reconstruction of the main house, the focal point of the Habitation, consisted of modelling a flattened clay platform, surrounded by dry stone walls which were composed of wattle and daub with wooden frames and a mud masonry joint filler. Large stone stairs provide access on three sides: front, rear and north façades etc.

2.1.2 Natural environment

For the natural environment, a 3.8x5.3kms field was first modelled thanks to altitude surveys, and both current and 18th-century maps. The vegetation in the 17th century differed from today's and, beyond plants used in the Habitation's activity (cacao tree, coffea, sugarcane and cotton plant), it is difficult to list other plants. However, a botanist stayed in the Habitation and listed some plants in his book (Fusée-Aublet 1775).

As the vegetation targeted in the reconstruction was very specific, we modelled most of the plants: balsam of Peru, Ceylon cinnamon tree, bloodwoodtree, campomanesia grandiflora, sandbox tree, cacao tree and black mangrove (Fig. 5). We also used 3D models of sugarcane plant, coffee and lemon tree from the 3D plants library (XfrogPlants 2015).

2.1.3 Human beings

There were a lot of human beings who carried out complex and various activities. Before implementing them, it was necessary for us to establish a restitution protocol. We used the software

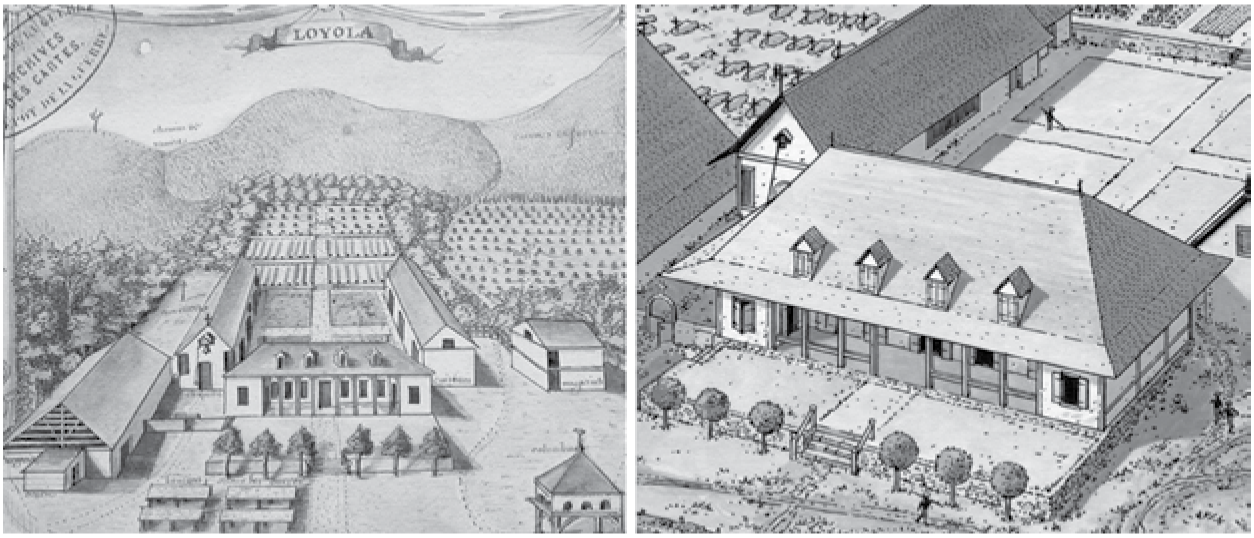

Fig. 2. Isometric view of the Loyola Habitation by Hebert (1730) / Restitution of the Jesuits' main house by Patrice Pellerin (2002).

Fig. 3. IGN and Joseph-Charles Dessingy (1738-1785) map sections showing around the Habitation.

Fuse 1.0 for 3D character creation, to assemble customizable body parts, clothing and textures (Maher 2014). Those characters were rigged with an online automatic model rigging service (Mixamo 2015) to be exported into Unity (Fig. 6). The activities represented in the reconstitution will be defined in further work, from documents and information supplied by archaeologists.

2.2 Virtual reality implementation

2.2.1 Technical implementation

Unity game engine has been chosen for 3D simulation because of its simplicity. It is provided with an all-in-one editor which contains all our needs: terrain manager, 3D

Fig. 4. 3D renderings (3Ds Max / VRay) of the main house, the windmill, a slave's small house, the backside of the chapel.

Fig. 5. 3D renderings of cacao tree, black mangrove and ceylon cinnamon tree.

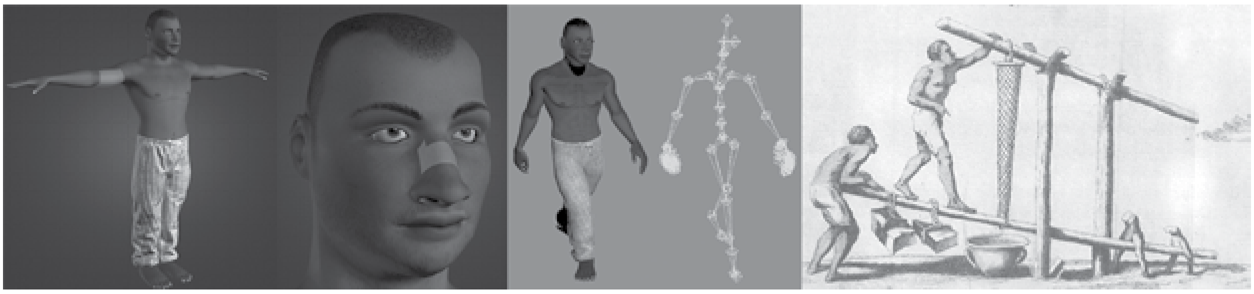

Fig. 6. Editable 3D slave's body and face / rigged 3D slave's body and skeleton / drawing of cassava pressing (Préfontaine 1763).

Fig. 7. 3D vegetation simulation overview.

spatialized sound, skysphere and a good lighting renderer with fine overall performance. MiddleVR, a virtual reality plugin for Unity, manages all of our peripherals like flystick and DTrack tracking system and displays active stereoscopy on our 13 nodes cluster. The framerate of the simulation stays around 30 frames per second in our cave (Intel Xeon W3670, Quadro 5000) depending of the current user location. For the integration in Unity, 3D models of plants and buildings were converted to FBX format and sometimes simplified thanks to the Decimate Blender modifier.

2.2.2 Simulation of vegetation and animals

A semi-automatic approach allowed us to place vegetation. Coffee farming and forest trees were planted with 'Unity terrain brush' in their specified area. The sugarcanes were automatically placed in the left area with a specified density and random range deviation (position, height, width) to simulate real world differences. There are around 787K trees in the current simulation with 782K sugarcanes and 5K coffees planted on a 0.8km² area. The distant area is simply textured. From a user's perspective, only the nearest vegetation (≈ 0.1%) is displayed as mesh with dynamic shadow and wind effects. Thus, most of the trees are drawn as a billboard, which is a simple textured quad facing the user. These optimisations keep the frame rate reasonable despite the huge environment size.


```
<animals>
  <animal name="Columbina passerina*">
  <area name="sugarcane" />
    <repartition number="2" delay="10"
variation="4" spawn="0.25" />
    <sound range="35" volume="0.5" file="…"
/>
  </animal>
```


Fig. 8. Xml structure of animal sound data.

Archaeoacoustics is a vast and complex scientific discipline (eds Scarre 2006) (ed. Eneix 2014). Concerning the study of the Habitation, human activity produced a sound environment that deserves to be studied. However, although we were fully aware of the rich fauna and flora of the site, we focused first on the sound of animals. Thanks to an ethology specialist in the fauna of the region, we made two coherent lists of animals consistent with the vegetation described above. The first, consisting of ten animals, includes the sugar cane crops and open fields, and the second one, consisting of 16 animals, consists of the tree line near the buildings. We gathered the animal sounds samples, available on a website specialized in sharing sound samples (Xeno-canto Foundation 2014), we

FIG. 9. SPHERES REPRESENTING THE SOURCES OF SOUND IN THE RECONSTRUCTION.

structured the data so as to fit in the xml format (Fig. 7) and then we integrated it into the virtual reality module (Fig. 8).

2.2.3 Time simulation

The evidence of a link between agriculture and exposition to sunlight made us work on the study of the evolution of sunlight throughout the day. For this matter, the position (latitude, longitude, altitude) of the site, associated with the NREL's Solar and Moon Position Algorithm (SAMPA) (Reda 2010) allowed us to calculate the solar and lunar zenith and azimuth angles, with uncertainties of +/- 0.0003 degrees for the Sun and +/- 0.003 degrees for the Moon, such as they were at that time. Therefore, knowing the positions of the Moon, we could also use and position the textures of a starry sky thanks to the Tycho Catalog Skymap - Version 2.0 (NASA/Goddard Space Flight Center Scientific Visualization Studio 2009). The complete evolution of natural light of the Habitation on a 24 hours time frame was also reproduced (Fig. 9).

2.2.4 Immersion and interaction

The simulation was deployed on an immersive facility, the Immersia platform.[1] This facility of the Irisa/Inria computer science laboratory is a large virtual-reality room dedicated to real-time, multimodal (vision, sound, haptic, BCI) and immersive interaction. It hosts experiments using interactive and collaborative virtual-reality applications that have multiple local or remote users.

Images are rendered on four glass screens: a front one, two sides and a ground one. Dimensions are 10m wide, 3m deep and 3m high. The number of pixels displayed is over 15 million. An infrared based tracking system enables real objects to be tracked within the scene, such as the hand and the head of the user. This system with high-resolution rendering, active stereoscopy, tracking and homogeneous colouring delivers a visually realistic and immersive experience, which is particularly suitable for 1:1 rendering (Fig. 10). Spatial sound can be rendered by the speakers of the platform with 10.2 format or by a wireless stereo headset, more suited to binaural rendering. To check the dimensions in the immersive platform, a reference item on the ground level at parallax 0 has been measured.

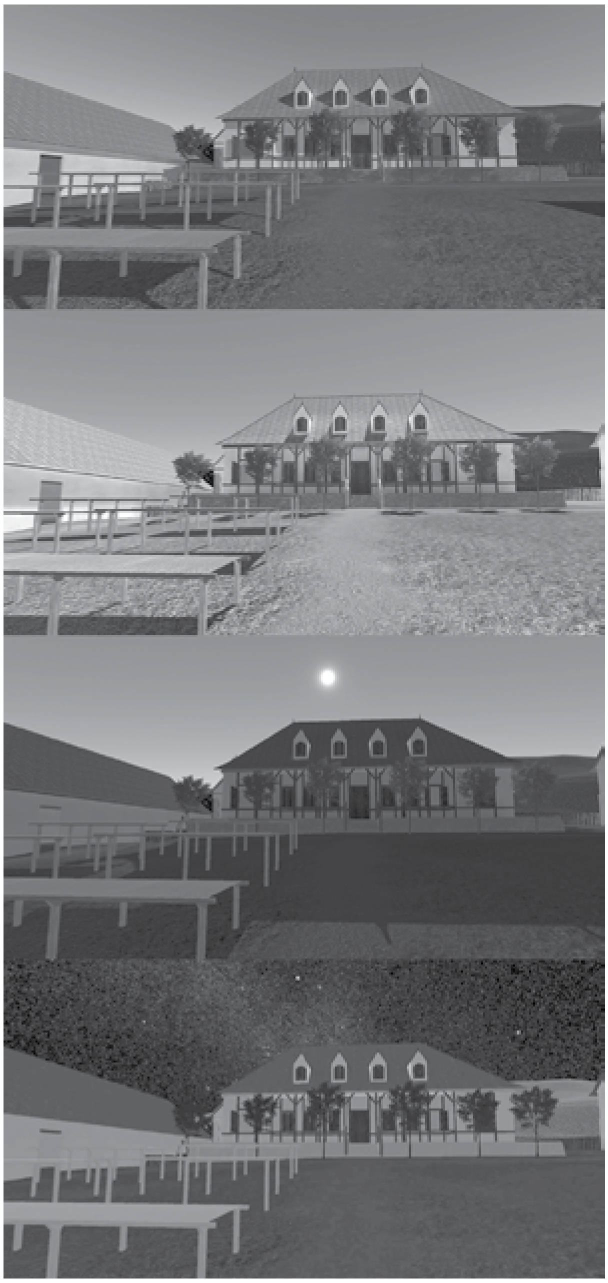

FIG. 10. SIMULATION OF NATURAL LIGHTING AT THE TIME ON A 24 HOURS PERIOD.

[1] http://www.irisa.fr/immersia

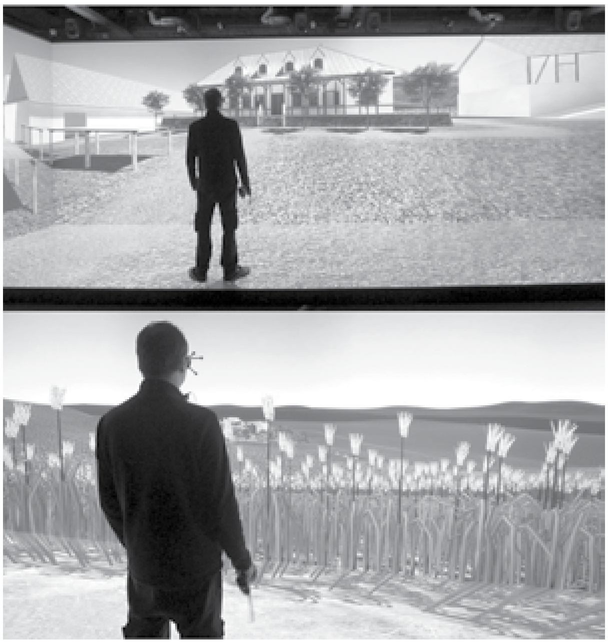

Fig. 11. Interactive simulation in Immersia.

2.3 Interactivity

Inside the simulation, the user can interact with the virtual environment through a wand-like device integrating a little joystick and five buttons (Fig. 11). The device position and orientation is tracked with the infrared cameras.

The user can explore the virtual environment either by naturally walking within the limits of the facility, or moving the universe with the joystick. They can also teleport to predefined points of interest by pushing one button. Two other buttons are used to increase or decrease the time of the simulation and influencing the speed of the alternation of night and day.

3 Discussion

Archaeological research on the French colonial America is a relatively nascent field. From about three quarters of a century ago, especially from the 1960s, archaeologists began excavations in all regions of the Americas that could reveal traces of this French occupation. However, the results of these archaeological research too often remain confined to technical literature and reports, hard to access for the general public, and even for researchers (Moussette 2013). The combined contributions of historical and archaeological sources provide a strong foundation for the restitution when, as here, there are not many remains. For example, the illustrations allow very effectively guide the 3D modelling. Thus, we believe that supporting the research by 3D reconstitutions, virtual reality applications and associated thoughts, right from its early stages, can be a major issue for its development that requires summaries, understandings and explanations.

Concerning virtual reality, immersion within the platform led to apprehend circulation paths and overall visibility between buildings and the various fields surrounding the plantation. Apart from natural interactions with various elements of the environment, different methods of navigation have been

Fig. 12. Interactions with the simulation.

implemented to enable archaeologists to move the entire site, which is extremely broad. They can currently do a scale-one immersion to experiment and rightfully check the visual and sound restitution of the site during one day, however without human beings and outside of the buildings. The next step should therefore consist of giving the opportunity to study the daily life of actors who made this site function.

4 Conclusion

The 3D reconstruction of buildings, vegetation, lighting and fauna sounds of the Habitation, integrated within a virtual reality platform, allow us to understand its layout, its access, its logic of evolution and to think about the production operated by several hundred people.

Many archaeological questions remain unanswered and we wish to imagine immersive working sessions with archaeologists and new VR interactive tools development. These would include:

- Automatic generation of study reports
- Dynamic positioning of bounding boxes marking the location of missing objects to model
- Autonomous design of buildings' structural system and vegetation areas
- Adapting these tools to other archaeological sites

Acknowledgments

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Bibliography

Arnaldi, B., Guitton, P., Fuchs, P., Moreau, G. 2006. *Le traité de la réalité virtuelle. Volume 4,* Paris: École des mines de Paris.

Barreau, J.-B., Gaugne, R., Bernard, Y., Le Cloirec, G., Gouranton, V. 2013. The West Digital Conservatory of Archaelogical Heritage Project. In *DH*. [Online]. 2013, France: 1-8. Available at: https://hal.archives-ouvertes.fr/hal-00881775.

Barreau, J.-B., Gaugne, R., Bernard, Y., Le Cloirec, G., Gouranton, V. 2014. Virtual reality tools for the West Digital Conservatory of Archaeological Heritage. In: *VRIC 2014, ACM*. [Online]. April 2014, New York, United States: 1-4. Available at: https://hal.archives-ouvertes.fr/hal-01003416.

Bigot, V. 2006. L'habitation Loyola dite Moulin à Vent d'après les sources archivistiques : la transmission du passé colonial en Guyane française. In *L'histoire de la Guyane depuis les civilisations amérindiennes: actes du colloque des 16, 17 et 18 novembre 2005, Cayenne*. Espace outre-mer: 599-617. Matoury, Guyane, Ibis Rouge Editions.

Christou, C., Angus, C., Loscos, C., Dettori, A., Roussou, M. 2006. A Versatile Large-scale Multimodal VR System for Cultural Heritage Visualization. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. VRST '06. New York, ACM: 133-40. Available at: http://doi.acm.org/10.1145/1180495.1180523.

Croteau, N. 2004. L'habitation de Loyola : un rare exemple de prospérité en Guyane Française. *Journal of Caribbean Archeology, Special publication number 1*: 68-80.

Eneix L. C. (ed.) 2014. *Archaeoacoustics: The Archaeology of Sound ; Publication of Proceedings from the 2014 Conference in Malta*. Myakka City, FL, The OTS Foundation.

Forte, M. 2011. Cyber-Archaeology: Notes on the simulation of the past. *Virtual Archaeology Review 2, 4*: 7-18.

Fusée-Aublet, J.-B.-C. 1775. *Histoire des plantes de la Guiane Francoise: rangées suivant la méthode sexuelle, avec plusieurs mémoires sur différens objects intéressans, relatifs à la culture and au commerce de la Guiane Françoise, and une notice des plantes de l'Isle-de-France*. [Online]. Londres;Paris; P. F. Didot jeune. Available at: http://www.biodiversitylibrary.org/bibliography/674. [Accessed: 25 june 2015].

Gaugne, R., Gouranton, V., Dumont, G., Chauffaut, A. AND Arnaldi, B. 2014. Immersia, an open immersive infrastructure: doing archaeology in virtual reality. *Archeologia e Calcolatori, supplemento 5*: 1-10.

Koller, D., Frischer, B. and Humphreys, G. 2010. Research Challenges for Digital Archives of 3D Cultural Heritage Models. *J. Comput. Cult. Herit.* 2 (3): 7.1-17.

Maher, K. 2014. *Mixamo, a company offering tools for character creation, is getting ready for GDC with new updates and a new pricing plan.* [Online]. Available at: http://gfxspeak.com/2014/03/12/mixamo-products-upgrades

Mixamo 2015. *Rig a character in the time it takes to get a cup of coffee.* [Online]. Available at: https://www.mixamo.com/auto-rigger

Moussette, M. and Waselkov, G.A. 2013. *Archéologie de l'Amérique coloniale française*. Réflexion. Montréal (Québec): Lévesque éditeur.

Nasa/Goddard Space Flight Center Scientific Visualization Studio 2012. *Deep Star Maps*. [Online]. Available from: http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3895.

Pellerin, P. 2001. *Le trésor du Mahury*. Paris, Dupuis.

Prefontaine De, J.-A.-B. 1763. *Maison rustique, à l'usage des habitans de la partie de la France équinoxiale connue sous le nom de Cayenne*. [Online]. Paris, Bauche. Available at: https://books.google.fr/books?id=0SAaAAAAYAAJ.

Pujol Tost, L. and Sureda Jubany, M. 2007. Vers une réalité virtuelle véritablement interactive. In: *Virtual Retrospect*. November 2007, Pessac: Robert Vergnieux, Caroline Delevoie: 77-81.

Reda, I. 2010. *Solar Eclipse Monitoring for Solar Energy Applications Using the Solar and Moon Position Algorithms*. Available at: http://www.osti.gov/servlets/purl/974908-APBEfU/. [Accessed: 25 june 2015].

Le Roux, Y. 2006. L'habitation Loyola à Rémire. L'archéologie coloniale pour l'histoire. In: *L'histoire de la Guyane depuis les civilisations amérindiennes: actes du colloque des 16, 17 et 18 novembre 2005, Cayenne*. Espace outre-mer. Matoury, Guyane: Ibis Rouge Editions: 599-617.

Le Roux, Y., Auger, R. and Cazelles, N. 2009. *Les jésuites et l'esclavage Loyola: l'habitation des jésuites de Rémire en Guyane française*. Québec, Presses de l'Université du Québec.

Scarre, C. and Lawson, G. (eds.) 2006. *Archaeoacoustics*. McDonald Institute monographs. Cambridge, Oakville, CT, McDonald Institute for Archaeological Research, David Brown Book Co.

Vergnieux, R. 2011. Archaeological research and 3D models (restitution, validation and simulation). *Virtual Archaeology Review 2, 4*: 39-43.

Xeno-Canto Foundation 2014. *xeno-canto Sharing bird sounds from around the world* [Online] Available at: http://www.xeno-canto.org/

Xfrogplants 2015. XfrogPlants - 3D Trees and 3D Plants. Available at: http://xfrog.com/category/xfrogplants.html

Integrated Survey Techniques for the Study of an Archaeological Site of Medieval Morocco

Lorenzo Teppati Losè
lorenzo.teppati@gmail.com
Department of History and Cultural Heritage, University of Siena, Italy

Abstract: This paper presents the first results of the study conducted on the archaeological site of Chellah (Rabat, Morocco). Chellah was the Roman city of Sala Colonia; the site has undergone various transformations during its history and became the Marinid royal necropolis at the end of the 13th century AD, a role that it maintained up to the end of 15th century AD. In particular, this research was focused on the study of the Marinid madrasa, that was a koranic school and a formation center of state functionaries.

The final aims of this work were: creating a corpus of surveys of the madrasa that fit the needs of accuracy and precision but also the needs of the archaeologists, testing and integrating different survey techniques (with considerations about methodology) and producing the final elaborates for the analysis of Building Archaeology.

Keywords: Photogrammetry, Islamic Morocco, Building Archaeology.

Introduction

The research presented in this paper is part of the recent activities of the Laboratory of Classical Archaeology of the University of Siena, under the direction of Prof. Emanuele Papi. It was also the subject of a Master's degree thesis. We studied part of the Islamic evidence for the archaeological site of Chellah, Morocco, and have undertaken three field missions for the survey and the study of the Marinid *Madrasa*.

The archaeological site of Chellah is located in the southern part of the modern city of Rabat, in the region of Rabat-Salé-Zemmour-Zaer in Morocco. The settlement was established on the slopes of two different hills, near the left bank of the Bou Regreg river. In 2012 the archaeological site together with other areas of the Moroccan capital was included in the World Heritage List of UNESCO. The region where the Islamic Chellah was built presents evidence for the settlements of different chronological periods: from Prehistory, through the Roman period, to the Middle Age. The Roman and Islamic phases are the ones that provided most of the data.

The Marinid occupation of Chellah and its transformation to a royal necropolis began in the second half of the 13th century AD; however, major building activities were realized a century later, in the second half of the 14th century. The Marinid sovereigns had a great impact on the construction of new public buildings and chose the *Madrasa* as a main instrument for their public promotion. These buildings, half way between religious and public, were intended as centres for the formation of state functionaries and as a pole for the diffusion of the political message of the sovereigns.

The presence of a *Madrasa* in a context such as the royal necropolis is still a *unicum* for the Islamic Morocco; these buildings are usually placed in urban areas and the case of Chellah left many unanswered questions. For these reasons we decided to study this specific building. Another reason is the fact that the building will be the object of a restoration project in the near future. We need a deep knowledge of the building to write a complete and detailed project of restoration, in collaboration with experts of other disciplines.

The *Madrasa* of Chellah was brought to light during the French excavations in the 1930s and, despite the heavy restoration that followed the excavations, it still offers a lot of information and is in a good state of conservation. The methodologies used by the French researchers that excavated the site were far from the modern stratigraphic methods and a loss of data during this archaeological works certainly occurred. The methodologies of Building Archaeology allows to retrieve part of this loss and to obtain new information on the building history of this complex.

Before writing a new survey project we examined all the existing documentation that was possible to obtain. As a result of this work it became apparent that new surveys of the complex were needed and we decided to write a new survey project.

1 The survey Project

The survey project was the preliminary and essential foundation of the fieldwork. First we chose the buildings we wanted to survey and then the techniques to be employed. Prior to the choice of the survey techniques we also considered other key factors: the daily presence of a great number of visitors in Chellah and the fact that the area of the *Madrasa* was not interdicted to the public, the time and the resources we had for the fieldwork (human and material), the complicated conditions of light and finally the presence of a large colony of storks that lives on the archaeological site for the major part of the year. The survey project is also strictly related to the archaeological project that determines the level of detail of the research and consequently the choice of the survey techniques. The methodology of Building Archaeology considered different levels of detail in the study of architectural evidence and these levels of detail influenced the choice of the survey techniques and the final delivery of the survey.

After evaluating all this conditions we decided to use three different integrated techniques: the topographic survey with total station, 2D photogrammetry and 3D photogrammetry.

The work of data collection on the site was conducted by three people within ten days. The first step was the creation of a local

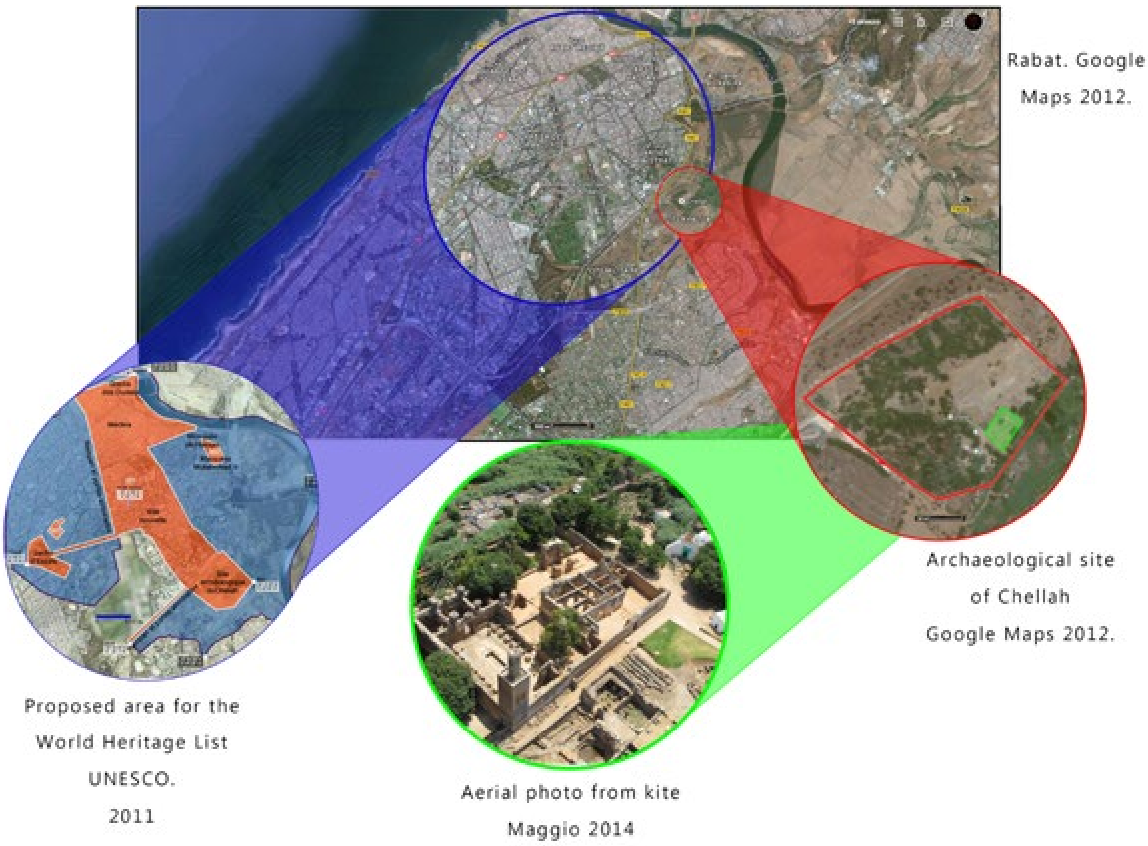

Fig. 1. Location of the archaeological site of Chellah.

topographic network and the creation of an architectural plan of the *Madrasa*.

The second one concerned the placement of the marker on the architectural remains and their recording. Finally, we shot the photos, both for 2D and 3D photogrammetry.

We decided to use these three integrated techniques to evaluate the final delivery of the survey and their use from the archaeological point of view. For this project we decided to work both with open source and proprietary software, testing advantages and disadvantages of the different solutions. The idea was to set a clear workflow for a fast acquisition of data, a quick post-processing and the generation of useful final products at different levels of detail. The economic part of the overall process was also very important. We needed to use low cost techniques and instruments, so the choice of photogrammetry was the one that best fitted our purposes.

The raw data collected on site were elaborated in laboratory in the months after the mission. The final resluts of the survey (an architectural-archaeological plan, different orthophotos of the main features of the complex and a point cloud of the major part of the *Madrasa*) became the basis of the whole archaeological research.

Among the final results of the survey, the one that consumed the major part of the time of post-processing was the 3D photogrammetry. The 3D models of the *Madrasa* were generated in 95 different projects, to simplify the management of the data, and were generated using different levels of detail. The levels of the detail were chosen depending on the quantity and quality of archaeological information held by the different portions of the complex. After this first part of the post-processing, single models were joined in a single point cloud. We chose to generate a 3D model based on the sole point cloud, without mesh and texture, because it fitted our necessities as archaeologists and we did not want to make the model heavier.

The final point cloud is composed of almost 300.000.000 points with RGB values and saved in the .txt format (ASCII code) and has a weight of 17.2 Gb. The accuracy of the model was checked using control point and linear measurements. The 3D models cover a large part of the complex of the *Madrasa* that has an area of almost 500 m² and presents walls preserved in some points at a height of 6 metres above ground. As said before we also chose to work with 2D photogrammetry: different walls of the *Madrasa* were surveyed using this technique. This choice allowed to compare 2D and 3D photogrammetry under different aspects: time needed in the field for the collection of data, time needed for the post processing, precision and use of the final results of the two techniques. The three final products of the survey techniques (topographic survey, 2D and 3D photogrammetry) were used in the process of the archaeological research and were the bases for the analysis of building techniques and for the creation of an interpretative

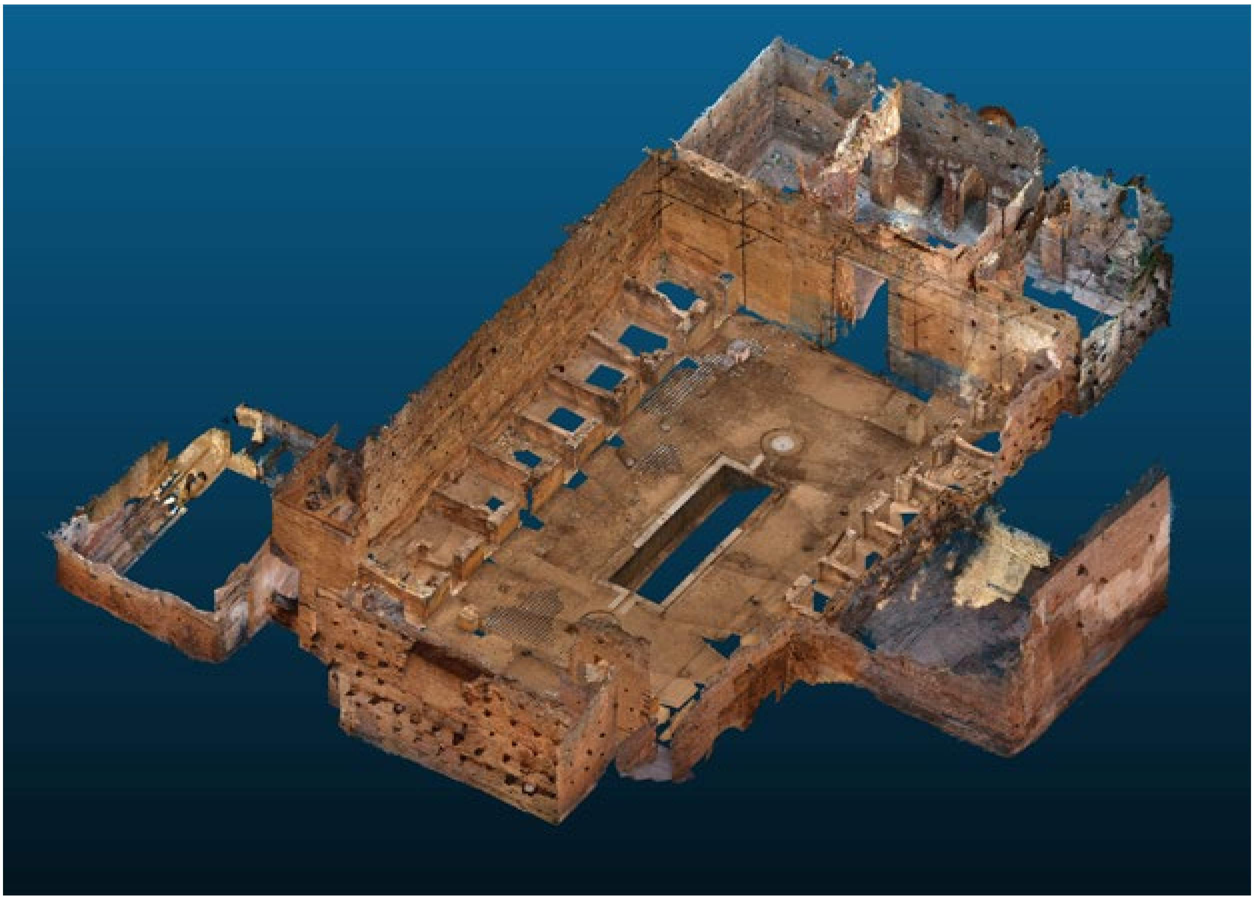

Fig. 2. A view from the final point cloud.

3D models in CAD environment. The analysis of the different set of data extrapolated from the three survey techniques were used during different phases of the archaeological research.

2 Issues with methodology

During the whole process of survey and research we reflected about some methodological problems. In the last years we saw the rise of new figures in the world of archaeology, experts halfway between archaeologists and surveyors, but there is still a lot to achieve. This hybridisation between archaeologists and surveyors is particularly clear in the Building Archaeology, in some Italian groups of researchers. In the Italian world of researchers we can appoint at least two main reasons to explain this phenomenon: the better accessibility of the photogrammetric techniques also to a non specialized public and the drastic decrease of resources for archaeology (that often doesn't allow the presence of professional surveyors on the site). It is difficult for an archaeologist to realize survey with the precision of a surveyor, and maybe it is not always necessary, but, with some efforts and studies, it is possible to obtain a good outcome.

Obviously, the whole process of hybridisation has both positive and negative aspects. The academic formation of students is technically inadequate from this point of view and the individuals that work in the field of archaeological surveys are often self educated, especially in the field of photogrammetric surveys.

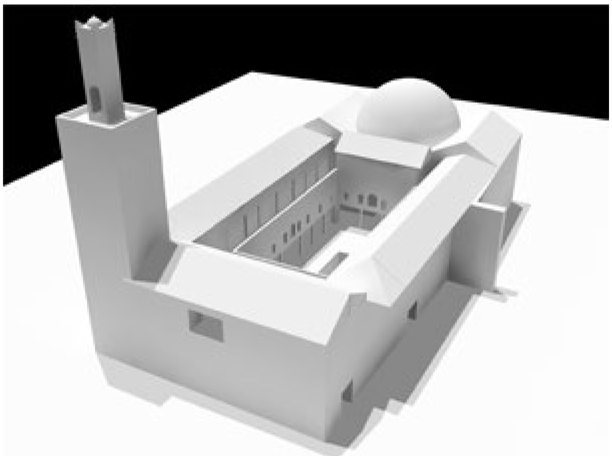

Fig. 3. 3D interpretative model.

Archaeologists should know in detail the different survey techniques and the possibilities they offer: if archaeologists could develop this knowledge, they could know what the best techniques for the studied context are.

A better knowledge of the different survey techniques could allow the archaeologists to set a congruent survey project, customized for every single feature; if the survey is made by surveyors this knowledge could allow archaeologists to ask for clear final results on the basis of the research project.

A lack of the knowledge of the possibilities offered by the different survey techniques leads to a series of problems. Firstly, we are observing an intensive use of 3D survey, and especially the use of 3D photogrammetry, although this is not necessary. In spite of being an extraordinary technique that will probably have an impressive development, it is not always fundamental for the archaeological research.

Archaeologists must be able to choose the best survey technique for the objects of their studies; in this way there will not be a waste of time and resources in the creation of useless survey products.

Sometimes an orthophoto is all that is needed for the research aims, sometimes a 3D survey could make the difference for the archaeologists to be able to arrange and manage it in the best way possible. They should be able to take part in the planning of the survey as well as in the use of the final results. For example, in our case the lack of experience led to the creation of a big point cloud that is not always easy to manage. The experience gained from this project will help us in the preparation of the survey project of our future researche. We are now more aware of the different possibilities that these techniques offer and of their practical use in the fieldwork. Be aware of this; it can help us in the choice of the best techniques to use, the time and resources needed for its employment and the results expected.

There is another issue that we noticed while we were working on the *Madrasa* of Chellah and that will probably be one of the major challenges of the photogrammetric surveys in the next years: the huge amount of data that it produces. If we consider the raw data, the project files, and the final resluts of a photogrammetric survey (2D and 3D) the amount of storage space taken is subjected to a tremendous growth. Until we see the next evolution in the storage technology, we can start realizing a photogrammetric survey just if useful and necessary; this could be a first step to reduce the amount of data.

Finally, archaeologists, at least the ones that work in the field of archaeological survey, must learn to work with the products of photogrammetry and of the other survey techniques. That is the only way to use them as real instruments for archaeological research. It is pointless to have beautiful and precise 3D models if they are not useful for the archaeological research.

3 Conclusion

The integration of the archaeological methodology and the instruments of other disciplines permitted work on the site of Chellah at 360 degrees. We had the chance to approach the site in different ways, analysing the different features separately and then reuniting the data in a single interpretation. The aid supplied by the survey techniques allowed us to obtain a huge amount of data and to perform a deep study of the archaeological evidence. We were able to understand part of the building history of the *Madrasa* and its evolution during time. We have now some clearer hypotheses about its foundation date and its collocation within the texture of other Islamic buildings.

Based on the experience acquired during the work on the *Madrasa* of Chellah, we also highlighted some points and proposed some considerations about general issues of the methodology of integration between archaeological research and survey techniques.

First, the interdisciplinarity: unfortunately this is often missing in the formation of an archaeologist, while it should be one of the essential abilities. Due to the diffusion of the new survey techniques a new study path for archaeologists must be created: all the students of archaeology should be trained also in the survey techniques (at least in the basic features) during their formation, independently of what will be their specialization. Students of archaeology who wish to specialize in survey techniques, should undertake a specific course on the newest techniques and their possibilities.

It is not mandatory to train archaeologists-surveyors, but it should be enough to train well informed archaeologists.

A strong synergy should exists between different departments and universities. It would be interesting if surveyors could have a confrontation with archaeologists more often, and vice versa.

This kind of relation will lead to facilitations for both professions: surveyors will have a better understanding of the needs of the archaeologists and archaeologists will have a better understanding of what they could ask the surveyors.

Bibliography

Basset, H. and Lévi- Provençal, E. 1922. *Chella: Une necropole merinide.* In: *Hesperis. Archives Berbères et Bulletin de l'Institut des Hautes Études Marocaines*, Paris, Edaraf.

Boato, A. 2008. *L'archeologia in architettura. Misurazioni, stratigrafie, datazioni, restauro.* Venezia, Marsilio Editori.

Boube, J. 1977. *Sala III,* Rabat, Musee des Antiquites.

Boube, J. 1999. *Les necropoles de Sala,* Paris, ADPF.

Cagnana, A. 2000. *Archeologia dei materiali da costruzione*, Mantova, SAP.

Cavallari, A., Gatti, M., Giberti, M., Hejira, H and Roccon, B. 2013. *Il sito archeologico-monumentale di Chellah, Rabat, tra storia e natura.* In Biscontin, G. and Driussi, G., *Conservazione e Valorizzazione dei siti Archeologici: approcci scientifici e problemi di metodo. Atti del convegno di studi Bressanone. Bressanone, 9-12 July 2013*: 1109-15. Venezia, Arcadia Ricerche.-

Chastel, R. 2013. *Rabat. Le destin d'une ville et des caprices d'un fleuve,* Rabat, Chastel.

Etthairi, A. 2012. *Genese et role de la medersa au Maroc islamique.* In: *Bulletin d'Archeologie Marocaine.* XXII: 267-86. Rabat, Imprimerie El Mâarif Al Jadida.

Fiorini, A. and Archetti, V. 2011. Fotomodellazione e stereofotogrammetria per la creazione di modelli stratigrafici in archeologia dell'architettura. *Archeologia e Calcolatori* 22: 199-216. Firenze, All'Insegna del Giglio.

Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A., Ercoli, S. 2009. *A Multi-Resolution Methodology for the 3D Modeling of Large and Complex Archeological Areas. International Journal of Architectural Computing* 7, 1: 39-55.

Hadda, L. and Jacobelli, L. 2008. *Le parc archeologique de Chellah,* Napoli, L'Isola dei Ragazzi.

Nagy, T. 2014. Sultans' Paradise: The Royal Necropolis of Shāla. Rabat. *Al-Masaq: Journal of the Medieval Mediterranean* 26 (2): 132-46. London, Taylor & Francis.

Parenti, R. 1985. La lettura stratigrafica delle murature in contesti archeologici e di restauro architettonico. *Restauro & Città* 2: 55-68.

Russo, M., Remondino, F., Guidi, G. 2011. Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico. In *Archeologia e Calcolatori* 22: 169-98. Firenze, All'Insegna del Giglio.

Terrasse, C. 1928. *Medersas du Maroc,* Paris, A. Morancé éditions.

Terrisse, M. 2013. *Proposition de Valorisation Du Site de Chellah*, Paris, Presses Academiques Francophones.

CHAPTER 3
Interdisciplinary Methods of Data Recording

3-Dimensional Archaeological Excavation of Burials Utilizing Computed Tomography Imaging

Tiina Väre[(1)]
tiina.vare@student.oulu.fi

Sanna Lipkin[(1)]
sanna.lipkin@gmail.com

Markku Niskanen[(1)]
markku.niskanen@oulu.fi

Jaakko Niinimäki[(2)]
jaakko.niinimaki@ppshp.fi

Matti Heino[(3)]
matti.heino@oulu.fi

Sirpa Niinimäki[(1,3)]
sirpa.niinimaki@oulu.fi

Annemari Tranberg[(1)]
annemari.tranberg@oulu.fi

Titta Kallio-Seppä[(1)]
titta.kallio-seppa@oulu.fi

Saara Tuovinen[(1)]
saara.tuovinen@student.oulu.fi

Juho-Antti Junno[(1,4)]
juho-antti.junno@oulu.fi

Rosa Vilkama[(1)]
rosa.vilkama@oulu.fi

Milton Núñez[(1)]
nunez.milton@gmail.com

Timo Ylimaunu[(1)]
timo.ylimaunu@oulu.fi

[1] Laboratory of Archaeology, Faculty of Humanities, University of Oulu
[2] Center for Medical Imaging, Physics and Technology Research, University of Oulu and Oulu University hospital
[3] Department of Biology, Faculty of Science, University of Oulu
[4] Medical Research Centre, University of Oulu and Oulu University hospital

Abstract: We use computed tomography (CT) to study early modern burials once deposited beneath Finnish churches, some of which contain mummified remains. The method allows us to perform repeated 3-dimentional layer-by-layer dissections not only of the human remains but of the whole burials. Moreover as the examination functions as a virtual, repeatable, non-invasive excavation, it is possible to conclude about the burial materials – such as the coffin itself but also the textiles, ornaments, plant's particles and other accessories sealed inside– without harming this unique heritage. This is the first CT study of Finnish mummies and examination of the artefacts associated with the burials via CT is also a relative novelty. The project was initiated with a CT study of the mummified remains of a 17th-century vicar, and coffins of seven sub-adults have been imaged since that. So far we have revealed pathological conditions the vicar suffered from and concluded about the preservation and funerary attires.

Keywords: Computed Tomography, Reconstructing Past Lives, Northern Finland, Mummies

1 Introduction

Crypt burials common around the Christian Europe for centuries were also practised in Finland,[1] although actual crypts were seldom part of the local church architecture. Instead, the coffins of members of the elite were buried in the churches' basal sand, placed in under-floor chamber tombs or simply deposited beneath the churches' floors-planks (Fig. 1). In most Northern Finnish parishes this burial practice originating from the Middle Ages ceased by the end of the 18th century. In others, it continued until the prohibition of 1822. Even this, however, did not necessarily rule out depositing burials in unused churches (Talve 1988; Cajanus 1927: 30; Lempiäinen 1990a; Lempiäinen 1990b; Satokangas 1997, endnotes; Paavola 1998: 39, 43, 87, 114, 166, 174–5; Paavola 2009).

Old Finnish churches still hold many of these Early Modern burials ('church burials'). What is more, the efficient ventilation below their floors, and – especially in the North – the subarctic climate have ensured cold-drying of the soft tissues of several of the deceased once deposited beneath these churches. (Núñez, Paavola and García-Guixe 2008). These mummified human remains have raised popular interest throughout the centuries. During the period these burials were made it was apparently not unusual for people to even visit the dead in graves under the church floors. (Olsson 1956: 18–9; Paavola 1998: 146–7, 157, 162, 166; Ojalatva 1997).

In the mid-1990s the burials in three Northern Finnish churches were inventoried and the burial practice studied in connection

[1] At the time, first a part of the Swedish Kingdom and after 1809 the Russian Grand Duchy of Finland.

Fig. 1. The burials deposited in this collapsed chamber tomb under the Haukipudas church are mostly those of adults. They almost certainly predate the 1762 completion of the current Haukipudas church, as after this only five children were buried under it. (Photograph above by S. Lipkin) In the Keminmaa old church these coffins right beneath the floor boards seen in the image probably date to the 19th century when the church was no longer in active use (Paavola 1998: 223). As the ground was frozen solid the otherwise unused church was utilized as a winter grave. Although originally these burials were intended as temporary, some of them were never removed. (Photograph below by T. Väre)

with a doctoral thesis research (Paavola 1998). Otherwise these burials have not received much scientific attention, which is mainly due to their relatively recent date. Most of them date to 17th and 18th centuries. Nevertheless, they offer a unique opportunity to study the people and traditions of the Early Modern period in the northern periphery of Europe.

These remains are especially important from the bioarcheological viewpoint as the long-term preservation of skeletal material is generally poor in Finnish soils. The bedrock predominantly consists of silicon dioxide based granite. As a result, the soils are often acidic, which advances the breakdown of bone tissue. (Tattari and Rekolainen 2006; Ebbing and Gammon 2013: 326; Spellman 2009: 50; Gordon and Buikstra 1981). Furthermore, in contrast to the usual archaeological human remains, mummification of the soft-tissues preserves the skeletal elements in correct articulation.

2 Research of the burials beneath the Northern Finnish churches

We have recently re-inventoried the burials in the three churches studied in the 1990s. The Kempele old church was built in 1691. Depositing burials under it begun once it was completed and continued until the 1780s (Paavola 1998: 26, 53). The oldest site, Keminmaa old church was built in the early 16th century. Right after this the members of the clergy, and later also other elite, could acquire a burial place under it. The last burials were made there as late as in the turn of the 20th century when the church was no longer in active use. (Hiekkanen 2014: 508; Cajanus 1927: 30; Lempiäinen 1990a; Lempiäinen 1990b; Satokangas 1997, endnotes; Paavola 1997; Paavola 1998: 43, 87, 114). The Haukipudas church, which still is used for regular church services, was built in 1762, after which only five burials were made under it. However, this new church was built to encircle its predecessor from the 1640s. Thus, most of the burials preserved under the current church were originally made beneath the older one. (Koskela 1997; Paavola 1998: 63, 67).

Unfortunately, when comparing the observations of the recent inventories with those of the studies carried out nearly two decades ago, it is obvious that the remains have deteriorated (Paavola 1998: 167; Väre *et al*. 2014). Since their future preservation is uncertain, we initiated a project to help their preservation but also to study them noninvasively before it is too late.

2.1 Computed tomography aiding the study of the 'Church Burials'

Computed tomography (CT) scanning is widely used in the study of mummified human remains (e.g. Lynnerup 2010; Donoghue *et al*. 2011; Panzer, Piombino-Mascali and Zink 2012; Pernter *et al*. 2007; Seiler *et al*. 2013). Thus, we decided to test the method in the study of the naturally formed mummies buried under Finnish churches.

Initially we wanted to learn about the anthropometric measurements and pathological conditions of the mummified remains to gather information about the early modern life for example in terms of health, nutrition and physical activity. Another goal was to study the mummification processes and to save the physical attributes of these remains into a database in digital form. This was not the first time we utilized biomedical imaging methods. For example, pQCT (peripheral quantitative computed tomography) scanning (XCT-960A with software version 5.20; Norland Stratec Medizintechnik GmbH, Birkenfeld, Germany) was previously applied in examination of the mid-site cross-sectional shape, bone distribution and bone mineral density of the radial tuberosity (Junno *et al*. 2011).

2.2 Study of the mummified remains of a 17th century vicar, Nikolaus Rungius

The project to study the 'church burials' was initiated in 2011 when the mummified remains of an early 17th-century Northern Finnish vicar, Nikolaus Rungius, were imaged using a clinical 64-slice CT scanner, Discovery 690 and the scans interpreted the Advantage Windows 4.6 diagnostic software (General Electric Medical Systems, Milwaukee, WI, USA) of Oulu University hospital (Fig. 2). (Niinimäki *et al*. 2011; Väre *et al*. 2011; Väre *et al*., in press).

In 1629, when vicar Rungius died at the age of about 70, his remains were buried under the church of Keminmaa (Vahtola 1997a; 1997b). He still is a well-known local figure thanks to the preserved state of his remains, which have apparently been exhibited to those interested since the 18th century. The current glass-lid coffin is not the original but was built in the 20th century to make the exhibition of the remains easier and safer. (Huurre 1983; Kallinen 1990; Vahtola 1997a). To prevent damage, the remains were transported to the hospital and imaged inside this coffin.

The scans revealed new information concerning both the Vicar's life and the preservation of his remains. External examination already reveals the mummy's right forearm to be missing. The scans further showed that also 6 of 7 cervical vertebrae are absent and the head nearly detached from the body. Also Vicar Rungius' stature was estimated from the scans. At the height of about 176 cm he had been relatively tall for his time. He was clearly also somewhat overweight, (Niinimäki *et al*. 2011; Väre *et al*. 2011) in relation to which a lesion typical for Forestier's disease (DISH) manifested in his thoracic spine. This condition, however, is also connected to male sex and old age, which are both attributes of the vicar. (Forestier and Rotes-

Fig. 2. Vicar Rungius' (c. 1560–1629) rather well-preserved remains were studied in April 2011 utilizing a clinical 64-slice CT scanner, Discovery 690 and Advantage Windows 4.6 diagnostic software. (CT image by J. Niinimäki; photographs by T. Väre)

Querol 1950; Denko, Boja and Moskowitz 1994; Musa *et al*. 2006).

There were other signs of pathological conditions as well, as for instance the anterior portions of the fourth and fifth thoracic vertebrae had collapsed likely as a result of an inflammation in the spine. (Niinimäki *et al*. 2011; Väre *et al*. 2011; Väre *et al*., in press) This type of spinal inflammation may be caused by tuberculosis, (Aufderheide and Rodriquez-Martin 2003: 135; Teo and Peh 2004) which is believed to be the case also here, (Väre *et al*. 2011; Väre *et al*., in press) although also DISH generally predisposes to spinal fractures (Manaster, May and Disler 2013: 272-3; Diederichs *et al*. 2011).

The study of the Vicar's remains still continues. For example, a paper on his diet in the light of his dental conditions, stable isotope analyses and the local diet at the time is forthcoming. Additionally, we will further ponder upon the likelihood of tuberculous infection and aim to estimate the age at death from the CT images using several diagnostic features, such as the pubic symphysis, the sternal ends of the ribs and the auricular surfaces of the ilia.

3 Imaging the infant burials

3.1 Material

The pilot study proved CT imaging to be a useful method in reconstructing life histories in Northern Finland. This

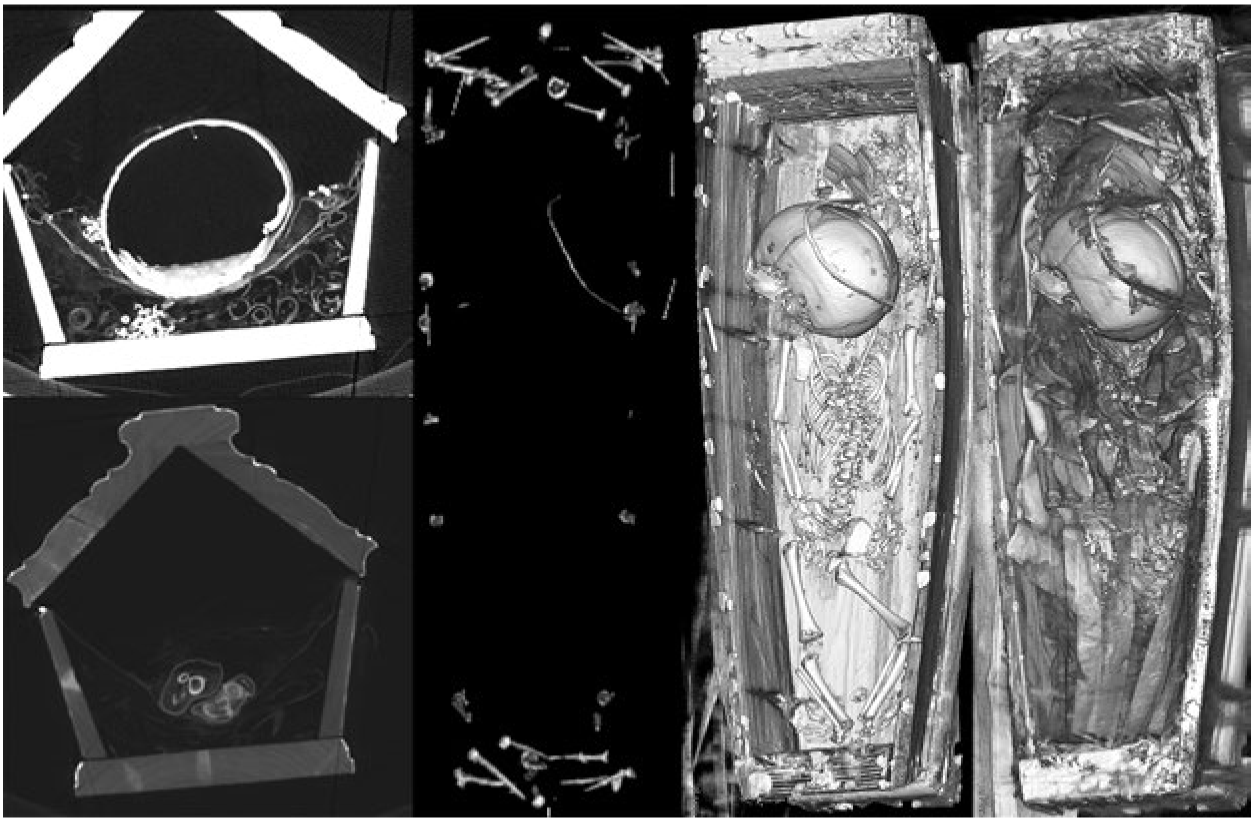

Fig. 3. The scans allow non-invasive examination of the features below the top layers of clothes. The birch-bark-roll stuffing of the mattress and the plant fibres – possibly flax or hay – at the bottom of the coffin are seen in the cross-sectional images (by S. Niinimäki). They also enable determining whether the deceased was dressed in certain garments, such as socks. In the other coffin, depicted from above, the textiles covering the poorly preserved remains of an infant from Keminmaa, as well as the decorations hanging outside the coffin have been attached to the coffin edges with needles and sealing wax. Although covered by textile layers they can be seen once settings are chosen for rendering metals, bones and other denser materials. Then, also the metal spine of the wreath around the head of the deceased is visible. (Images by S. Niinimäki and J. Niinimäki)

encouraged us to proceed with similar studies of other mummified remains. So far, seven coffins of infants have been imaged with an updated hardware, a 2x128-slice dual-energy CT scanner, Somatom Definition Flash, (Siemens Healthcare, Erlangen, Germany and Syngo.via) and interpreted using OsiriX Imaging Software for clinical use.

Four of these infants had been buried under the old church of Keminmaa and three under the Haukipudas church. The preservation of the remains varied from almost completely skeletonized with missing skeletal elements to excellent external soft-tissue mummification. In addition to observing the state of preservation, we were able to approximate their age at death by measuring the long bones (Niinimäki *et al*., manuscript).

Moreover, the method of CT scanning allowed us to perform repeated 3-dimentional, layer-by-layer dissections, not only to the human remains, but also to any other material within the sealed coffins. To begin with, the most obvious advantage of the method is that it allows a peek inside any closed entity – in this case a coffin – without prying it open. However, as most of the studied coffins had been re-opened at some point after the burial, we did have the benefit of being able to examine both the opened coffins, as well as the CT scans of them. If anything, this reassured us of the applicability of the method in not only the study of the human remains, but also all the other material associated with the burial. By adjusting the window level and width the CT scanned material can be rendered into 2D and 3D images according to differences in densities. This allows rough differentiation between materials. Hence, it may – to an extent – be possible to manage a rather thorough study exclusively by CT imaging. Moreover, the obtained images reveal whether further, perhaps more invasive, studies are in place.

3.2 Study of funerary textiles and decoration utilizing computed tomography imaging

In terms of textile studies, the CT scans enable non-invasive reconstruction of several elements of both the padding and clothing within the coffin (Lipkin *et al*. 2015). Perhaps the greatest advantage is that we can actually examine the whole funerary attire without removing any cover textile layers. In addition, needles and metal frames of decorations such as headdresses and flower bouquets can be recognised and their structure examined. Even when the coffin is open the scans allow non-invasive examination of the features below the top layers of clothes. For instance, the stuffing of the mattress at the bottom of the coffin can be assessed through the scans. Otherwise, access to these fillings would require destroying

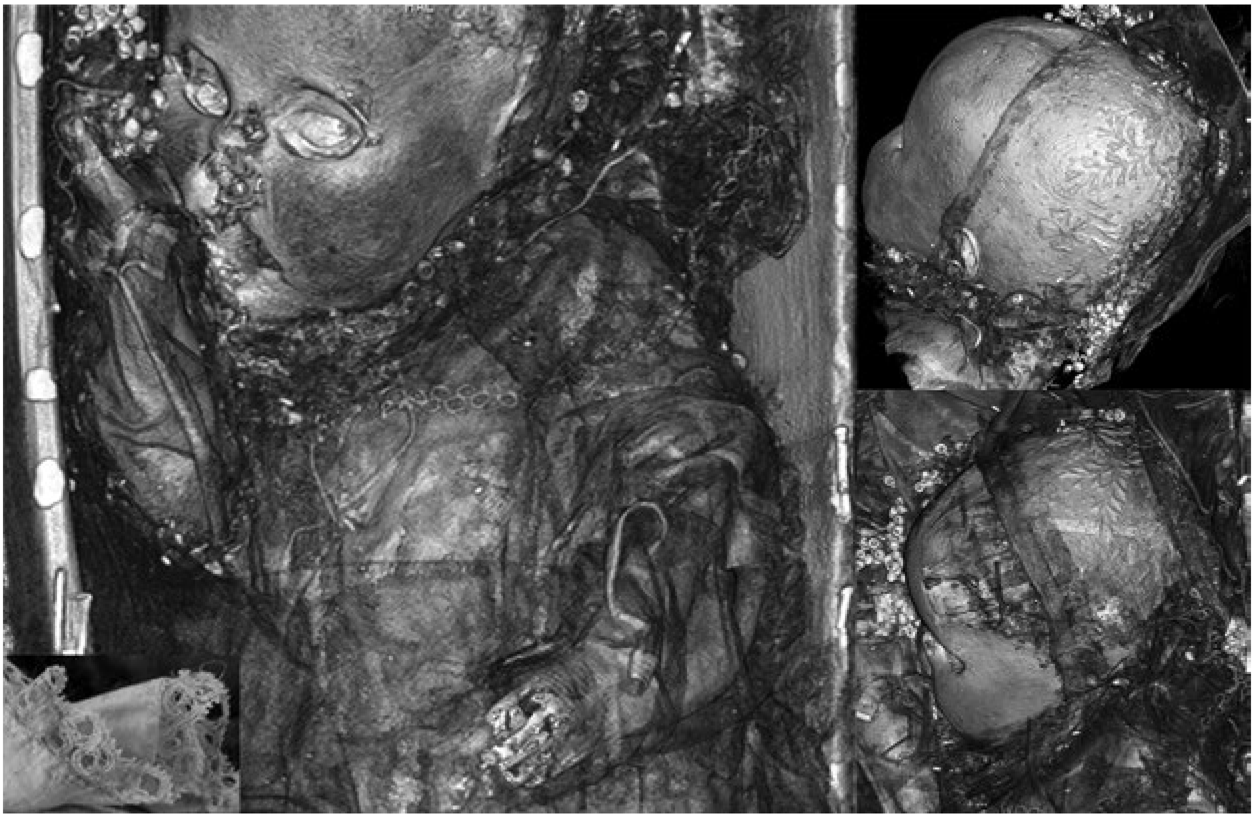

Fig. 4. The scans revealed that rather than real clothes the funerary garments of this well-preserved infant mummy from Keminmaa were pieces of textile stitched to resemble proper attire. Separating textiles of different densities becomes possible by altering the window level and width. This way the decorations such as the embellishment of the edge of this pillow case and flower ornaments on the cap worn by the deceased can be studied. (Photograph by S. Lipkin; CT image by J. Niinimäki and S. Niinimäki)

the burial. Furthermore, it is possible to determine the type of garments and the amount of clothing layers on or under the deceased without disturbing the entity. As adjusting the image makes the materials of different densities visible, the various textiles as well as structures of other decorations of the burial can be visualized (Fig. 3).

Even the seams of clothes can be seen in the scans. Thus, it is for example possible to tell whether the funerary garments are real clothes – or merely pieces of textile fashioned to remind proper attire by utilizing needles and rough stitches (Fig. 4).

CT images have been used in few previous studies of ancient textiles (e.g. Taylor 2004; Peek and Nowak-Böck 2007). Textiles are often almost completely absent in the archaeological material. Therefore the availability of these well-preserved 'church burials' and their CT scans has already changed our understanding of the local burial customs and the interpretation of the early modern textile materials. Thus, further development of this methodology in textile studies is one important aim of our project.

In Finland, abundant grave goods have been uncommon during the Christian period. Nevertheless, especially from the 18th century onwards, in some occasions additional objects may be present in the graves (Valk 1994). In one particular case a wooden doll with a stylized face and a simple dress was placed in the coffin of one of the infants in Haukipudas Church (Fig. 5).

As a curiosity, the burial in question dates to the first half of the 18th century. The inscription inside the coffin lid allowed tracing further information from the archives. The church records revealed that this infant boy was born in the end of October, died in November less than a month later and was buried almost 2 weeks after this. Although these remains have not preserved especially well, the winter temperatures ensured some soft-tissue mummification. The doll described above, however, was necessarily not originally part of this burial but belonged in some other coffin of an infant buried in the same church. Unfortunately, in which coffin, has already been forgotten (Tikkala 1997).

3.3 The coffins and computed tomography imaging

CT scanning may also be used in dating wooden material related to the burials. The scans reveal the growth rings of the coffin planks, which can be measured (Fig. 6). This dendrochronological method is based on the annual tree-ring growth of coniferous and deciduous tree species. Any wooden object containing minimum of 40 tree-rings can be dated by comparing its tree-ring width measurements to those of the regional absolute tree-ring calendar with known dating.

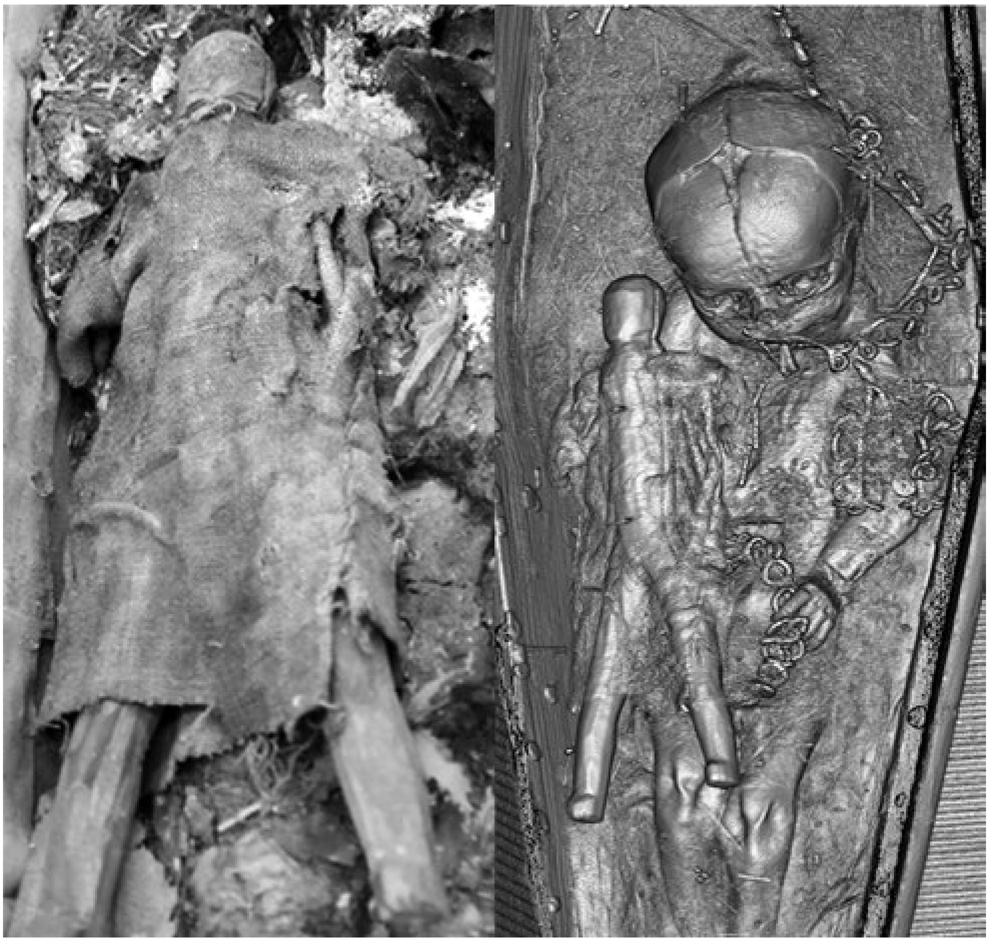

Fig. 5. This infant in the Haukipudas church could be identified due to the obituary of the inner lid of his coffin and the church registers in the Swedish Kingdom. The simplified wooden doll has probably been placed in the coffin secondarily. (Photograph by T. Kallio-Seppä; CT image by J. Niinimäki)

Usually the tree-ring widths are measured by taking either a cross-section or drilled sample from the object of interest. In archaeological contexts this is naturally problematic as sampling damages the artefacts. Although measuring the tree-rings from the object's surface can be done, it requires an access to a laboratory with the needed equipment. Here the CT scanning can help the process and this dating method has been studied in connection to CT scans since the 1980s (e.g. Onoe *et al*. 1984; Preuss, Christensen and Peters 1991; Grabner, Salaberger and Okochi 2009).

Unfortunately, in the case of the material in the church graves, there is the problem of the absence of the outermost rings, which could be tied to an exact calendar year of felling. Lack of the outermost growth rings always means that an otherwise successful dating only gives a rough estimate of the earliest possible felling date after which the wooden material must have been cut and the coffin built (cf. Taft *et al*. 2000). In addition, some coffins have been provided with the death dates, and thus, can be tied to the burial registers of the churches. However, there is also the possibility that the planks and coffins have been recycle or reused, as was often the case at the time (Paavola 1998: 140, 156). However, being able to date the coffins would help us to better understand the changes in burial traditions, and for instance, aid the study of temporal variation in coffin types, funeral clothes and other funerary decorations, but also the custom to reuse the coffins.

CT images also aid studying how the coffins were constructed. For example, they reveal usage of iron nails as well as other – perhaps hidden – structures and building solutions. The scans also allow the precise drawing of coffin cross-sections, which can be useful in the study of the coffin types and styles.

3.4 Considerations of preservation state of the remains

We detected several signs of rodent activity in the base floors of the churches. Alarmingly, also droppings of vole and mouse, and even lairs and food storages of these animals were identified beneath the churches and also inside the coffins and the remains. These signs had been less abundant in the 1990s although some damages by rodents and other animals have been reported also earlier (Minutes of the Bishop's visitations - 17 September 1892, The Collection of the Diocesan Chapter of the Diocese of Oulu Eb: 32, OMA; Paavola 1998: 167). In any case, increase in such activity suggests an urgent demand for digital documentation of the burials.

Fig. 6. The growth rings are visible in these CT scans of the coffins. In spite of some clear problems, dendrochronology may aid dating some of the coffins through the scans. With certain limitation, this would be helpful in the study of the temporal changes in funerary customs. (CT image by J. Niinimäki)

Round radiopaque particles can be seen abundantly in the scans (Fig. 7). They are remnants of seeds. Under microscope, they could be determined as bird cherry seeds with rodent bite marks. Although identifying the plant species requires more invasive methods, some seeds are recognisable by form, and the scans enable their identification to genus.

The scans may also reveal whether a proper macrofossil study should be conducted. It should be noted that the plants or parts of them have sometimes been placed in coffins deliberately as a part of the funerary decoration. CT scanning also enables observations concerning such features in the burials.

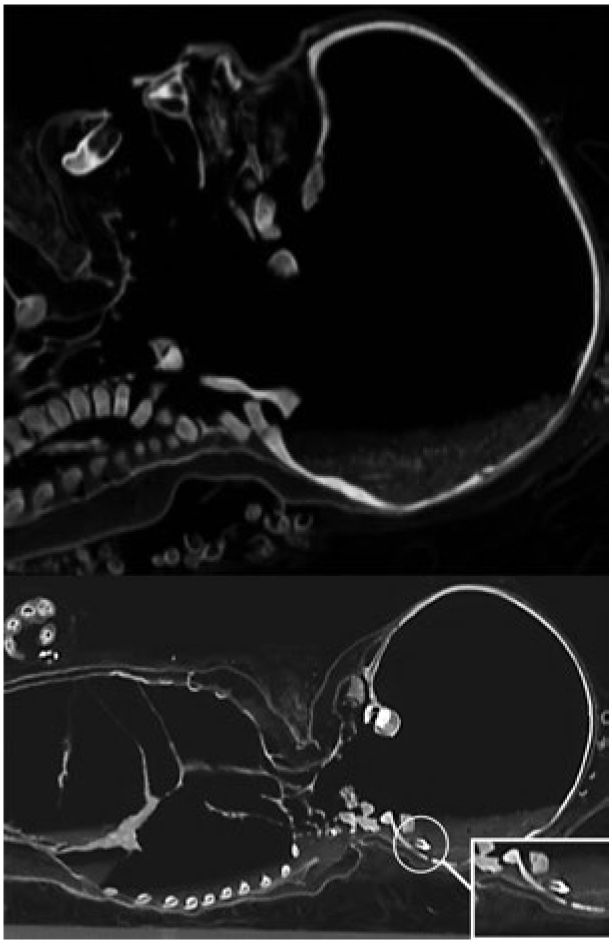

Fig. 7. The CT images revealed that the mouth of this mummy has functioned as an entrance to the lair inside the cranium. This has disturbed the skeletal structures and for example a tooth is seen among the material brought by rodents. (CT image by J. Niinimäki)

4 Conclusion and future research

The project to utilize CT scanning to study the mummies found in old Northern Finnish churches has produced new information about their preservation. We, for instance, revealed that most cervical vertebrae of Vicar Rungius are missing and that there are rather extensive signs of rodent activity inside both the vicar's and the infants' remains. In addition, we were able to conclude about the Vicar Rungius' body size as well as about his health. He was a relatively large man who had suffered from some age- and overweight-related conditions but likely also from more severe health problems, as indications of tuberculosis were found.

Examination of the textiles and decorations related to the infant burials have also revealed information about the funerary attires and practices in the Early Modern Northern Finland. Although in most cases we were able to open the coffin lids for an ocular estimation the examination was otherwise non-invasive. Thus, without the CT scans we could not have detected details such as the socks hidden below the top layers of cloths. As adjusting the images visualize materials of different densities, were could also determine that the funerary garments were mainly made of pieces of textile, which were then fashioned to resemble proper clothes.

In essence, despite of some of its shortcomings, CT examination functions as a virtual, repeatable, non-invasive excavation of the burials found beneath the old Finnish churches. In general, the method is helpful when invasive studies are out of question as it can – to an extent – replace some other methods of information gathering.

However, methods, such as stable isotope analyses, are also being applied to study the Finnish mummified remains. They provide information on the individuals' diets, which can be checked against possible nutrition related pathological features in the scans. For example, the stable isotope ratios indicated that vicar Rungius' diet mainly consisted of foodstuffs of animal origin, which agrees with the presence of DISH. We are also monitoring the humidity and temperature in the three inventoried churches for two years in order to collect information about the environments beneath the churches and the processes affecting the mummification and preservation of the remains.

Bibliography

Aufderheide, A. C. and Rodriquez-Martin, C. 2003. *The Cambridge Encyclopedia of Human Paleopathology*. Cambridge, Cambridge University Press.

Cajanus, K.I. 1927. *Piirteitä Kemin maaseurakunnan kirkkojen historiasta*. Tornio.

Coaccioli, S., Fatati, G., Di Cato, L., Marioli, D., Patucchi, E., Pizzuti, C., Ponteggia, M., Puxeddu, A. 2000. Diffuse idiopathic skeletal hyperostosis in diabetes mellitus, impaired glucose tolerance and obesity. *Panminerva Medica* 42 (4): 247–51.

Denko, C.W., Boja, B., Moskowitz, R. W. 1994. Growth promoting peptides in osteoarthritis and diffuse idiopathic skeletal hyperostosis–insulin, insulin-like growth factor-I, growth hormone. *The Journal of Rheumatology* 2: 1725–30.

Diederichs, G., Engelken, F., Marshall, L. M., Peters, K., Black D. M., Issever, A. S., Barrett-Connor, E., Orwoll, E., Hamm, B. Link, T. M. 2011. Diffuse idiopathic skeletal hyperostosis (DISH): relation to vertebral fractures and bone density. Osteoporos International 22, 6: 1789-97.

Donoghue, H. D., Pap, I., Szikossy, I. Spigelman, M. 2011. Detection and characterization of Mycobacterium tuberculosis DNA in 18th century Hungarians with pulmonary and extrapulmonary tuberculosis. *Yearbook of Mummy Studies* 1: 51–6.

Ebbing, D., Gammon, S. D. 2013. *General Chemistry*. Belmont, Cengage Learning.

Forestier, J. and Rotes-Querol, J. 1950. Senile ankylosing hyperostosis of the spine. *Annals of the Rheumatic Diseases* 9: 321-30.

Gordon, C. C. and Buikstra, J. E. 1981. Soil pH, Bone Preservation, and Sampling Bias at Mortuary Sites. *American Antiquity* 46, 3: 566–71.

Grabner, M., Salaberger, D., Okochi, T. 2009. The Need of High Resolution μ-X-ray CT in Dendrochronology and in Wood Identification. *Proceedings of the 6th International Symposium on Image and Signal Processing and Analysis:* 349–52.

Junno, J. A., Niinimäki, S., Niskanen, M., Núñez, M., Tuukkanen, J. 2011. Cross sectional properties of the human radial tuberosity. *Homo* 62, 6: 459–65.

Kiss, C., Szilágyi, M., Paksy, A., Poór, G. 2002. Risk factors for diffuse idiopathic skeletal hyperostosis: a case–control study. *Rheumatology* 41: 27–30.

Koskela, T. 1997. Haukiputaan kirkkohautojen dokumentointia ja kirkon historiaa. In J. Alakärppä and K. Paavola (eds.), *Meteli: Haukiputaan kirkkohaudat* 13: 7–12. Oulu, University of Oulu.

Lempiäinen, P. 1990a. Hautausmaaperinteen rikkaus. In P. Lempiäinen and B. Nickels (eds.), *Viimeiset leposijamme. Hautausmaat ja hautamuistomerkit:* 6–20. Helsinki.

Lempiäinen, P. 1990b. Hautausmaidemme suunnittelu ja hoito. In P. Lempiäinen and B. Nickels (eds.), *Viimeiset leposijamme. Hautausmaat ja hautamuistomerkit*: 68–74. Helsinki.

Lipkin, S., Vajanto, K., Kallio-Seppä, T., Kuokkanen, T., Niinimäki, S, Väre, T., van Bommel, M. 2015. Funeral dress and textiles in 17th and 19th century burials in Ostrobothnia, Finland. In K. Grömer (ed.), *Proceeding of the XII NESAT Conference at Hallstatt, 2014*: 141–153.

Lynnerup, N. 2010. Medical Imaging of Mummies and Bog Bodies – A Mini-Review. *Gerontology* 56: 441–8.

Macko, S. A., Engel, M. H., Andrusevich, V., Lubec, G., O'Connell, T. C., Hedges, R. E. 1999. Documenting the diet in ancient human populations through stable isotope analysis of hair. *Philosophical transactions of the Royal Society of London, Series B, Biological sciences* 354, 1379: 65–76.

Manaster, B. J., May, D. A., Disler, D. G. 2013. *Musculoskeletal Imaging: The Requisites*. Philadelphia, Elsevier.

Musa, A. K. M., Nazimuddin, K., Huq, S. A., Sarker, R. S. C., Ahmed, A. K. M. S. 2006. Rheumatic disorders and bone problems in diabetes mellitus. *The ORION Medical Journal* 23: 344–6.

Niinimäki, S., Heikkilä, T., Niinimäki, J., Niskanen, M., Núñez, M., Junno, J. A. 2011. Rungiuksen muumion osteoantropologinen tutkimus. In J. Ikäheimo, R. Nurmi, R. Satokangas (eds.), *Harmaata näkyvissä – Kirsti Paavolan juhlakirja*: 265–74. Vaasa, Waasa Graphics.

Niinimäki, S., Vilkama, R., Väre, T., Niinimäki, J., Junno, J. A., Kallio-Seppä, T., Heino, M., Lipkin, S., Núñez, M., Tranberg, A., Tuovinen, S., Ylimaunu, T., Niskanen, M. (manuscript), Life and health of children at Keminmaa during the 19th century - a computed tomography study. *Values of Childhood and Childhood studies, 7–9 May 2014,* Oulu.

Núñez, M., Paavola, K., García-Guixe, E. 2008. Mummies in northern Finland. In P. Atoche Peña, C. Rodgues Martin, M. Ángeles Ramírez Rodríquez (eds.), *Mummies and Science, World Mummies Research, Proceedings of the VI Wold Congress on Mummy Studies*: 123–8. Teguise, Lanzarote.

Ojalatva, E. 1997. Haukiputaan kirkkohautojen dokumentointia ja kirkon historiaa. In J. Alakärppä and K. Paavola (eds.), *Meteli: Haukiputaan kirkkohaudat* 13: 1–6. Oulu, University of Oulu.

Olsson, M. 1956. *Vasagraven i Uppsala domkyrka: historiska, konst- och kulturhistoriska samt medicinska och antropologiska undersökningar*. Stockholm, Nordisk rotogravyr.

OMA (The Provincial Archives of Oulu), Oulun hiippakunnan tuomiokapitulin arkisto (The Collection of the Diocesan Chapter of the Diocese of Oulu) Eb: 32, Piispantarkastuksenpöytäkirjat (Minutes of the Bishop's visitations) 1862 – 1978: 14–17.9.1892.

Onoe, M., Tsao, J. W., Yamada, H., Nakamura, H., Kogure, J., Kawamura, H., Yoshimatsu, M. 1984. Computed tomography for measuring the annual rings of a live tree. *Nuclear Instruments and Methods in Physics Research* 221, 1: 213–20.

Paavola, K. 1997. Keminmaan vanhan kirkon hautojen tutkimus, In E. Ojalatva and K. Paavola (eds.), *Keminmaan kirkkohaudat*: 1–5. Oulu, University of Oulu.

Paavola, K. 1998. *Kepeät mullat – Kirjallisiin ja esineellisiin lähteisiin perustuva tutkimus Pohjois-Pohjanmaan rannikon kirkkohaudoista*. Oulu, University of Oulu.

Panzer, S., Piombino-Mascali, D., Zink, A. R. 2012. Herniation pits in human mummies: a CT investigation in the Capuchin Catacombs of Palermo, Sicily. *PLoS ONE*. 7, 5. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0036537. [Accessed: 3 May 2015].

Peek, C. U. and Nowak-Böck, B. 2007. 3D – Computertomographie – Neue Möglichkeiten zur Untersuchung archäologischer Textilien. *NESAT IX. Archäologische Textilfunde – Archaeological Textiles*: 79–85. Ennenda, ArcheoTex.

Pernter, P., Gostner, P., Egarter Vigl, E., Rühli, F. J. 2007. Radiologic proof for the Iceman's cause of death (ca. 5'300 BP). *Journal of Archaeological Science* 34: 1784–6.

Preuss, P., Christensen, K., Peters, K. 1991. The use of computer-tomographical X-ray scanning in dendrochronology. *Norwegian Archaeological Review* 24, 2: 123–30.

Reimers, P., Riederer, J., Goebbels, J., Kettschau, A. 1989. Dendrochronology by means of x-ray computed tomography. In Y. Maniatis (ed.), *Archaeometry: proceedings of the 25th international symposium*: 121–5. Amsterdam, Elsevier Science Publisher.

Resnick, D. and Niwayama, G. 1976. Radiographic and Pathologic Features of Spinal Involvement in Diffuse Idiopathic Skeletal Hyperostosis (DISH). *Radiology* 119: 559–68.

Satokangas, R. 1997. Nousun aika (1721–1859). In R. Satokangas (ed.), *Keminmaan historia*: 178–248, endnotes 599–600. Keminmaa.

Seiler, R., Spielman, A. I., Zink, A., Rühli, F. 2013. Oral pathologies of the Neolithic Iceman, c. 3300 BC. *European Journal of Oral Sciences* 121: 137–41.

Spellman, F. R. 2009. *Geology for Nongeologists*. Plymouth.

Taft, W. S., Mayer, J. W., Newman, R., Kuniholm, P. I., Stulik, D. 2000. Dendrochronology (Tree-Ring Dating) of Panel Paintings. In W. S. Taft and J. W. Mayer (eds.), *The Science of Paintings*: 206–15. New York, Springer-Verlag.

Talve, I. 1988. Kalmisto – hautausmaa – kirkkotarha. In M. Taipale (ed.), *Elämän merkit. Turun arkkihiippakunta. Vuosikirja XXXVIII*: 55–75. Loimaa.

Tattari, S. and Rekolainen, S. 2006. Finland. In J. Boardman and J. Poesen (eds.), *Soil Erosion in Europe*: 27–34. Chichester, John Wiley and Sons, Ltd.

Taylor, J. H. 2004. *Mummy: the inside story*. London, Harry N. Abrams.

Teo, H. E. L. and Peh, W. C. G. 2004. Skeletal tuberculosis in children. *Pediatric Radiology* 34: 853–60.

Tikkala, E. 1997. Haukiputaan kirkon multahaudat. In J. Alakärppä and K. Paavola (eds.), *Meteli: Haukiputaan kirkkohaudat* 13: 19–24. Oulu, University of Oulu.

Vahtola, J. 1997a. Vaikea vuosisata (1601–1721). In R. Satokangas (ed.), *Keminmaan historia*: 151–174. Keminmaa.

Vahtola, J. 1997b. Rungius, Nicolaus (noin 1560 - 1629). *Kansallisbiografia-verkkojulkaisu 16.9.1997*. Helsinki, Finnish Literature Society. Available from: http://www.kansallisbiografia.fi/kb/artikkeli/463/. [Accessed: 3 May 2015]

Valk, H. 1994. Neighbouring But Distant: Rural Burial Traditions of Estonia and Finland During the Christian Period. *Fennoscandia archaeologica* 11: 61–76.

Väre, T., Niinimäki, S., Junno, J. A., Niinimäki, J., Niskanen, M., Núñez, M. 2011. Computed tomography in aid of osteoarchaeology – a case study of mummified remains of Vicar Nikolaus Rungius. *Fennoscandia Archaeologica* 27: 85–8.

Väre, T., Heino, M., Junno, J. A., Lipkin, S., Niinimäki, J., Niinimäki, S., Niskanen, M., Núñez, M., Tranberg, A., Tuovinen, S., Vilkama, R., Ylimaunu, T. Kallio-Seppä, T. 2014. Kempeleen ja Keminmaan vanhojen kirkkojen muumiot. *Muinaistutkija* 1: 17–32.

Väre, T., Junno, J. A., Niinimäki, J., Niskanen, M., Niinimäki, S., Núñez, M., Tuukkanen, J., Tranberg, A., Heino, M., Lipkin, S., Tuovinen, S., Vilkama, R., Ylimaunu, T., Kallio-Seppä, T. 2015 (in press), Computed Tomography of Mummified Human Remains in Old Finnish Churches. A Case Study: Mummified Remains of 17th Century Vicar Revisited. *Post-Medieval Archaeology*.

Palaeoenvironmental Records and Php Possibilities: Results and Perspectives on an Online Bioarcheological Database

Enora Maguet
enora.maguet@gmail.com

Jean-Baptiste Barreau
jean-baptiste.barreau@univ-rennes1.fr

Chantal Leroyer
chantal.leroyer@univ-rennes1.fr

UMR 6566 CREAaH, Université de Rennes 1, France

Abstract: ABCData project is an online bioarchaeological database, that essentially gathers palynological and anthracological data. This relational database was built using a framework (FuelPHP), and the different interfaces and applications were all developed through computer programming, using several languages and open access libraries. In particular, we developed a palynological query interface associated to a SVG graphics generation tool. We tested ABCData's functioning through the integration and the analysis of numerous palynological cores that had already been studied with a different method. This study revealed a great accordance between the two methods, and highlighted some bias and the necessity of permanently watching over of the statistic distribution of the samples.

Keywords: Database, Programming, Palaeoenvironment, Interdisciplinary, PHP

Introduction

Over the last few years, palaeoenvironmental matters have been more systematically integrated to archaeological questions. The difficulties that are inherent to these multiproxy studies lead us to attach a prior attention to the IT management of a huge data corpus, which gather several disciplines and set numerous problems of storing, safeguarding, using and standardizing this complex information.

In the national and European context, there are many projects (GDRE Bioarch, ANR Bioarchéodat) and databases (Arbodat, I2AF, European Pollen Database) whose main objective is to enable the data collection, comparison and overview through a normalized frame of reference and appropriate computer-based tools. All these bases, if meant to coexist and enrich each other, must allow collaboration and must be fully compatible or interoperable. Such aspect is perhaps the biggest difficulty and one of the main concerns databases creators and administrators have to deal with.

Nevertheless, these projects mostly concern anthracology, carpology and archaeozoology. As a consequence, palynological data is often treated separately since its applications are out of the field of archaeology. It is also challenging to handle these data because of the difficulties linked to the chronological assignment of samples, the amount of data required to interpret the results, the differences between the sequences in terms of preservation and level of taxinomical identification, as well as the conditions which affect the archaeological site (Reille 1990).

Our project ABCData (Archaeology, Biodiversity, Chronology Data) focused on creating a tool for the input, the visualisation and the use of paleobotanical data which works in consonance with the specificities of this discipline. In order to overcome the difficulty of using a local software program, we transferred the data to a server, and we built a website (http://archeosciences-abcdata.osuris.org) which handles all the functionalities of the database. The start of the programming work used an open framework (FuelPHP 5.3) to develop the interface basic tools. This database was then fully programmed with different languages (php, javascript, html, css) and different libraries in open access gives. As a result, it is a very flexible tool which fits well the needs of paleoenvironmental disciplines, helping us to explore new possibilities in terms of analysis and graphic visualisation of results. Thus, one of the major aspects of this project is the setting of a query interface (for the time being, the interface deals only with palynological input) which allows us to conduct both synthetic and parametric approaches of the integrated data. A graphic displaying tool and a library (PHPExcel) which enables importing and exporting results under a spreadsheet are also related to the query interface.

The final phase was devoted to a series of analyses of the palynological content of 43 sedimentary cores from the Paris Basin, in order to compare ABCData performances to the synthetic history of the basin vegetation set on the empirical merging of the same data, since the late Epipaleolithic times (Leroyer 1997).

1 Database creation

ABCData's functioning relies on the existence of two complementary interfaces: an administrator interface handled by PhpPgadmin, and a user interface, resulting from our programming work. The putting on line of the database has therefore taken place in several steps. First we designed the

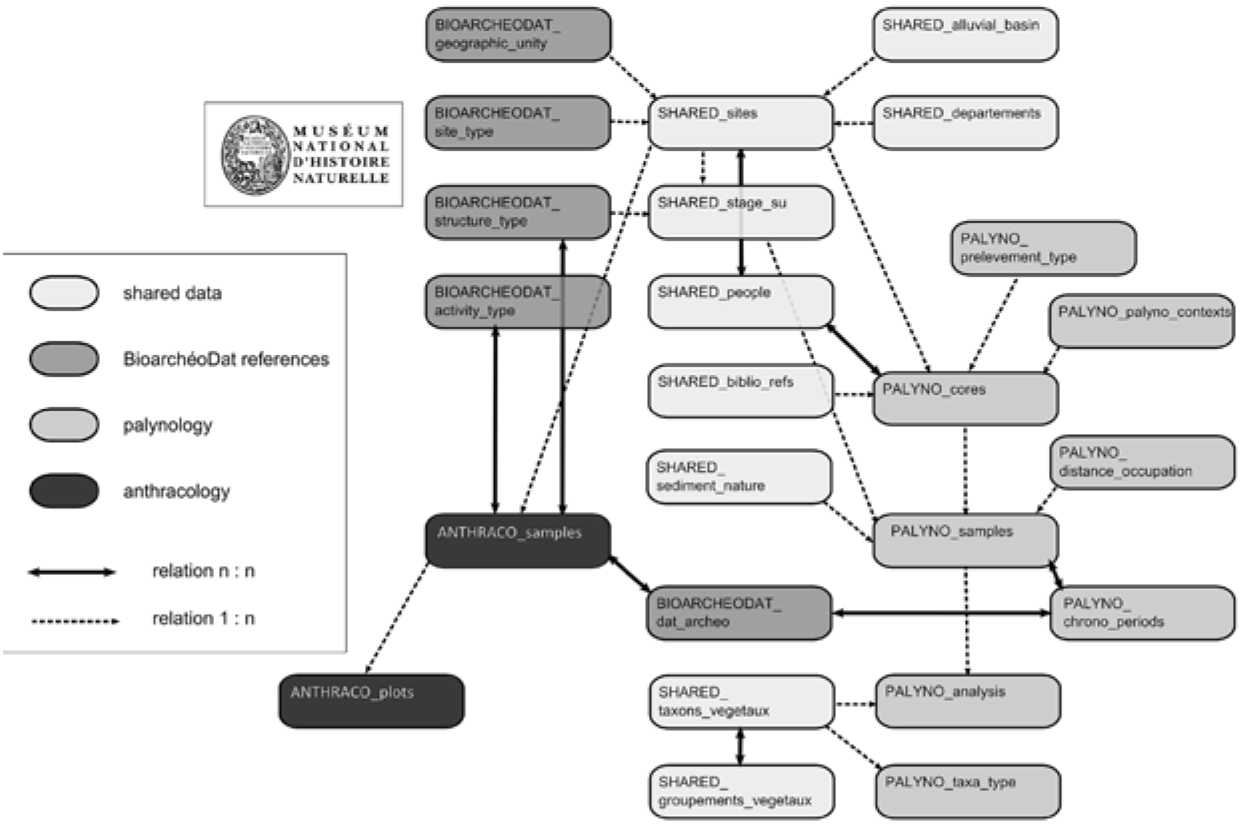

Fig. 1. ABCData's relational architecture.

structures of the tables and the nature of the links between them, then we had to create these tables in PhpPgadmin, to translate this architecture within the source files, and finally to program all the ABCData's specific functionalities.

1.1 Data architecture

Fundamentally the data dealt through ABCData aim to quantify the taxa occurrences (only botanical taxa for the moment) in the analysed samples, while preserving all information liable to enlighten this analyse such as dating, evaluation of the preservation quality, analysis methods or archaeological context.

It is particularly essential to use common and normalized vocabulary in order to carry out analyses on different sequences or different materials. This is one of the advantages of using permanent tables (Kreuz and Shafer 2002), which help to standardize input and exclude redundancies. All the data shared by several elements must appear in one same table in order to avoid as far as possible the redundant elements. ABCData is therefore composed by a large number of tables (Fig. 1) belonging to four categories identified with a prefix: the specific data about anthracology, the specific data about palynology, the data belonging to the different disciplines and the permanent data issuing from Bioarcheodat project frame references. Each table includes an identifying field on which weighs a uniqueness obligation and which is automatically filled by the sequence associated to the table. The n-n (or many to many) relation type are expressed within specific tables. It constitutes an adapted answer to situations where a record can be associated to different values of the same attribute, and these attribute values associated to several records.

The organisation of palynological data, widely inherited from the already developed SGBDR (Maguet 2013), has nevertheless gone through many modifications, for it was absolutely necessary to take into account the interoperability with other SGBD and the compatibility with anthracological data. The table corresponding to botanical taxa was conceived in order to deal with problems caused by the differences in the resolution level of taxa determination, both between palynology and anthracology, and between several sequences of pollen or charcoal. Indeed, many parameters may influence upon the degree of precision of these determinations, such as material preservation, microscope performances or the analyst's own sensibility (Maguet 2014). It therefore contains a field 'name' which corresponds to the most common degree of determination, and a field 'precision' which allows the user to indicate additional information when a more precise degree of determination is possible.

1.2 Data integration into PhpPgadmin

The administrator interface PhpPgadmin, which works with PostgreSQL, allows us to create, to define, to update and delete the different tables and their fields. The link between these tables relies on the existence of primary keys ('id') that are absolutely unique and automatically incremented using numerical sequences. The use of a relational model had already

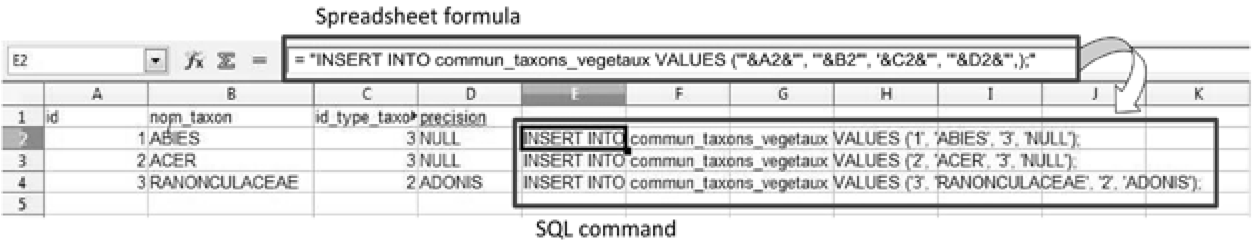

Fig. 2. Spreadsheet formula and SQL commands.

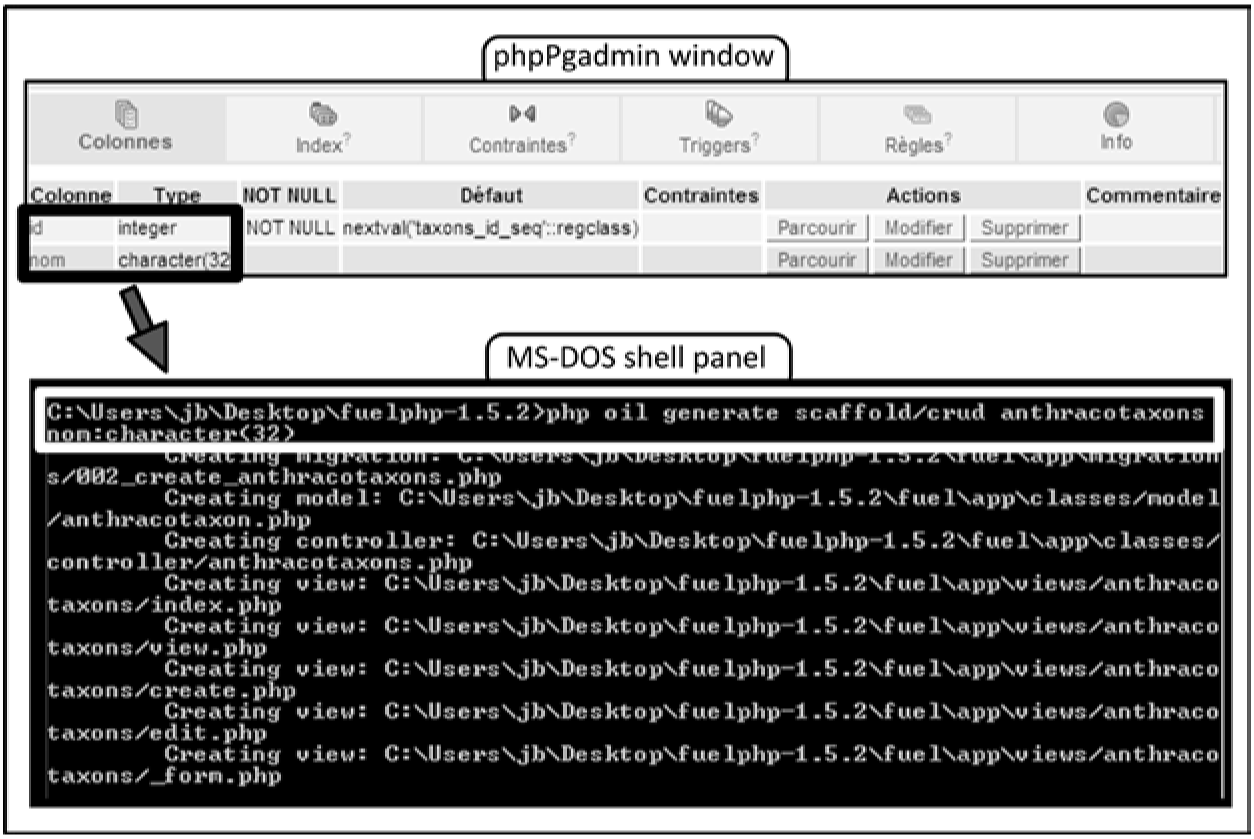

Fig. 3. MS-DOS files generating process.

been recommended and the functioning widely described by Tomlinson (1993), when he created an archaeobotanical database on British and Irish datasets. He particularly insisted on the fact that this relational model is based on the creation of independent tables in which every line must be different and identified by a primary key that should preferably be a numeric element.

In phpPgadmin, you can input your data directly, but generally it is more convenient to use SQL commands which correspond to the updating commands (INSERT, UPDATE, and DELETE) (Fig. 2). Using these commands, the integration of data from spreadsheets goes very fast.

1.3 Creation of the source files

The creation of the CRUD (Create, Read, Update, Delete) source files was realized thanks to a web open-source framework called FuelPHP. This framework follows the HMVC (Hierarchical Model View Controler) architecture. This technology ensures the possibility to generate automatically the source files when their architecture is widely repeated, as well as writing the code which corresponds to the major functions from the CRUD. This first step is realized through the MS DOS Shell (Fig. 3), and allows us to have, for each table of phpPgadmin, different source files: a controller, a model, and a set of five different views (index, view, _form, create, edit). In the controller, there are different functions that are associated to each view, and who define and compute every variable that is called in the view files.

Mostly, these variables rely on the data from the phpPgadmin interface, and it is the model that ensures the link between these data and the controller (Fig. 4). The variables often correspond to associative tables, called 'arrays', which means that they are composed by the association of a key to a set of different values

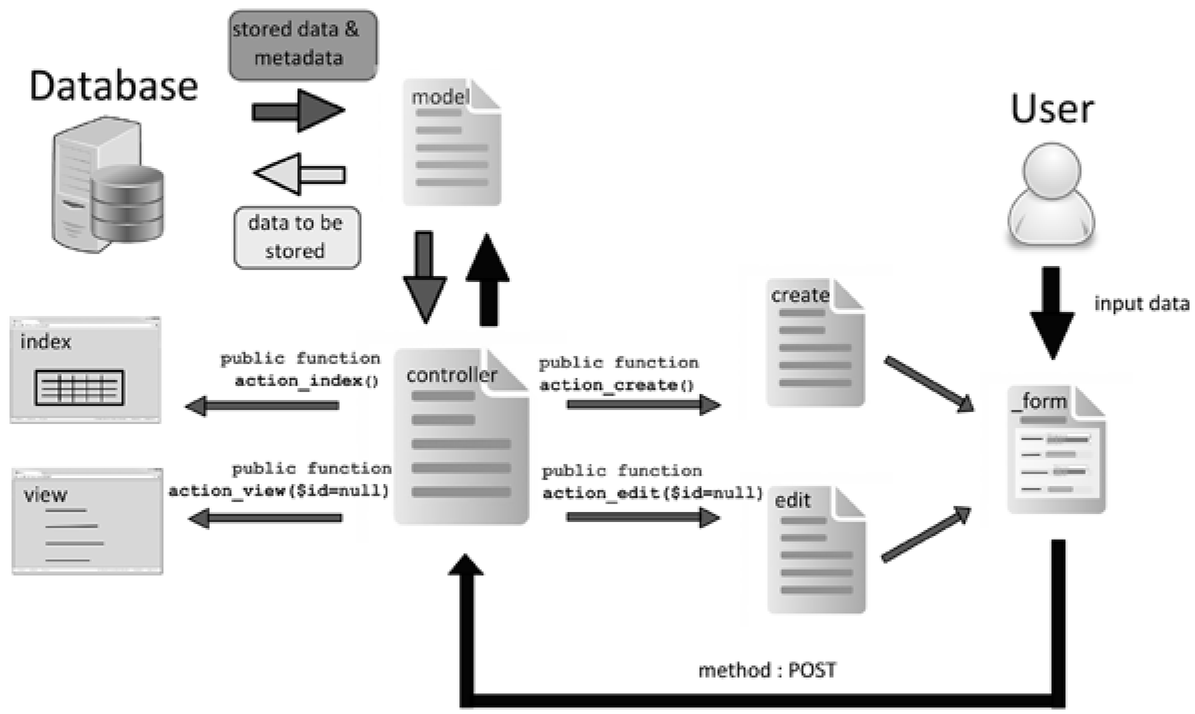

Fig. 4. Relations between the different source files, the base and the user.

or attributes. Again, this attribute can also be an array, which is nested within the first one. This interlocking of data constitutes an essential point concerning php data management. To access the different levels and values, you can use the square bracket based syntax when the loop system allows you to browse every line of a given array (Fig. 5).

All these source files must be then transferred on the server using a FTP client such as FileZilla. After that, they can be updated through a code source editor (such as Notepad ++), connected to the FTP server.

2 Development of tools

We were able to work on an interface which met our needs in terms of display, input, import/export, queries and even security, from the files generated by the FuelPHP framework and thanks to different programming languages. Generally, the structure of the files proposed by the framework imitates the structure of the base, its tables and fields. The interface we seek to construct, however, is different from this architecture so as to answer as efficiently as possible to the users' demands.

Furthermore, we analysed the functionalities of Gpalwin, a program that was adapted to the palynologists' needs (Goeury 1997), and it led us to add more fields. These fields contain information mainly about calculations on the characteristics of samples and profiles in terms of diversity of the pollen content.

2.1 Data import and export: Forms

The use of forms ensures the direct input of the data into the base. Different data types correspond to different field types: Text data will be shown in drop-down lists; numerical data must be provided in numbers whose format is defined in the structure of the table. Another possibility is creating checkboxes for Boolean data. In the forms, the fields correspond mainly to html programming, where data is retrieved from php variables, essentially for displaying drop-down lists (Fig. 6).

[Fig. 6: Relations between different source files while creating form fields]

All data provided by the user will be inserted into the controller through the $_POST variable, and then it will be treated by a function dedicated to saving these values in the corresponding tables. This function submits all provided data to the model of the table in order to verify that the proposed values correspond to the format defined for each field. It the user tries to insert data in a different format, the information will not be saved and an error message will appear.

2.2 Data import and export: PhpExcel

The tools to import and export spreadsheet files have been developed from a PHPExcel 1.8.0 library, which is integrated to the base as a package. It enables reading, writing and creating spreadsheet files under several formats.

For us, it was of vital importance to ensure the possibility to add the provided data directly into other types of support. This functionality is guaranteed for the main tables; secondary tables have a small number of entries. Thus, for the main tables, data can be imported from spreadsheet files through the creation of a visible element (upload), which is associated to an action in the controller (action_upload), and allows the user to affect the columns of the file s/he designed in different fields of the selected table. Another function (uploaded data), is executed as

```
<?php

    //Declaring an array
        $array[] = array('id' => 0, 'value' => 10);
        $array[] = array('id' => 1, 'value' => 20);
        print_r($array);

            //Will display: Array ( [0] => Array ( [id] => 0 [value] => 10 )
                                      [1] => Array ( [id] => 1 [value] => 20 ) )

    //Accessing the values
        $value_0 = $array[0]['value'];
        echo "value of line 0 = ".$value_0;

            //Will display: value of line 0 = 10

    //Creating a loop
        foreach ($array as $line):
            echo "value of pointed line = ".$line['value']."<br>";
        endforeach;

            //Will display:
                // value of pointed line = 10
                // value of pointed line = 20

     //Declaring a variable from the database
            $data['table'] = Model_table::find(array('order_by' => array('id' => 'asc')));


?>
```

Fig. 5. Examples of array management in php.

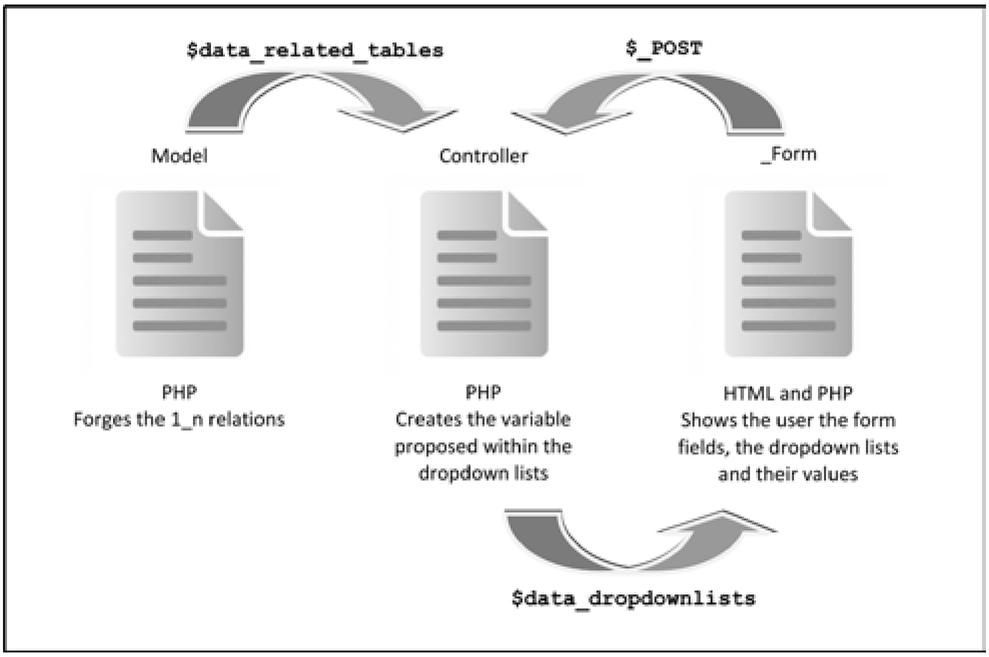

Fig. 6. Relations between different source files while creating form fields.

the visible element is loading. Thanks to the PhpExcel library, this function allows saving the posted file on a temporary location and reading it in order to retrieve the data it contains and to construct a PHP variable (Fig.7a.). Then, for each column identified in the file, the drop-down list of the different table fields will be shown. Once each column has affected a field, the data in each line of the sent file will be compared to the model and then it will be added to the table. There is, nonetheless, an aspect which must be taken into account. The imported file must not contain any empty cell. These must be necessarily replaced by the value 'NULL' in the case of text type fields and '-1' in the case of number type fields.

Likewise, exporting tables under the excel file format goes through the addition of a new visible element (download), controlled by a function (action_download). The variables to be exported are posted from the element which corresponds to their visualisation thanks to a PHP form. This form contains a hidden field which allows sending the variable containing the data in a linear form (thanks to the serialize function). It is

```
<?php
//UPLOAD                    a. upload function code elements

    if(!empty($_FILES))
    {
        //Setting the temporary name and temporary location
            $filename = 'uploaded_file.xlsx';
            $tmp_name = $_FILES["my_file"]["tmp_name"];
            move_uploaded_file($tmp_name, DOCROOT.'assets/files/'.$filename);

        //Uploading the file using the PHPExcel library
            $excel = new PHPExcel();
            $inputFileName = DOCROOT.'assets/files/uploaded_file.xlsx';
            $inputFileType = PHPExcel_IOFactory::identify($inputFileName);
            $objReader = PHPExcel_IOFactory::createReader($inputFileType);
            $objReader->setReadDataOnly(true);
            $objPHPExcel = $objReader->load($inputFileName);
            $sheet = $objPHPExcel->getSheet(0);
    }
//DOWNLOAD                  b. download function code elements

        $objPHPExcel = new PHPExcel();

        $head = array('id', 'label_1', 'label_2', 'label_3');

        //head
            $head_col = 0;
            foreach ($head as $col):
            $objPHPExcel->getSheet()->setCellValueByColumnAndRow($head_col, 1, $col);
            $head_col++;
            endforeach;

        //body
            $body_line = 2;
            foreach ($data['requetes'] as $line):
                $body_col = 0;
                foreach ($line as $cell):
                    $objPHPExcel->getSheet()->setCellValueByColumnAndRow($body_col, $body_line, $cell);
                    $body_col ++;
                endforeach;
                $body_line ++;
            endforeach;

        //Writer
        $objWriter = new PHPExcel_Writer_Excel2007($objPHPExcel);
        $objWriter->save(DOCROOT.'assets/files/downloaded_file.xlsx');
?>
```

Fig. 7. Parts of the upload and download functions code involving the PhPExcel library.

possible then to write the document, to save it on a temporary location and to request its download from a visible element thanks to the functionalities of the library (Fig. 7b.).

2.3 Query interface

The creation of a query interface adapted to palynologist's issues constituted one of the most important goals of the ABCData project. One of the prior concerns about it was to guarantee on one side the possibility to have numerous parameters of queries while being able at a later stage to add some more developments (and especially to include anthracological queries), and on the other side the accuracy of the results. Results have been permanently checked using the local RDBMS query results (Maguet 2013).

To build up this query interface, we added to the original MVC a new set of source files, including new controllers, models and views. Users can select a great amount of parameters to run their queries, then the base computes the results to be displayed, and offers one to download the table or to see the results on the form of a graph.

2.4 Query fields management

The query interface shows the user a list of parameters he can select in order to study the effect of this parameters selection on the global results. The view that manages this selection is deeply associated to a javascript file which handles the interactions between the user and the base (for example with dropdown lists, checkboxes, etc.). All parameters are linked to information available about samples, cores, sites, datings or taxa, or even calculation methods (tab. 1).

2.5 Calculation of the results

The calculation of the results necessitated the creation of a great number of new functions, added to the controller. First of all, all the values corresponding to the selected criteria and all the primary keys of the sample responding to these criteria must be identified and isolated. If the samples must be classified according to their chrono-cultural attribution, a specific function orders these chrono-cultural periods so that they will appear in a consistent way on a temporal axis.

Characteristics of the samples location Alluvial basin Altitude Sediment nature Palynological context (river bed, swamps, archaeological site...) Distance to the nearest archaeological site	**Calculation methods** Vary the taxa excluded from the sum base (i.e. the total number of pollen grains) Express the results in quantity of pollen grains or in % of the sum base Express the results in % of the samples in which the selected taxa are lower or higher to a given quantity. Express the results for each selected taxa or sum the results of all the taxa
Chronological attributions Lower and upper chronological boundaries Chrono-cultural period(s)	**Selection of the taxa** By name By group (heliophytic, ruderals...) By type (woody plants, grass plants, ferns...)
Quality of the samples Preservation rating Diversity Relative diversity	**Clustering queries** By chrono-cultural period(s) By alluvial basin By distance to the nearest archaeological site Palynological context

Tab. 1. Parameters displayed in ABCData's query interface.

The values corresponding to the rate of each plant among each sample is recalculated depending to the sum base parameters, and several functions are in charge of the reliability and representation evaluations.

One of the biggest issues concerning this kind of programming work is to take into account all the values that can be possibly chosen for each parameter. In order to simplify these numerous possibilities management, a specific function was designed, its role is to analyze the chosen parameters list and to build a variable that turns all the parameters into a set of numeral codes. Depending on these codes, the different functions that must be run to compute the results will not be the same for each query.

2.6 Display of the charts

Different kind of graphic representation (Fig. 8) that had to undergo a specific programming phase, are supported by ABCdata. The type of graphic representation known as pollen diagram generally corresponds to the analysis of a sedimentary core in which different samples have been isolated at different depths. But here, the data to be represented are obtained from queries that combine the results of several cores. This does not allow using depth as an axis of the graph. Nevertheless, in many cases, queries show results according to well-defined chronological periods, which can be placed on a time axis. Therefore, values to be shown do not correspond to exact points but to intervals, hence its representation as a histogram. Furthermore, graphics obtained from these queries contain a significantly higher number of taxa than that of a single sequence. The way it is presented on a website, needs an adapted solution. The setting of this tool begins with the creation of a php files group (controller, model, view), associated with a javascript file stored in the */.../public/assets/js* directory. Same as with exporting spreadsheet files, the results of the queries are linearized and sent through a hidden form.

The functions of the controller are designed to define the variables that are later used by the javascript file. Once the php variables are declared in the controller, it is necessary to declare them in javascript, in the view. A tag which will work as a support for the construction of the graph is inserted, and then a script is opened so as to write on it. This procedure corresponds to the javascript language. We also use an online javascript library, D3.js, called in the template file. This library allows us to use the data corresponding to the query results as a material for the construction of a *Scalable Vector Graphic* (SVG) that represent these results. Finally, by doing a *mouseover*, it is possible to read the values of the different histogram windows. In order to export these graphs, a plugin such as SVG Crowbar proves to be an excellent solution. The .svg files, once they have been downloaded, can be opened and edited with Inkscape.

3 Database testing

The functioning of the base was tested through a series of queries we run after the integration of a great amount of palynological data coming essentially from the research work of Chantal Leroyer (UMR 6566 Rennes). All the palynological records we integrated to ABCData have therefore already been analyzed and commented (Leroyer 1997; Leroyer and Allenet de Ribemont 2006), allowing us to compare ABCData's results to the previous numerous publications. Furthermore, the exploitation of these data places itself among a vivid research dynamic supported by the remarkable quantity of palynological and archaeological data available in this region, due to the importance of rescue archaeology surveys in this area.

3.1 Palynological integrated data

Altogether, 31 sites which are mainly located in three different valleys (Oise, Marne and Seine) have been recorded (Fig. 9). In these locations 43 cores were removed, not in the archaeological

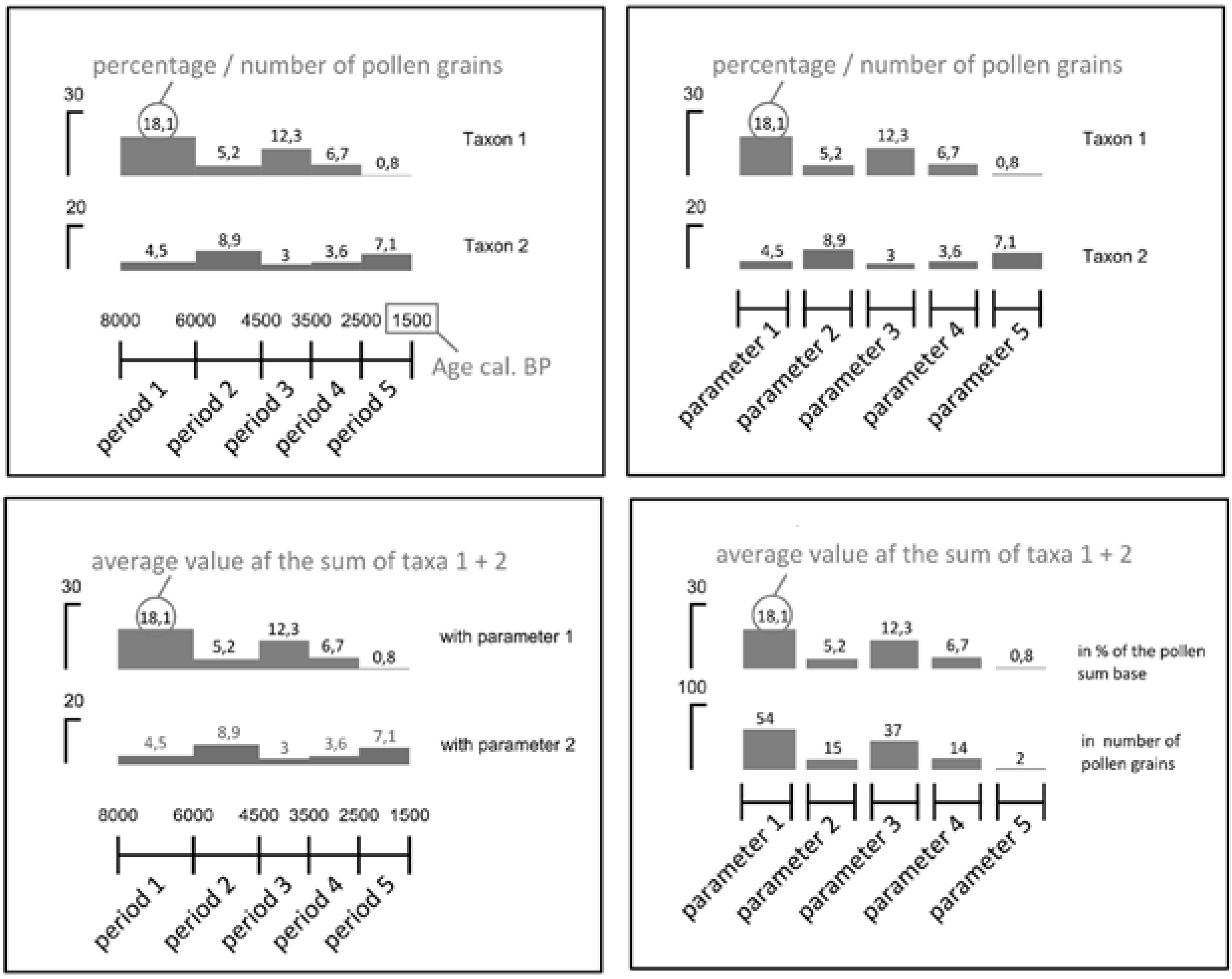

Fig. 8. The different diagrams displayed in ABCData's query interface.

sites themselves but in more suitable contexts, mainly in valley-bottom infilling contexts. They represent a total of 996 samples that have been considered as reliable and associated to a chrono-cultural period (tab. 2). This chronological attribution is firstly set on the pollen-assemblage zone (PAZ), but also on various dating methods (^{14}C, dendrochronology, archaeological remains), as well as age-depth models (David, 2014). We characterized 32 chrono-cultural periods (annexe 2), their age is defined in calibrated BP, and that may be replaced in a larger context corresponding to the local pollen-assemblage zones identified in the area (Leroyer 1997), and to the Mangerud's chronozones (Mangerud *et al*. 1974) calibrated in B.C. (Walnus and Nalepka 2010).

The sample distribution has also been studied according to the periods and the distances between the collecting area of the samples and the nearest attested archaeological site (Fig. 10).

3.2 Results produced

The exploitation of the data through the query interface, associated to the chart displaying tool, enabled us to obtain the synthetic diagrams showing the evolution of all vegetation taxa within a period from the end of the Late Glacial Period (12350 cal. BP) to the middle of the 19th century. On the diagrams presented here (Fig. 11; Fig. 12), we have chosen to represent only the major or the particularly significant taxa concerning the history of the evolution of the vegetation cover.

The results of this study were compared to the data already published on the history of the vegetation in the Paris Basin (Leroyer 1997; David *et al*. 2012; David 2014) and especially to numerous works focused on the identification of ancient marks of anthropization of the natural landscape (Leroyer 2004; Leroyer 2009; Leroyer and Allenet de Ribemont 2006; Leroyer *et al*. 2012; Leroyer *et al*. 2014). They constitute a statistical synthesis of the totality of the available data, and as such they provide precious information about the evolution of the proportion of the different taxa throughout time. Nevertheless, they should not be considered as a quantitative restitution of the vegetation cover composition during the Holocene Period, that only the modelling studies of the pollinic data may approach. However, these synthetic results are enhanced with the results of queries allowing us to isolate some samples or to carry out different statistical reasoning, more adapted to palaeoenvironmental questionings. The distribution of the available samples according to the chrono-cultural period and the distance in relation to the settlements also constitute an important source of information allowing us to qualify or to explain some observations.

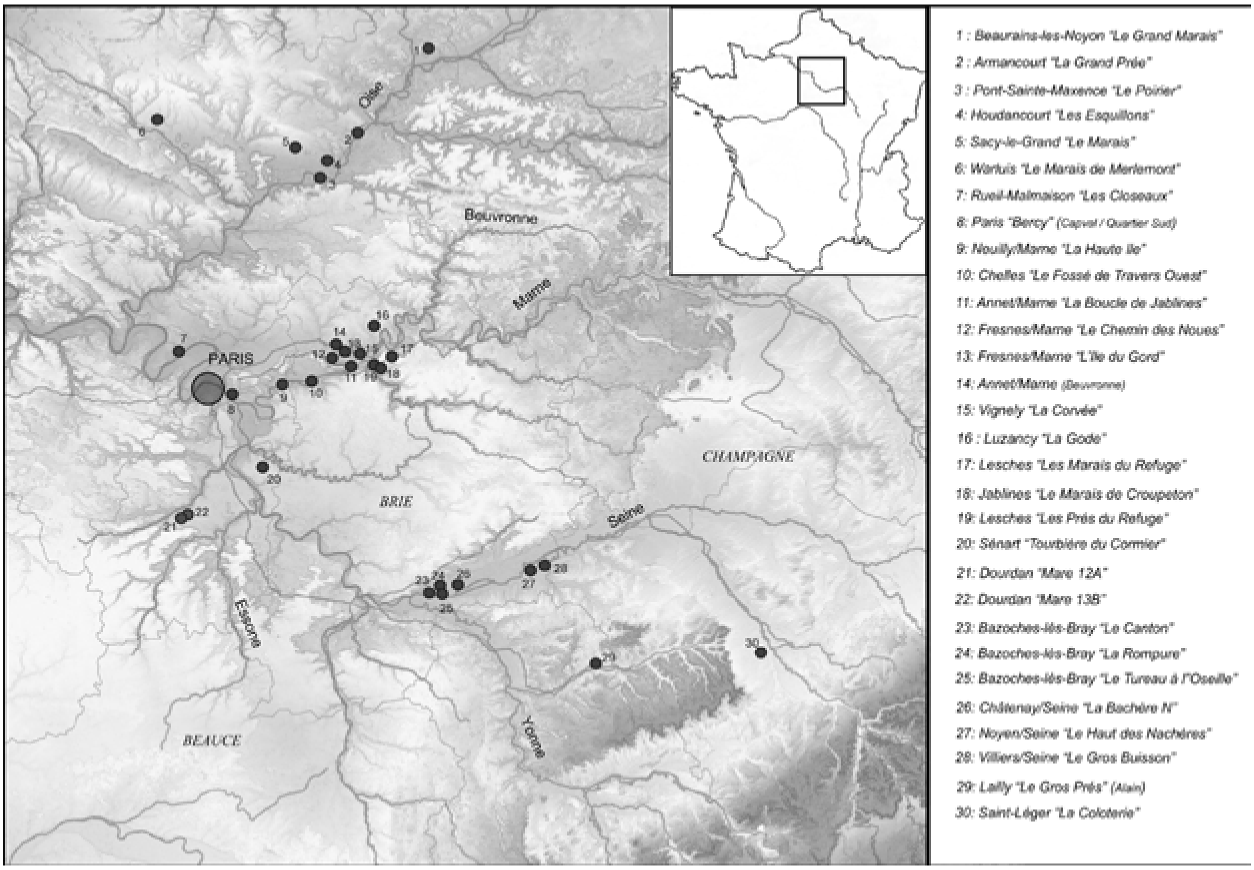

Fig. 9. Locations of the different palynological cores integrated into the base.

4.1 Mesolithic Period

The records corresponding to the end of the Late Glacial Period and to the Mesolithic times send back a quite expected picture of the vegetation evolution, with firstly an open field landscape associated to steppe vegetation. Then the transition to the Preboreal period is clearly marked by a forest recapture stage led by heliophytic taxa, mainly the birch (*Betula*) and the pine (*Pinus*). From the Early Atlantic, corresponding to the transition between medium and recent Mesolithic in the Paris Basin, a remarkable phenomenon can be observed: the queries studying the average of ruderal vegetation show us that in the samples collected less than 100m from an attested human settlement, the rates of ruderal species can reach more than 8%, whereas they are usually included between 2.5 and 3.5% among the other samples (Maguet 2014). These differences could then reveal the mark of a very light form of anthropization of the landscape that can only be observed at immediate proximity of human occupations. However, the traces of cereals in samples assigned to the Late Mesolithic could show a vice of designation or a problem of chronological assignation of the samples. The final stages of the Mesolithic period can in fact be sometimes contemporary of the arrival of the first Danubians (Leroyer *et al*. 2014).

4.2 Neolithic Period

During the Neolithic times, no disturbance of the woody plants, nor noticeable increase of pollinic evidences of anthropization can be detected, although the presence of cereals pollens leaves no doubt about the existence of agricultural activities. The study of the assemblages in accordance with the distance to the human occupation shows us again that the recording of ruderals and cereals is much more important near the sites. This is what notably explains the importance of the ruderals (more than 5%) in the Chasséen-Michelsberg Kultur, period for which about half the samples are located less than 100 meters far from an archaeological site (Maguet 2014). These elements therefore speak in favour of the hypothesis of an anthropogenic impact perceptible as soon as the earliest Neolithic groups settle down, but effective and observable only on local scale. The environment during this period seems therefore relatively open, although the main woody plants keep an important part, and the traces of the cereal agriculture remain low. Furthermore, it is important to note that the first farming exploitation methods and their environmental impact are still not well known. It is more likely that a part of the agro-pastoral activities of the Neolithic period have left very few traces in the palynological records. Especially the semi-nomadic agricultural techniques called slash and burn, that places the crops in the middle of a mass of forest acting as a filter and stimulates the renewal of the forest areas, have few chances of being detected only by means of palynology (Vuorela 1986). Finally, the filter put upon these data by the expansion of the alder during the Late Atlantic, which has an affect both during the material dropping in ponds surrounded by the waterside woodland, and also during the calculation of the results in percentage of the sum base (Leroyer 1997; Leroyer and Allenet de Ribemont 2006), creates a further obstacle to the identification of the first landscape disruptions.

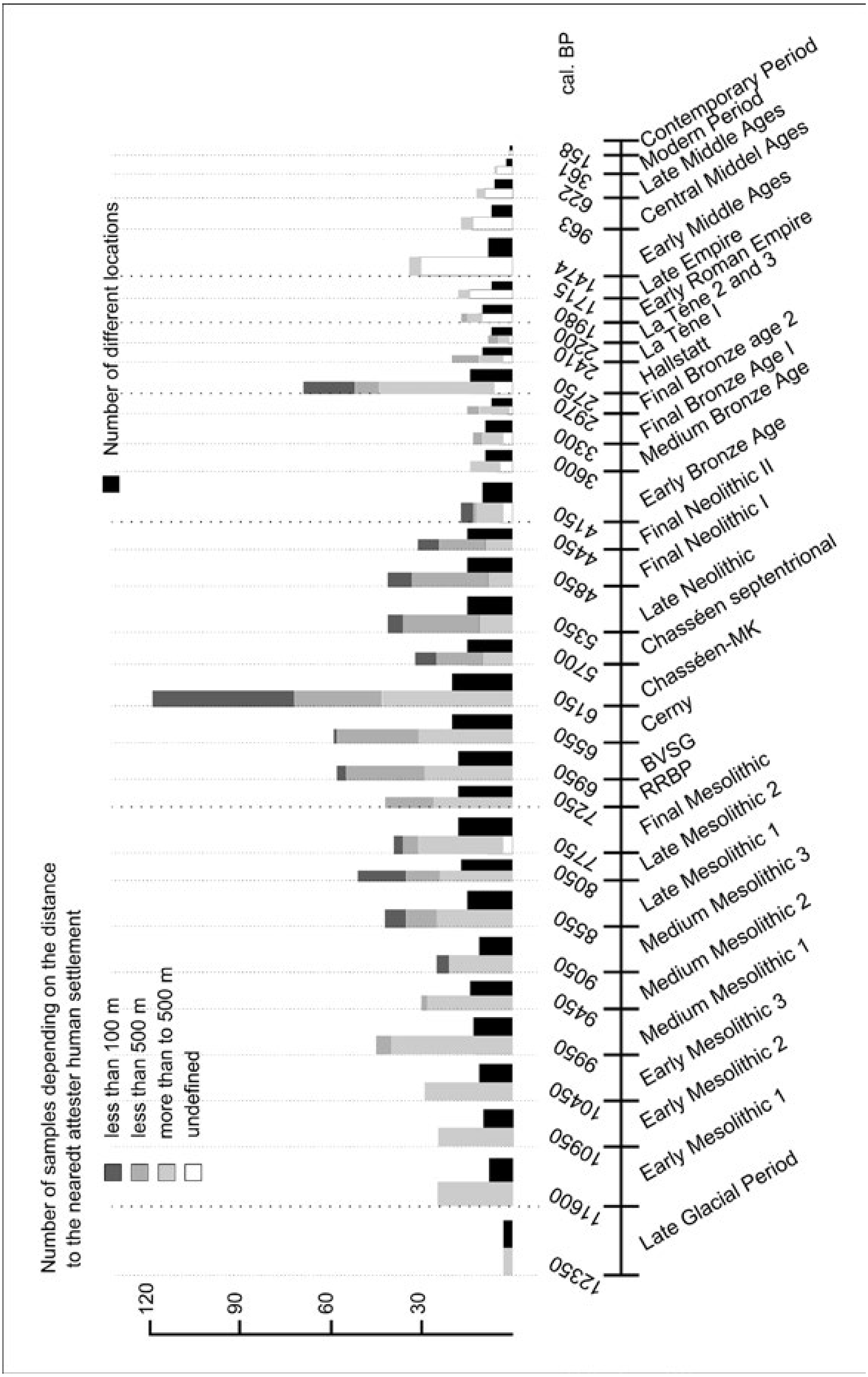

Fig. 10. Distribution of the samples integrated into the base.

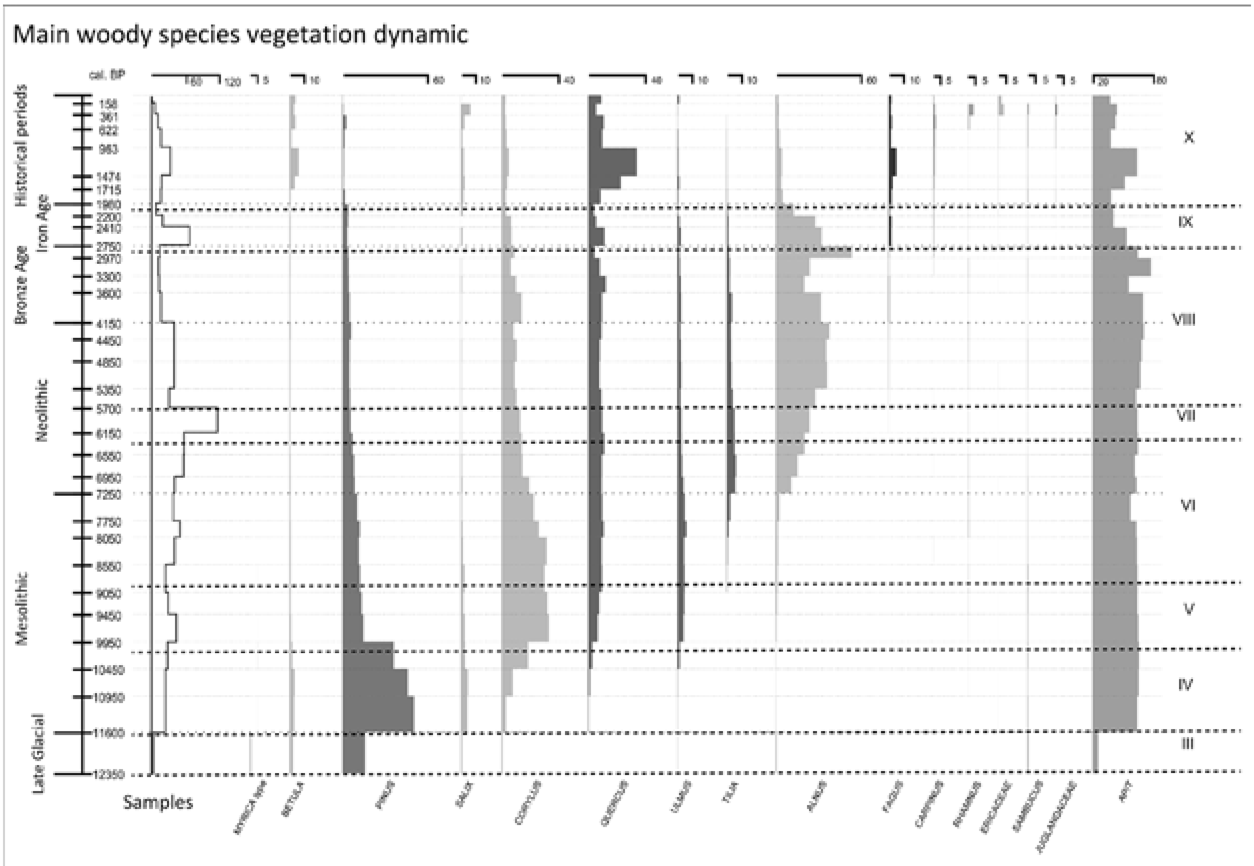

Fig. 11. Palynological diagram of the main woody species.

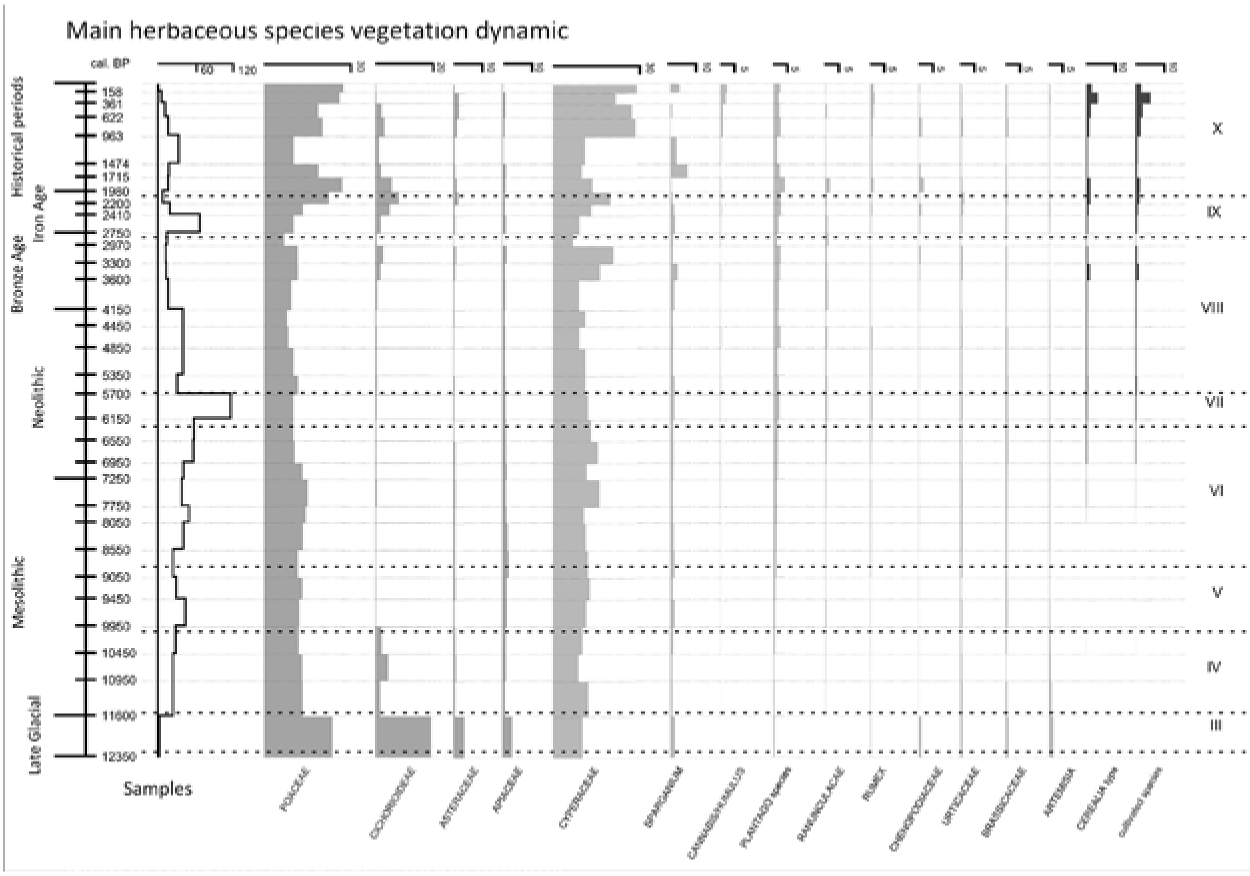

Fig. 12. Palynological diagram of the main herbaceous species.

Dates cal. BP	PAZ	Chronozones (Mangerud and al. 1974)	Chrono-cultural periods of reference		Dates cal. BC/AD
	X	Subatlantic	Historical Periods	Contemporary period	1950
				Modern period	1792
				Late Middle Ages	1474
				Central Middle Ages	1328
				Early Middle Ages	987
				Late Roman Empire	476
				Early Roman Empire	235
-2050	IX		Iron Age	La Tène 2 and 3	-30
				La Tène 1	-250
				Hallstatt	-460
-2850	VIII	Subboreal	Bronze Age	Final Bronze Age 2	-800
				Final Bronze Age 1	-1020
				Medium Bronze Age	-1350
				Early Bronze Age	-1650
			Final Neolithic	Final Neolithic 2	-2200
				Final Neolithic 1	-2500
			Late Neolithic		-2900
			Central Neolithic	Chasséen septentrional	-3400
-5750	VII	Late Atlantic		Chasséen-MK	-3750
				Cerny	-4200
			Early Neolithic	BVSG	-4600
-6350		Atlantic		RRBP	-5000
	VI	Early Atlantic	Final Mesolithic		-5300
			Late Mesolithic	Late Mesolithic 2	-5600
				Late Mesolithic 1	-6100
			Medium Mesolithic	Medium Mesolithic 3	-6600
-8950	V	Boreal		Medium Mesolithic 2	-7100
				Medium Mesolithic 1	-7500
-10150	IV	Preboreal	Early Mesolithic	Early Mesolithic 2	-8000
				Early Mesolithic 1	-9000
-11450	III	Late Dryas	Late Glacial Period	Quaternary/Late Glacial	-9650
-12950	II	Alleröd			-10400
-13650		Early sup. Dryas			
-13600	I	Bölling		Late Glacial	
					-16050

Tab. 2. Chrono-cultural periods and chronozones of references.

4.3 Bronze Age

From the Bronze Age, a smaller number of samples are available, and we know less about the population of the Paris Basin during this period. The synthetic diagrams prove us a relative continuity between the Neolithic period and the Early Bronze Age, with only a short rise of the hazel (*Corylus*) noticeable at less than 100 meters from the sites (Maguet 2014). This may show a short phase of forest recovery, or eventually new forms of forest management (David 2014). Indeed, together with the increasing growth of the hazel, important rates of the nitrophilic group can be observed. The move to the Medium Bronze Age is branded by a slight increase of the poaceae averages, which suggests a dynamic of landscape opening or woodland clearing, the poaceae being eventually able to grow among lightly thick forest areas (Leroyer 1997). Otherwise we can notice an increase of recorded cereal (*Cerealia* type) quantities as well as a greater proportion of samples in which the cereal ratio is higher than the 1% threshold, even though it happens to be samples to which no nearby settlement is connected. During the Medium Bronze Age, the sudden decrease of cereal quantities seems startling. Actually the explanation of these values comes from a lack of sample diversity: half of them come from a unique site consequently carrying a disproportionate weight in the averages calculation (Maguet 2014). This point highlights an important bias which puts in evidence the necessity of a stronger development of the means of controlling the distribution and the representativeness of the samples, in order to regulate the synthetic results. Keeping in mind these reticences about the reliability of the study bearing on the 2nd Final Bronze, it looks as if the end of Subboreal period could correspond to a stage of wood plants destabilization revealed by the forest and heliophitic vegetation decrease. To sum up, the Bronze Age appears therefore printed by a better perception of anthropization evidences suggesting reinforcement of human grip on the environment, a rise of farming lands or even a use of forest resources for metallurgy (Leroyer 1997). Though no samples closely related to an archaeological settlement after the Early Bronze Age can be found, the recording of the varied IPAs tends to reinforce this hypothesis.

4.4 Iron Age and Historical times

If the samples associated to the Hallstatt culture constitute a quite satisfying corpus, they are less numerous and more disconnected with the archaeological sites of the 2nd Iron Age. Nevertheless the transition to the Subatlantic period around 600 cal. BC corresponds to the beginning of a dynamic which will last until the end of the Early Roman Empire. It starts with a quick withdrawal of alder linked to the expansion of the beech tree and of the opening of the landscape, colonized by *Poaceae* and *Cichorioideae*, opening realized against most of the wood plants to the exception of the hornbeam (*Carpinus*) which slightly gains ground. At the beginning of the Gallic period, the timid presence of new crops such as fax, rye, walnut, and vine can be noticed. It is mainly from the beginning of the La Tène culture that a significant increase of the cereal percentage is recorded (Maguet 2014).

Between the Early and the Late Roman Empire, a very clear break is characterized by the lessening of crops excepting rye (*Secale* type) and chestnut (*Castanea*) as well as ruderals, together with a very clear increase of the oak and the heliophytic plants. Therefore the dynamic initiated since the Bronze Age seems then to invert as a new growth of forest vegetation can be observed. The rates of the heliophytic plants (*Corylus* and *Betula*), correlated to the weakness of anthropization indicators confirms a recovery of the environment by these pioneering vegetation. The ruderal assemblage composition and the low averages of *Cerealia,* suggest a predominance of pastoralism as the main agricultural activity until the High Middle Age, in accordance with the expected results (Leroyer, 1997). From the Carolingian times an increase of all the crops and pastures (dry or damp) can be observed. This tendency persists from the Early Middle Age to the 20th century, with a drop of *Castanea* and *Secale* type to the benefit of C*erealia* type which confirms its supremacy among the cultivated taxa. Nevertheless the poverty of the available sample corpus for the more recent periods forbids any further interpretations.

5 Conclusion

With this project, we aimed to open new perspectives for the development of palaeoenvironmental field, as the archaeologists are more and more interested in reconstructing the past ecosystems, understanding the evolution of animals and plants, and comprehending the role of human societies within the natural landscape.

The creation of ABCData, from the base programming to the analysis of the integrated data, allowed us to evaluate the interest computer programming could bring to our domain, and to get a better estimation of the advantages, requirements and issues of this application. Now we must highlight the complexity of the program writing and the weight of the IT resources used notably for the query results computing with the php language. Consequently, the results must always be cautiously considered before validation. We also discovered new possibilities in terms of storage, exploitation and visualisation of the results. The integration of information about the samples, together with the paleobotanical data, allows us to run queries that study the impact of some influent parameters in order to try out some hypothesis and explain some phenomena. It particularly pointed out the misrepresentation of the global results caused by unbalanced distributions of the samples.

Interdisciplinarity is also an essential element that still has to be developed, particularly concerning the comparison between palynological and anthracological data. That confrontation has already proved to be fertile (Leroyer *et al*. 2011). Besides, the archaeozoological part is currently being developed, and on the long term ABCData should be able to host malacological data. It would also be interesting to integrate into the base a larger quantity of data, from other areas or attributed to other periods, in order to run queries involving new parameters. Finally, GIS interface will soon be added to the base and we would like to be able to explore the graphic possibilities offered by the D3.js library and to consider the creation of a 3D landscape reconstruction tool.

Bibliography

David, R., Leroyer, C., Mazier, F., Lanos, P., Dufresne, P., Allenet De Ribemont, G., Aoustin, D. 2012. Les transformations de la végétation du bassin parisien par la modélisation des données polliniques holocènes. In Bertoncello, F. and Braemer, F. (eds.), *Variabilités environnementales, mutations sociales. Nature, intensités,* *échelles et temporalités des changements. Actes des XXXIIe rencontres internationales d'archéologie et d'histoire d'Antibes*: 53-68. Antibes, Éditions APDCA.

David, R. 2014. *Modélisation de la végétation Holocène du Nord-Ouest de la France : Reconstruction de la chronologie et de l'évolution du couvert végétal du Bassin parisien et du Massif armoricain.* Unpublished PhD thesis, Université de Rennes 1.

Goeury, C. 1997. GpalWin : gestion, traitement et représentation des données de la paléoécologie. In *Actes du XVe symposium de l'A.P.L.F.* : 31. Lyon.

Kreuz, A. and Shafer, E. 2002. A new archaeobotanical database program. *Vegetation History and Archaeobotany* 11: 177–9.

Leroyer, C. 1997. *Homme, climat, végétation au Tardi- et Postglaciaire dans le Bassin parisien : apport de l'étude palynologique des fonds de vallée*. Unpublished PhD thesis, Université Paris 1 Panthéon-Sorbonne.

Leroyer, C. 2004. L'anthropisation du Bassin parisien du VIIe au IV millénaire d'après les analyses polliniques des fonds de vallées : mise en évidence d'activités agro-pastorales très précoces. In Richard, H. (ed.), *Néolithisation précoce. Premières traces d'anthropisation du couvert végétal à partir des données polliniques*, Collection Annales littéraires, série 'Environnement, Sociétés e t Archéologie' 7: 11-27. Besançon, Presses Universitaires de Franche-Comté.

Leroyer, C. and Allenet De Ribemont, G. 2006. L'anthropisation du paysage végétal d'après les données polliniques : l'exemple des fonds de vallées du Bassin parisien. In P. Allée and L. Lespez (eds.), *L'érosion, entre société, climat et paléoenvironnement* : 63-72. Clermont-Ferrand, Presses Universitaires Blaise Pascal.

Leroyer, C. *et al*. 2009. Base de données et S.I.G. palynologiques sur l'Age du Fer en France : une autre approche du paysage végétal et de son anthropisation. In I. Bertrand, A. Duval, J. Gomez De Soto, P. Maguer (eds.), *Habitats et paysages ruraux en Gaule et regards sur d'autres régions du monde celtique. Actes du XXXIe colloque international de l'Association Française pour l'Etude de l'Age du Fer, Chauvigny, 17 - 20 mai 2007*, II, Mémoire A. P. C. XXXV: 447–68.

Leroyer, C., Coubray, S., Allenet de Ribemont, G., Perrière, J., Pernaud J.-M. 2011) Vegetation dynamics, human impact and exploitation patterns in the Paris Basin through the Holocene: palynology vs. Anthracology. *SAGVNTVM* 11: 81-2.

Leroyer, C., David, R., Mazier, F., Allenet de Ribemont, G., Lanos, P., Dufresne, P. (2012) Environnement et anthropisation du milieu durant l'âge du Bronze dans le Bassin parisien : l'apport des données polliniques et de la modélisation du couvert végétal. In Melin, M., Mougne, C. (eds.), *L'Homme, ses ressources et son environnement dans le Nord-Ouest de la France à l'âge de Bronze : actualités de la recherche. Actes du Séminaire Archéologique de l'Ouest*: 7-26. Rennes.

Leroyer, C., David, R., Maguet, E., Mazier, F., Allenet de Ribemont, G., Lanos, P., Dufresne, P. 2014. *Environnement et anthropisation du milieu durant le Néolithique dans le Bassin parisien : l'apport des données polliniques et de la modélisation du couvert végétal* (in press).

Maguet, E. 2013. *Création et exploitation d'une base de données palynologiques sur le Mésolithique et le Néolithique du Bassin parisien*. Rennes, Mémoire de Master 1 « Histoire et Archéologie », Université de Rennes 2.

Maguet, E. 2014. *Mise en ligne d'une base de données paléoenvironnementales : développement et applications*. Rennes: Mémoire de Master 2 « Paléontologie, Préhistoire, Paléoenvironnements », Université de Rennes 1.

Mangerund, J, Andersen, S. T., Berglund, B.E., Donner, J. 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas* 3, 3: 109–26.

Reille, M. 1990. *Leçons de palynologie et d'analyse pollinique*. Paris, Éditions du CNRS.

Tomlinson, P. 1992. Design and implementation of a relational database for archaeobotanical records from Great Britain and Ireland. *Circaea, The Journal of the Association for Environmental Archaeology* 10, 1: 1–30.

Vuorela, I. 1986. Palynological and historical evidence of slach-brun cultivation in South Finland. In Behre, K. E. (ed.), *Anthropogenic indicators in pollen diagrams*: 53-64. Rotterdam, A. A. Balkema.

Walanus, A., Nalepka, D. 2010. Calibration of Mangerud's boundaries. *Radiocarbon* 52, 4: 1639–44.

Integrated Methodologies for the Reconstruction of the Ancient City of Lixus (Morocco)

Cynthia Mascione
cynthia.mascione@unisi.it

Rossella Pansini
rossella.pansini@gmail.com

Luca Passalacqua
luca.passalacqua@unisi.it

Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Abstract: In this paper we present the research strategy adopted during our archaeological survey in Lixus (Larache – Morocco). The aim of the project was to update the existing topographical documentation, based on previous researches, and to create the starting point for a new study of the evolution of the urban tissue through time.

The survey adopted a combination of different methods and techniques: DGPS survey, geophysical prospections of unexcavated areas, topographical survey of emerging structures, study of published documentation and archival records, 2D and 3D land-based and aerial photogrammetry.

The results of these activities led to the revision of Lixus plan. In particular, the survey and analysis of the archaeological stratification and building techniques of the city walls and of a quarter located on the eastern slope of the hill brought new light to the diachronical evolution of the city.

Keywords: Topographical Survey, Photogrammetry, Integrated Methodologies, Morocco.

1 Introduction

The Archaeological Project of Lixus started in 2010 with the collaboration of three Institutions, the Moroccan National Institute for Science Applied to Archaeology and Cultural Heritage (INSAP), the University Mohamend V- Souissi of Rabat (Morocco) and the University of Siena (Italy). The main aim of this project was to enhance our knowledge on the ancient city of Lixus and in particular to clarify the urban evolution of the settlement through history. Given the large extension of the city (18 hectares in the period of maximum extension), we decided to adopt an approach that combined different methods of investigation, for most non-invasive, that would allow us to cover the largest possible area and, at the same time, to choose the most strategic areas for a stratigraphic excavation.

The archaeological site is located on a hill called Tchemich, about 4 km far from the modern city of Larache, not far from Tangier, along the Moroccan Atlantic coast and nearby the estuary of the Loukkos River (Fig. 1). This settlement is considered to be one of the oldest foundations in the West, with a very long history testified by several public, private and productive structures belonging to different eras. It probably started as a Phoenician settlement in 8th-7th century BC (Aranegui Gascó 2009) and had an active harbour that was located in the southern part of the hill, along the riverside (Tissot 1877). The particular shape of the hill has influenced the organization of the town and its defensive wall circuits, as the various districts are distributed on layered terraces. The South-western corner of the relief, near the right bank of the river, houses the production area of the settlement, with structures devoted to the processing and conservation of fishery products (Ponsich 1982, 1988; Habibi 2007). Higher up, in the North-eastern area, there are an amphitheatre (Hallier 2003), a bath complex and an apsidal building traditionally considered as a Roman basilica. Great dwellings of the Roman period can be seen in the North-western part of the settlement (Lenoir 1992), while the remains of two necropolis lay in the eastern and western part of the city, out of the defensive walls. The monumental core, known as Temple Quarter (Ponsich 1981; Brouquier-Reddé, El Khayari, Ichkhakh 2008), is located on a large plateau on the top of the Tchemich and is characterized by the presence of three temples and other buildings of uncertain interpretation (Aranegui Gascó and Mar 2010; Papi 2013, *contra* Aranegui Gascó 2015), while a set of structures which include a mosque develop along the eastern slope of the hill (Akerraz 1992). The major monumental evidence belongs to the Mauretanian (Temple Quarter), Roman (dwellings, amphitheatre-baths complex and the fish sauce production quarter) and Islamic period (mosque area).

1.1 Main previous research and background

Most of the known structures of Lixus are located in the northern area of the hill, as it was the most explored and excavated by various researchers in the past. On the other side, the southern slope still remains mostly unknown, except for the fish sauce production quarter. All the districts were excavated between 1912 and 1956, during the Spanish Protectorate in Morocco, with scarce attention to stratigraphy and detailed documentation. In recent years, other archaeological expeditions were led in collaboration with the INSAP by the

FIG. 1. PONSICH'S PLAN (FROM PONSICH 1981, FIG.5, MODIFIED). BOTTOM RIGHT: POSITION OF LARACHE ALONG THE MOROCCAN ATLANTIC COAST.

École Normale Supérieure of Paris (Brouquier-Reddé, El Khayari, Ichkhakh 2006, 2008; Brouquier-Reddé *et al*. 2010) and the University of Valencia (Aranegui Gascó 2001, 2005; Aranegui Gascó and Hassini 2010). Among the researchers who worked in Lixus, Miquel Tarradel Mateu deserves special attention: he worked on the site extensively and was the first person to apply the principles of stratigraphy in his excavations (Tarradell Mateu 1950, 1959). Unfortunately, most of his work, including the reports of his excavations, remained unpublished. Another important figure was Michel Ponsich, who inherited Tarradell's research and produced in 1966 the first plan of the entire archaeological site by using aerial photogrammetry (Ponsich 1981, Fig. 5). The remarkable outcome of his work still constitutes the principal source for Lixus topography (Fig. 1). Nevertheless, it lacks in detail and accuracy, as the aerial survey was not combined with a systematic field survey that could verify the correct positioning of the structures and add those not visible from above.

Fig. 2. Custom-made devices for 2D photogrammetry (a, b) and aluminium cradle for kite (c).

2 The Archaeological Project of Lixus: purposes, methods and development

The understanding of Lixus development along time had to start from the realisation of a reliable and precise topographical map that would record all the buildings and structures present in the settlement. The new plan was the starting point for our further analyses, which were aimed at understanding the development of the urban tissue in the various periods of its occupation. As a result our project was developed for three basic purposes:

- the survey and the documentation of the visible structures, so to complete and correct the data coming from previous surveys.
- the evaluation of the archaeological potential of unexcavated areas, like the southern slope of the hill.
- the analysis of the evolution of the city in its history.

It was crucial for the project to achieve these purposes through rapid and efficient methods that were compatible with our strict timetable. We decided to combine more traditional methodologies, like DGPS, Total Station Survey and magnetometry, with others that saved time without losing quality: photogrammetry seemed to be the best solution. We used it both for 2D and 3D elaborations: 2D applications were adopted for documenting standing structures and detail plans, while 3D solutions were experimented for the documentation of the general plans of some districts of the settlement. We built custom-made devices that could help during the field survey and assure good results. They also had to be functional, non-expensive, lightweight and transportable by plane. The cameras were housed on an assembled aluminium poles system that helped in documenting detail plans, while the photographs of standing structures were possible by positioning the camera on the telescopic pole of the total station through a special double screw anchoring system (Fig. 2a-b). We also decided to apply low-height aerial photogrammetry using a kite, as this technology presented several advantages in the realization of aerial photographs of Lixus. Lying at a distance of less than 4 km far from the sea, the site is characterized by ideal wind conditions for the use of the kite. Almost every day a strong and constant wind starts to blow from west, allowing new flights. The use of a kite has been preferred to the balloon as it presents problems in conditions of high wind, in addition to the difficulty in finding the helium.

We started with the creation of the topographical base for data collection, consisting of a Digital Elevation Model and a closed georeferenced traverse. The DGPS survey started with the positioning of a base point in UTM 29 N. The DGPS survey marked points at intervals between 1.5 and 2m, depending on the archaeological evidences and the morphology of the land. The objective was to provide a thorough and homogenous reading of the terrain (Fig. 3).

The next step was to collect all published studies related to the topography of Lixus that constituted the starting point for our fieldwork. They included both general plans (like Ponsich 1981, Fig. 5) and other more accurate studies of particular compounds or buildings. Once all these plans were placed together, and their accuracy was verified, the best ones were chosen (Ponsich 1982, Fig. 10, 11; Ponsich 1988; Brouquier-Reddé, El Khayari, Ichkhakh 2008, Fig. 2). The positioning in CAD environment was made with ground control points related with the closed traverse.

Another important issue was the valuation of the archaeological potential of the unexcavated areas. We paid more attention to the southern slope of the hill, and, in particular, we aimed to identify and examine the urban structure of this area. The magnetometry recorded the traces of the buildings and the streets, helped to determine the function of some of the quarters, revealed the traces of the wall circuit, almost invisible in the South-eastern area of the hill, and identified some buildings in the suburban area (Fig. 4).

One of the purposes of this research was to define the diachronical evolution of the city, and especially of the wall circuits. In this case a detailed study was necessary to reach all the information we needed. We chose the combination of field survey with total station and the application of 2D photogrammetry for recording all the details of the building techniques. These researches lead to the identification of new traces of the city walls (Fig. 4). In particular, the two important issues were the mapping of the different paths along the southern slope and the identification of the Islamic circuit. The application of 2D photogrammetry for the analytical documentation of standing structures allowed us to identify

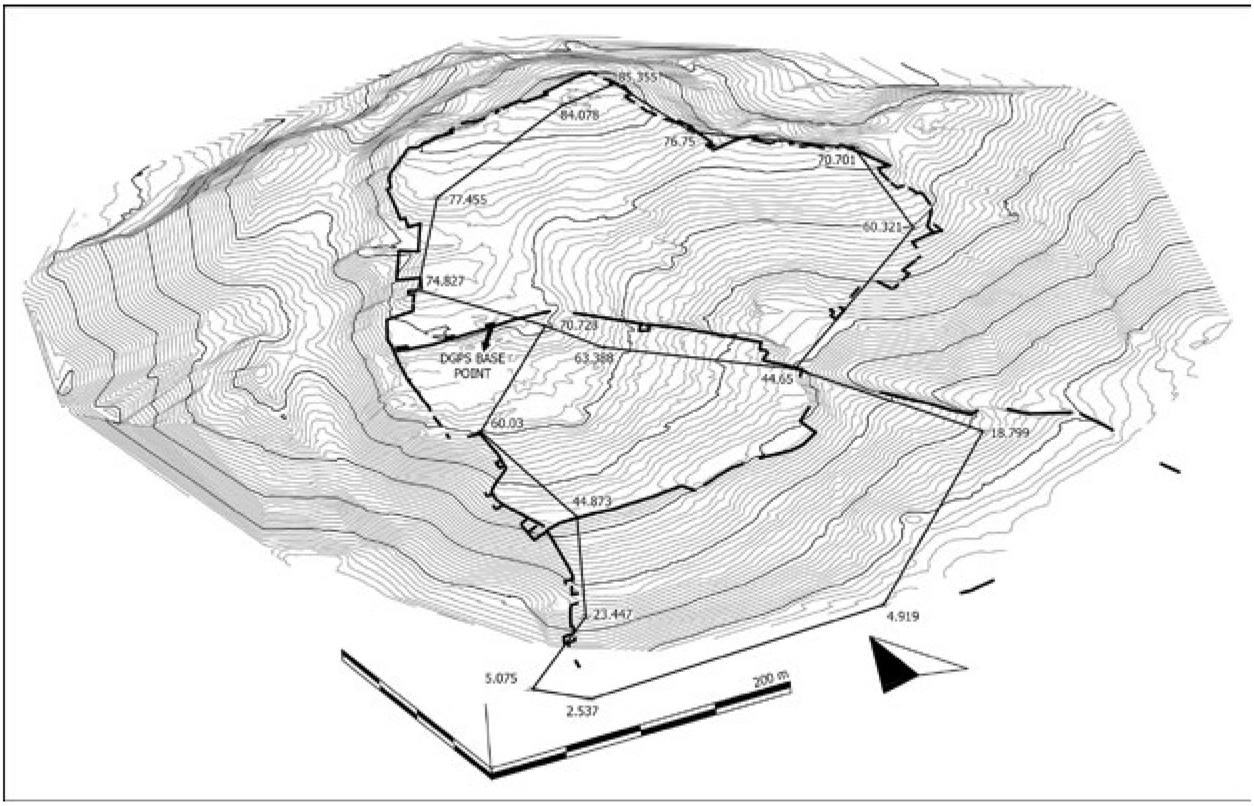

Fig. 3. DEM, georeferenced traverse and Lixus city walls.

the constructive phases of the city walls, from Mauretanian to Islamic period and thus the changes of the urbanization process (Fig. 5). The complete wall path in the southern part of the city still remains undefined because of modern interventions, such as the construction of the road leading to Tangier that destroyed most of the archaeological remains. The few visible traces of ancient structures are difficult to identify as well as the location of the ancient port, which was most likely near the productive quarter, still remains controversial.

All the new data emerging from the fieldwork helped to select the strategic areas for the new excavations that were carried out to determine a more accurate dating for the city walls. The material coming from the excavations is still undergoing study and thus the chronologies proposed here are preliminary.

Another aspect of our research was the analysis of a central but still unknown zone of the city. The Mosque area had already been explored and excavated in the past, but the results of these activities were never published in detail. There is only a brief report written by Michel Ponsich that describes the main structures located in the area (Ponsich 1981, 113-22). The quarter covers the eastern slope of the hill, and its importance lays on the presence of the Mosque and of other buildings belonging to the last period of the city, that is still mostly unknown. It also hosts residual material evidences from previous phases of occupation. The proximity to the so-called Temple Quarter indicates that it had some kind of importance in the antique urban tissue. Here too, we decided to integrate data coming from the topographical survey with total station and 2D photogrammetry for the detailed documentation of building techniques, that were useful to make a more precise hypothesis on their dating and thus to outline the urban evolution of the area through time.

In a first phase we decided to experiment with 2D aerial photogrammetry for the documentation of the general plan of the area. The results were good in terms of image detail, but lacked in precision, as the quarter developed on the slope of the hill, and therefore has great height differences that couldn't be well processed by a 2D application. Moreover, a detailed study of the morphology of the landscape was needed to determine its urban evolution. The 3D photogrammetry approach seemed the best solution to document and analyse these aspects.

We used a static kite with a wingspan of about 3m and a total area of about $5m^2$. This type of kite is able to fly with wind strengths ranging from 5 to 40km/h. The kite string has a section of 2 mm and length of 200m and is housed on a reel, to which it is possible to add a second reel to reach higher altitudes. Being attached to the cable restraint when the kite is already stable, the camera can be raised to a maximum height from the ground of about 300m, taking into account the inclination determined by the strength and direction of the wind .

The digital camera is housed on an aluminium cradle (Fig. 2c) that can be activate through a servo and remotely controlled via radio. Thanks to this, the cradle can make a 90-degree rotation on its horizontal axis and take zenithal or panoramic photographs. A second servo provides 360-degree horizontal rotation, while a third servo takes the picture. The camera is set to manual focus and fixed exposure time of 1/200 to prevent oscillations and blurry images. A First Person View (FPV) device with a transmitter on board the kite captures the video

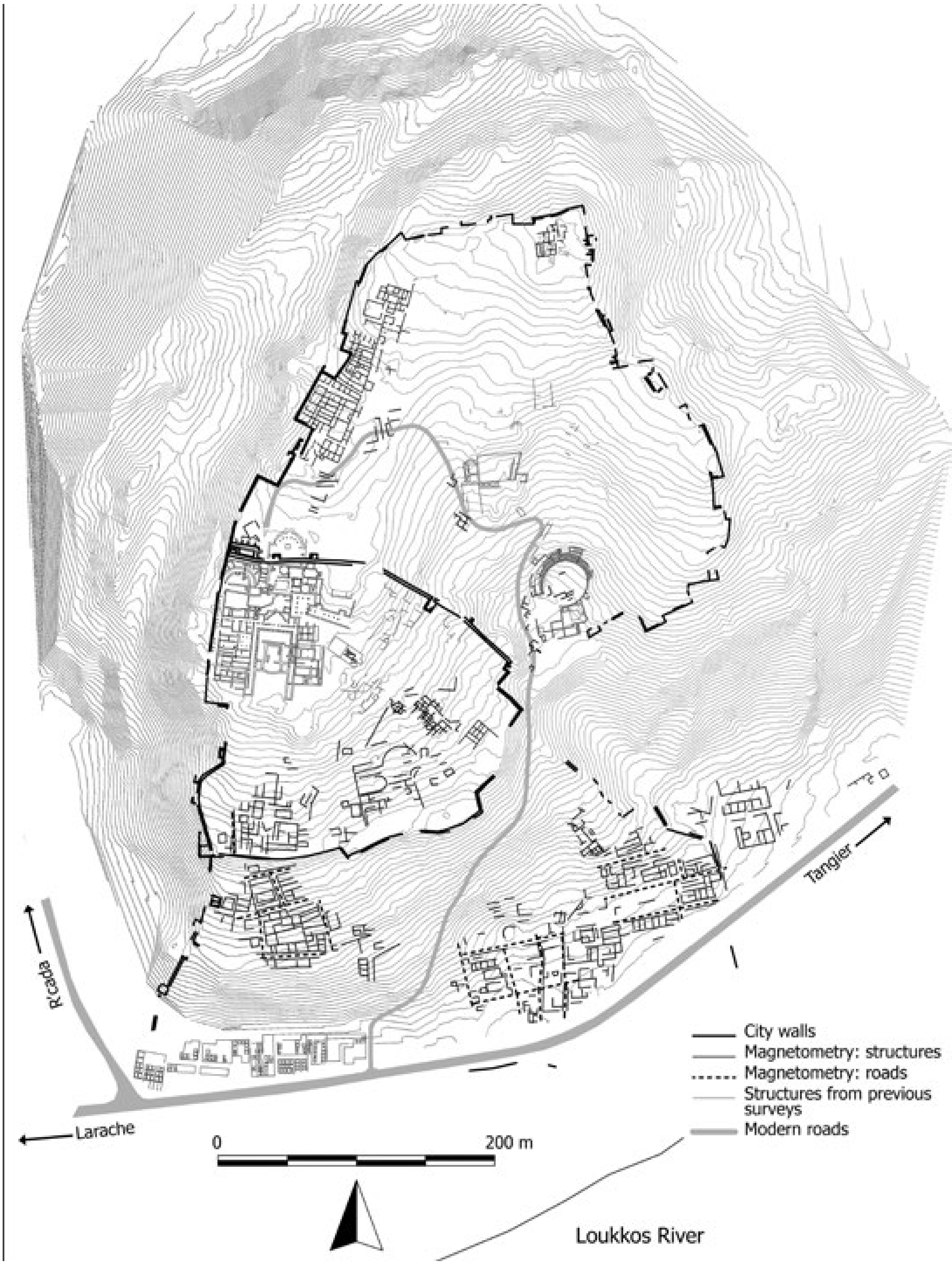

Fig. 4. City walls and results of the magnetometry.

of the digital camera and a receiver on the ground, attached to a field computer, displays the images and allows taking shoots.

The cradle is attached to the kite string through a Picavet suspension system formed by a single cable that runs through eyelets or pulleys attached to the edge of a cross; line ends with two carabiners equipped with two loops each. The Picavet system, with the cradle, is fixed to the cable of the kite, after that this stabilizes to the wind, through two loops for the insertion of snap hooks. The distance between the two loops varies depending on the intensity of the wind, as it increases due to the force of the wind to ensure stability to the instrumentation.

The photogrammetric survey can thus be carried out with two operators: one leading the kite and the other, connected by microphone and headset, giving the move, making the shots and directing the camera depending on the desired subject through the remote control.

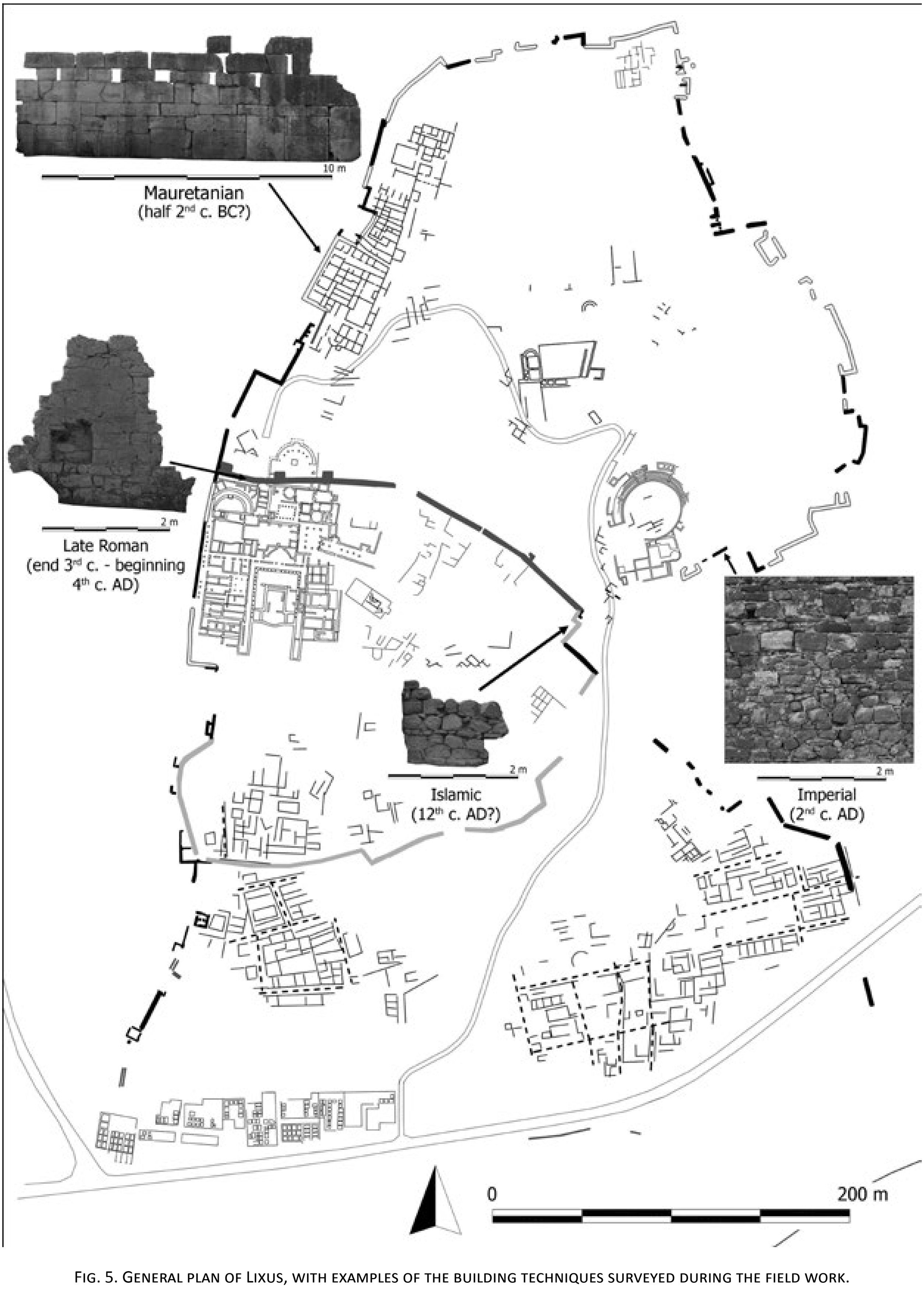

Fig. 5. General plan of Lixus, with examples of the building techniques surveyed during the field work.

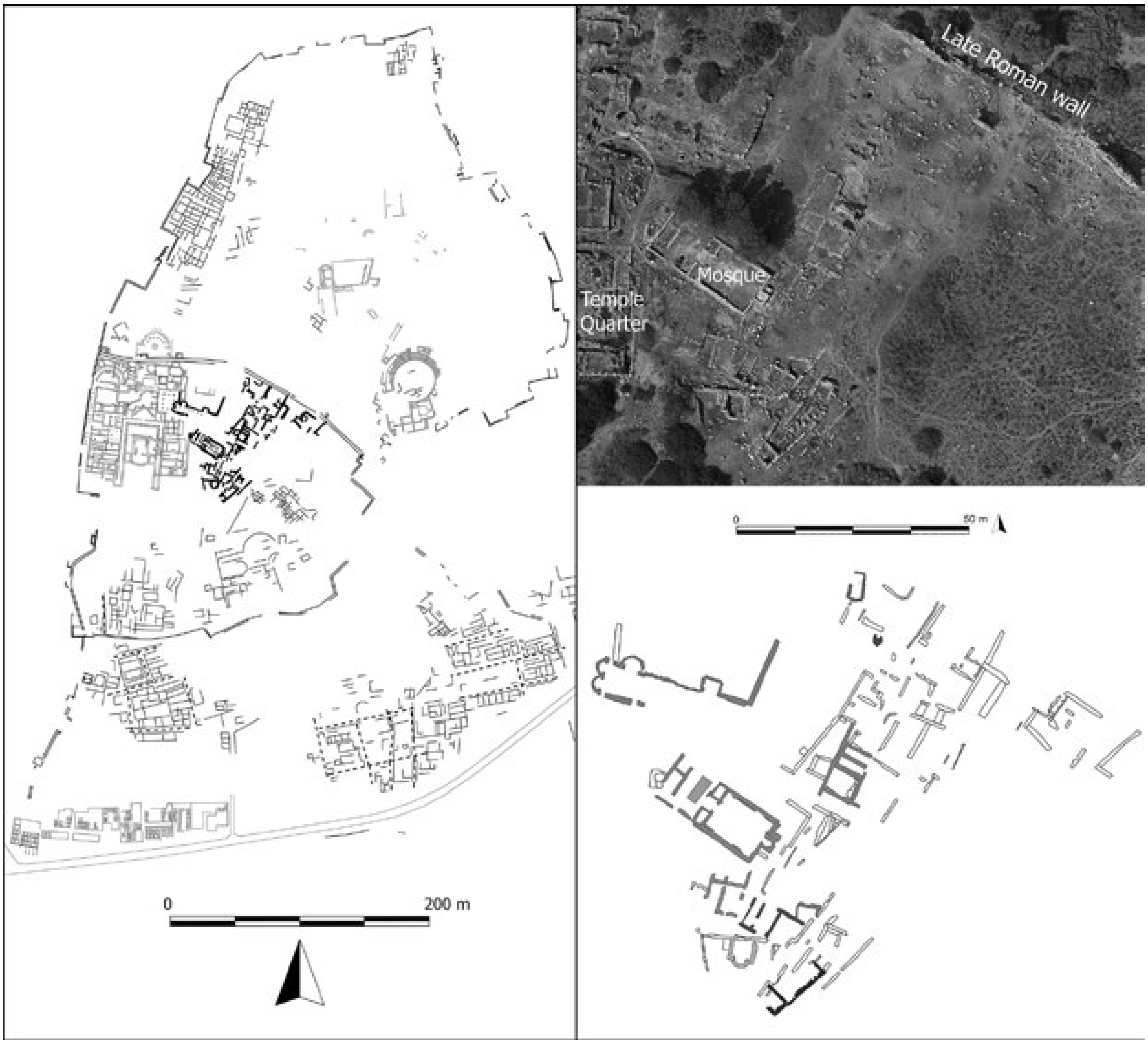

FIG. 6. GENERAL PLAN, ORTHOPHOTO AND DETAIL PLAN OF THE MOSQUE AREA.

The products of the processing were a 3D texturized mesh and a more precise orthophoto of the whole area (Fig. 6), together with a set of orthophotos documenting all the building techniques (Fig. 7).

The same procedure was applied for the Roman houses area and the amphitheatre-baths quarter (Fig. 8): the combination of topographical survey and 3D aerial photogrammetry allowed to correct the previous plans and to create the starting point for the study of the building sequence.

3 Results, conclusions and next steps

Our methodological approach, while using well-known techniques in archaeology, led to the integration of data coming from different sources and thus to the acquisition of new information about Lixus. The use of relatively cheap and easy to transport equipment helped in solving the problems of logistics and transport, and the use of photogrammetry allowed us to save time during the survey without losing quality. A weakness of this integrated approach can be to work with a large amount of data, which are no easy to manage. The parallel work of individual team members, each with their own specific skills, and the ability to interface with each other was essential for the success of the project.

The fieldwork lasted 12 weeks and all of the goals were met. By integrating of all the methods described in previous paragraphs, the topography and development of Lixus are now more defined (Fig. 9). The wall circuits have been better understood, both in their constructive and chronological development. Through the combination of DPGS survey, magnetometry and topographical survey it is now possible to speculate about the external and internal road network and the gates that led to the city. We collected new data on the urban organization of the settlement and added to the general plan new areas that had never been surveyed, documented and studied before. An important goal was the acquisition of new data belonging to the Islamic period, which was mostly ignored by the previous researchers who worked in the settlement. The

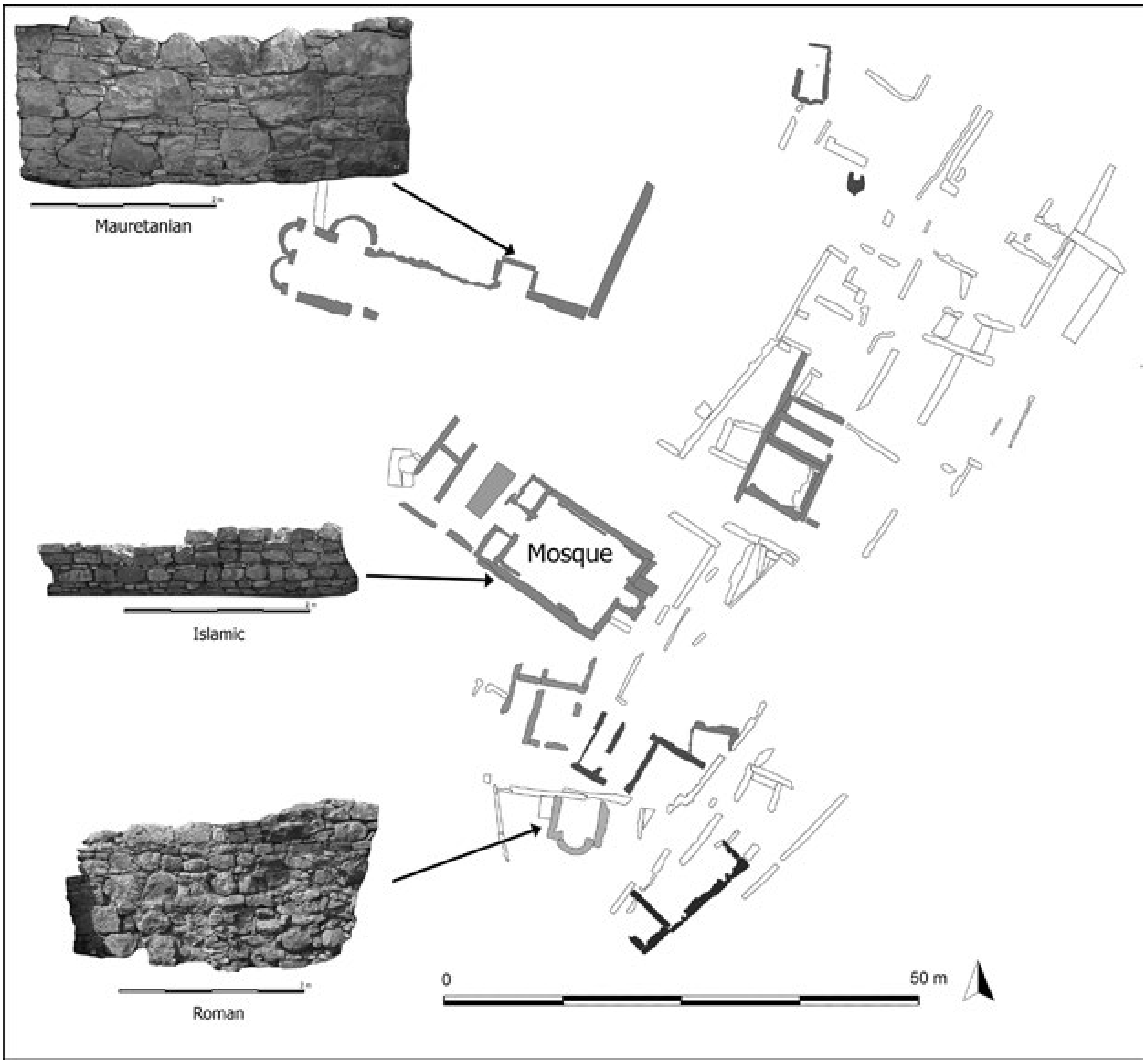

Fig. 7. Detail plan of the Mosque area, with examples of the building techniques surveyed during the field work.

analysis of the Mosque area, the definition of the Islamic circuit and the information collected during our excavations give us a better definition and dating to this very important part of Lixus history. Other districts, as the fish sauce production quarter and the Temple Quarter, are still to be surveyed and documented: for this reason, new devices are being tested. A drone seems to be the most functional and easy-to-use equipment for a proper documentation, as in these parts of the city lifting the kite is a challenge for strong winds and little room to manoeuvre.

All the data are being transferred from CAD environment to a GIS platform, which represents the best solution for storing and managing great amounts of information and for further analyses on the buildings volumes and their relationships.

At the same time, the unpublished archival records belonging to Miquel Tarradell are under study. Thanks to his daughter, Nuria Tarradell Font, we are able to collect and study this documentation. These records consist of typescripts, manuscripts, graphics and photographs related to the excavations he made during 16 years, between 1948 and 1964, both inside the city and in the suburban area. The main goal at the moment is to store all these information on our GIS platform to better understand the city development, to organize all the documents and make them available to the archaeological community and wider audiences. The creation of a web GIS platform will allow everybody to explore and understand Tarradell's work in Lixus.

Acknowledgements

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Fig. 8. General plan with the orthophotos of the Roman dwellings and the amphitheatre area.

3D aerial photogrammetry: C. Felici and L. Passalacqua; study of the mosque area, survey, photogrammetry and analysis: R. Pansini.

Bibliography

Akerraz, A. 1992. Lixus, du Bas-Empire à l'Islam, In *Lixus. Actes du colloque organisé par l'Institut des sciences de l'archéologie et du patrimoine de Rabat* (Larache, 8-11 novembre 1989): 379-385. Rome, École Française de Rome.

Aranegui Gascò, C. (ed.) 2001. *Lixus: colonia fenicia y ciudad púnico-maurtitana. Anotaciones sobre su ocupación medieval*, Saguntum. Papeles del Laboratorio de Arqueología de Valencia, Extra-4. Valencia, Universitat de Valencia

Aranegui Gascó, C. (ed.) 2005. *Lixus 2- Ladera sur. Excavaciones arqueológicas marroco-españolas en la colonia fenicia. Campañas 2000-2003*. Saguntum, Papeles del Laboratorio de Arqueología de Valencia, Extra-6. Valencia, Universitat de Valencia

Aranegui Gascó, C. 2009. Lixus. Paisaje, arquitectura y urbanismo (ss. VIII - I a.C.). In S. Helas and D. Marzoli

Fig. 9. Extension of the town during the Imperial, Late Roman and Islamic periods.

(eds.), *Phönizisches und punisches Städtewesen. Akten des internationalen Tagung* (Rome, 21-23 febbraio 2007), Iberia Archaeologica 13: 133-46. Mainz am Rhein, Philipp von Zabern.

Aranegui Gascó, C. 2015. Response by C. Aranegui Gascó to E. Papi's review of *Lixus 3* (*Journal of Roman Archaeology* 26, 2013, 800-7). *Journal of Roman Archaeology* 28: 962-4.

Aranegui Gascó, C. and Hassini, H. (eds.) 2010. *Lixus - 3. Área suroeste del sector monumental [Cámaras Montalbán] 2005-2009*. Saguntum, Papeles del Laboratorio de Arqueología de Valencia, Extra-8. Valencia, Universitat de Valencia

Aranegui Gascó, C., Mar, R. 2010. De vuelta al "Barrio de los Templos". Los origenes fenicios de un gran sanctuario mauritano. In: Aranegui Gascó, C. and Hassini, H. (eds.) 2010. *Lixus - 3. Área suroeste del sector monumental [Cámaras Montalbán] 2005-2009*. Saguntum, Papeles del Laboratorio de Arqueología de Valencia, Extra-8: 225-252. Valencia, Universitat de Valencia

Batut, A. 1890. *La photographie aérienne par cerf-volant*. Paris, Gauthier-Villars et fils.

Brouquier-Reddé, V., El Khayari, A., Ichkhakh, A. 2006. Lixus, de l'époque phénicienne à la période médiévale: le quartier dit "des temples". In Akerraz, A., Ruggeri, P., Siraj, A. and Vismara, C. (eds.), *L'Africa Romana. Mobilità delle persone e dei popoli, dinamiche migratorie, emigrazioni ed immigrazioni nelle province occidentali dell'Impero romano. Atti del XVI convegno di studio, Rabat, 15-19 dicembre 2004*: 2157-74. Rome, Carocci.

Brouquier-Reddé, V., El Khayari, A., Ichkhakh, A. 2008. Les édifices religieux de Lixus (Maurétanie Tingitane). In *Lieux de cultes: aires votives, temples, églises, mosquées, IXe Colloque international sur l'histoire et l'archéologie de l'Afrique du Nord antique et médiévale*, *Tripoli, 19-25 février 2005*. Collection Etudes d'Antiquités Africaines: 129-39. Paris, CNRS.

Brouquier-Reddé, V., Ichkhakh, A., Poupon F., El Khayari, A., Hassini, H. 2010. L'occupation phénico-punique du quartier dit des temples de Lixus. In G. Bartoloni, P. Matthiae, L. Nigro 2010. *Tiro, Cartagine, Lixus: nuove acquisizioni : atti del convegno internazionale in onore di Maria Giulia Amadasi Guzzo, Roma, 24-25 novembre 2008*. Quaderni di Vicino Oriente 4: 39-59. Roma, Università di Roma "La Sapienza.

Habibi, M. 2007. Nouvelle étude chronologique du quartier industriel de Lixus. In L. Lagóstena Barrios, D. Bernal Casasola, A. Arévalo González (eds.), *Cetariae 2005. Salsas y salazones de pescado en occidente durante la antigüedad. Actas del Congreso internacional* (Cádiz, 7-9 novembre 2005). British Archaeological Reports International series 1686: 183-9. Oxford, John and Erica Hedges Ltd.

Hallier, G. 2003. Un amphitéâtre militaire à Lixus ? In M. Khanoussi (eds.), *L'Afrique du Nord antique et médiévale : protohistorie, les cités de l'Afrique du Nord, fouilles et prospections récentes. Actes du VIIIe Colloque international sur l'histoire et l'archéologie de l'Afrique du nord. 1er Colloque sur l'histoire et l'archéologie du Maghreb (Tabarka, 8-13 maggio 2000)*: 351-80. Tunis, Institut national du patrimoine.

Lenoir, M. 1992. Lixus à l'époque romaine. In *Lixus. Actes du colloque organisé par l'Institut des sciences de l'archéologie et du patrimoine de Rabat* (Larache, 8-11 novembre 1989): 271-87. Rome, École Française de Rome.

Papi, E. (2013) Châteaux en Espagne? Lixus 3 et le palais de Juba II. *Journal of Roman Archaeology*, 26: 800-7.

Ponsich, M. 1981. *Lixus : le quartier des temples (étude préliminaire)*, Études et travaux d'archéologie marocaine 9, Rabat, Musée des antiquités.

Ponsich, M. 1982. Lixus. Informations archéologiques. *Aufstieg und Niedergang der römischen Welt*, 2.10.2: 817-49.

Ponsich, M. 1988. *Aceite de oliva y salazones de pescado. Factores geo-económicos de Bética y Tingitana*, Madrid, Ediciones de la Universidad Complutense.

Tarradell Mateu, M. 1950. La arqueología romana en el protectorado de España en Marruecos. *Archivos del Instituto de Estudios Africanos*, 4.12: 31-44.

Tarradell Mateu, M. 1959. *Lixus. Historia de la ciudad. Guía de las ruinas y de la sección de Lixus del Museo arqueológico de Tetuán*, Tetuán, Instituto Mulay el-Hassan.

Tissot, C. J. 1877. *Recherches sur la géographie comparée de la Maurétanie Tingitane*, Paris, Imprimerie nationale.

A Dig in the Archive.
The Mertens Archive of Herdonia Excavations: from Digitisation to Communication

Giuliano De Felice
giuliano.defelice@unifg.it

Andrea Fratta
andrea.fratta@unifg.it

Departiment of Humanities, University of Foggia, Italy

Abstract: Since 2004 the Department of Humanities at the University of Foggia has held the historical archive of Herdonia, containing the documentation of archaeological research carried out in the Roman town of Northern Apulia from 1963 to 2000.

The story hidden in the archive is long and complex, written in the documentation produced during 40 years of excavation and survey that led to the discovery of one of the largest Daunian, Roman and medieval sites in southern Italy. The archive is a unique memory covering a long time-span, containing documents that are parts of the history of archaeological research, linked with various methodologies (from long trenches and Wheeler methodology to big areas) and realized using different techniques and technologies (from paper drawings to CAD models, to 3D scans).

The purpose of activities carried out at the Digital Archaeology Lab is to share all the documents of the Herdonia archive starting from spatial data, carrying out specific workflows for building a common environment in which the digitized legacy data and digital born data can stay together.

The first phase of the project has been thus the recovering all the hand-drawn maps, their digitizing and georeferencing in an open source GIS. For the first time all of the sectors and trenches dug up on the site of Herdonia stay together, georeferenced, under the same roof.

Keywords: Archaeological archives, GIS, Communication

1 *Herdonia*: a Roman city in southern Italy (G.D.F., A.F.)

Herdonia is more of a unique case than a rare one in the archaeology of southern Italy. Abandoned in the Late Middle Ages, in comparison to other equally important sites, it has conserved exceptional monumental traces of a multi-millennial history that dates from the pre-Roman era to the 12th century AD. In the conspicuous mounds, which are over 7m high in some places, the histories of an uninterrupted *continuum* are stratified: from the indigenous populations to the Roman settlements, through the centuries of the Republic to the Roman Empire; from being the exceptional witness to centuries of decadence and to the transformation of a wealthy Roman city into a village, to its abandonment and the reconstruction of a small rural borough which still exists near the site (Fig. 1.1).

The main goal of Mertens' first excavations in *Herdonia* was to understand the general topography of the ancient city, starting from the detection of the city walls (Mertens 1965) (Fig. 2.1). This was one of the most important discoveries made by the Belgian team. In the 3rd century BCE, a first dirt wall was built, surrounded by a moat; it was soon replaced by a new wall of unfired bricks. Only at the beginning of the 1st century BCE did a new solid wall in *opus cementicium* replace the ancient fortifications and delimit an urban space of 20 hectares (Fig. 3-1).

During the Second Punic War (218-201 BCE) *Herdonia* was destroyed by Hannibal's army and its population was deported to Metapontum and Thurii. In the 1st century BCE *Herdonia* became a *municipium* and it was assigned to the *gens Papiria*. Many monuments and public structures were built. *Herdonia* experienced a flourishing period after the *Via Traiana* was created. It became an important commercial city, especially for agricultural products.

Between the 2nd and 3rd centuries the city centre of *Herdonia* was pleasant and elegant thanks to the monumental forum surrounded by temples, public buildings and markets; there were also affluent homes and thermal baths. Though earthquakes in the 4th and 5th centuries destroyed many buildings, such as the Basilica, *Herdonia* still kept its importance, as the presence of the bishop *Saturninus*, at the end of the 5th century, proves (Fig. 4-1).

The large quantity of graves and cultivated areas seems to confirm the reduction of the urban space during the Dark Ages, until a new phase began in the 11th century, after a new church was built on the northern hill of *Herdonia* and a village of wooden houses arose around it. In the 12th century the church was converted into a *castellum* surrounded by a defensive moat and it became a royal residence owned by Frederick II. The medieval village of *Herdonia* was ultimately abandoned between the 14th and 15th centuries.

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 4.

Excavations had to stop in 2000 because of disputes over the ownership of plots of land, with the result that the archaeological area is currently abandoned. It seems that such is the fate of this extraordinary site, as predicted by Silius Italicus in the 1st century CE, when he called the city '*obscura Herdonea*' (Volpe *et al*. 2007).

Yet it is not only the material dimension that makes *Herdonia* an 'object of memory'. The history itself of the discovery and the long experience of field investigations, which have brought to light a large part of the site, help make it a unique case and enhance its value even more. Explorations in the area began in 1962 and continued uninterrupted for 40 years. Under the direction of J. Mertens of the Catholic University of Leuven (Belgium) and Giuliano Volpe of the University of

Bari (Italy), *Herdonia* was the longest archaeological research project in southern Italy, a melting pot in which archaeologists from different nations and cultures met and exchanged their experiences, field investigation methodologies and techniques over nearly half a century (Mertens 1995). There was not one methodology that was not applied to the sites of *Herdonia* nor one technique of documentation that was not tested out. From the small sites managed by a few archaeologists with many workmen to the international sites with over a hundred archaeology students; from the long trenches and squares using Wheeler's method to the large areas and surveys; from the excavation notebooks, plans and sections of every millimetre to the first experiments in CAD surveys and digital management of the data, from the negatives on glass and the 35mm films to digital photos and laser scans.

From this exceptional experience of research and training an important and unique trace remains: the historical archives of the digs. A veritable palimpsest of memories and techniques, materials and testimonials, which records in analytical form 40 years of archaeology. An extremely important documentary base, yet very complex too, given the nature of its history and the great variety of its contents, from the first historical nucleus of the digs by the Belgian team, donated by Prof Mertens to the University of Foggia in 2003, to the documentation of the Italian digs (1993-2000) (Volpe, Leone 2008). Hence it was decided to undertake an ambitious project to integrate, transfer to digital format and make available the data to researchers and, more in general to the community (Fig. 5-1).

2 A dig in the archive. The project

The main aim of the project is the definition and experimentation of a workflow for referencing and blending sources belonging to different phases of the research, starting from graphic documentation and written sources. These kinds of documents represent the majority of our - and we can imagine most - archaeological archives and it is mandatory to extract from this kind of documentation as much information as it is possible.

From the time of the acquisition of the archival core, the digital archaeology lab of the University of Foggia has taken on the task of preserving and using the archival data. After field work was halted, several projects of digital archaeology were commenced that were dedicated to the reconstruction of the different phases of the city, starting from the research data and obviously using the data in the historical archives. As of today, reconstructed models of the principal monuments of the Roman forum and baths have been realised.

As we believe that it is mandatory to make these data available for all kind of users, we are currently implementing a WebGIS platform that can be handy for several purposes, from research planning to visitor support. This platform is currently undergoing test phase on a smaller context of the roman Forum, where a very complex stratigraphy describes life phases from pre-roman times to early Middle Ages; the aim is to build an interactive 3D environment with a reconstruction of the whole chronological sequence and share it on a website.

'A dig in the archives' forms part of a doctoral project in 'History and Global Landscape Archaeology', a postgraduate course in the Department of Humanities at the University of Foggia. The idea is part of the research being carried out by our Digital

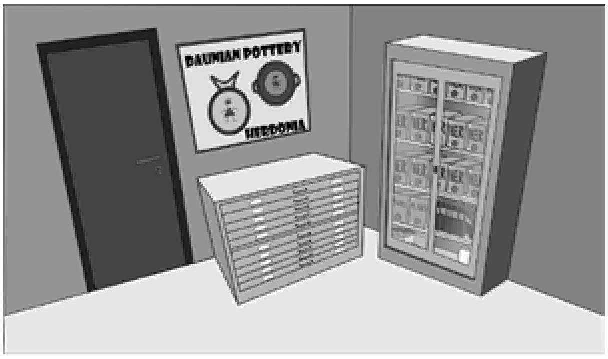

FIG. 5.

Archaeology Lab: archaeological survey and documentation, data processing and communication to the general public. We are seeking to examine the real potential of a complete data processing workflow, focused on sharing information and, in this way, spreading archaeological knowledge (Bonacchi 2012). The project was started at the beginning of 2013 with the aim of digitising the whole of the archives and testing some possible ways of sharing the informative potential of visual archaeological documentation using web applications.

The methodological planning adopted for this task was divided into three main phases:

1. Data acquiring and processing
2. Management
3. Sharing

The *Herdonia* archive is a very interesting case study because it allows us to deal with issues concerning both topographic data management – such as integration between different kinds of data, collected in different periods with different techniques – and social repercussions.

Moreover, the recovery and digitising of the archives fit in well with the general debate over sharing and open access in archaeology: in 2008 the Europae Archaeologiae Consilium created a specific working group to examine the processes of archiving archaeological documentation in the ARCHES project. The main goal of ARCHES is 'to make archaeological archival practice throughout Europe consistent, in order to facilitate access to and preservation of archaeological records. This is achieved by producing standards and best practices for the creation, compilation, transfer and custody of archaeological archives that are sustainable and open to further development' (ARCHES Project 2012).

Therefore archives represent the place where archaeological information is deposited and encoded in many kinds of documents. For us, the *Herdonia* archives represent the ideal case–study to test all the methodologies of documentation which we carry out, to integrate different spatial and topographical data and to give them a wider social role in order to make people aware of *Herdonia*, even though it looks abandoned because of ownership disputes.

3 First steps (2013–2015). Acquiring, processing and managing documentation

Though *Herdonia* is well known to archaeologists,[1] it still lacks any real knowledge among the communities that live in the region and, more in general, among a larger public. This is the reason why we believe that sharing data from Mertens' archives is absolutely necessary. We are convinced that archaeology must have a positive social role, and to fulfil this aim we need to make research available to the general public. If we dig in these archives we can get and share information not only about the history of *Herdonia* but also about the history of excavations, methodologies and practices adopted in archaeology.

3.1 Acquiring data

The archives contain many kinds of documents. All the written records are stored in binders divided into chronological order; here we can find daily journals, reports, many articles from both Belgian and Italian newspapers about Belgian archaeological projects in Italy and letters that J. Mertens received from his collaborators. There are also sketches and drafts of particular finds, such as ceramics, coins and architectural elements. Archaeological finds have been listed in many inventories grouped by year. Most of them are collected in the Museum of Foggia and in the soon to be opened Museum of Ordona, but we still have their descriptions, slides and drawings in the archives.

Visual documentation consists of geographic aero–photogrammetric maps with a rough positioning of excavations and many ground plans and archaeological sections of the dig areas; stratigraphic units are often filled with different colours: each colour corresponds to a chronological phase. Studying the archives helps us better understand not only how archaeological information had been organised, but also the methodologies adopted by the Belgian team in the practice of digging and spatial data recording.

As already mentioned, the archives contain many kinds of data and several investigations could be carried out. However, for at least for two reasons, we considered overriding the creation of a global digital cartography where spatial data can be kept together in a geo–referenced system:

- After 40 years of excavations we still don't have a complete map of the Roman city.

- If we convert maps into digital format we can integrate both analogical and digital data such as total station and photogrammetric data.

3.2 Processing

Considering that we chose to work on the topography of *Herdonia*, the first step focused on the collection and examination of all the charts drawn by Belgian archaeologists. The investigations in the archives had different purposes, first of all the arrangement of the visual documentation. We organised all the charts following the order used by the Belgian archaeologists. Each chart was labelled with a number to indicate a precise topographical context of the archaeological area. Each chart has been scanned and converted from a raster format to a vector one in order to give each geometrical entity three dimensional spatial coordinates.

Visual documentation is strongly conditioned by the methodology of excavation. As we can easily imagine, a map drawn in the 1960s might look very different from the normal visual outputs we use today. This is the case with the Mertens archives. There are many differences compared with the features of current visual documentation. For example, single stratigraphic unit overlays do not exist. Belgian archaeologists drew plans with logical groups called *niveaux* (levels), where stratigraphic units were represented in different chronological phases but were connected for functional reasons.

Another considerable difference is the lack of elevation quotas. This is an issue we have had to deal with, because it makes 3D modelling of archaeological layers more difficult and less accurate. However it is very important to notice changes in the methodology of excavations by analysing visual documentation. After the long trenches of the early 1960s, Mertens decided to investigate larger areas, digging with Wheeler's method in the 1970s, until definitively pass to even larger areas at the end of the 1980s (Fig. 6-1).

After maps were entirely vectorised with CAD software, we created a GIS by positioning them on a digital CTR, the Regional Technical Map of Apulia. An initial positioning has been carried out thanks to the measurements of angles and distances from a modern building that Belgian archaeologists used as a reference point. Of course we had to deal with many errors in the global positioning of these maps in current digital cartography. We managed to check the errors of positioning by working on fields with electronic instruments; however, with the exceptions of the areas where there are still remains of ancient buildings, it is quite impossible to carry out, since many trenches have been covered over due to the use of the land for agriculture. Nevertheless, global positioning of archaeological entities made by Mertens on an aero–photogrammetric map is almost correct, even if we take into account the approximation occurring with elevated scale factors.

In this phase we also studied all the diaries of the excavations in order to understand better the criteria that conditioned the field work and, of course, the visual documentation, and to collect precise information about stratigraphic layers.

3.3 Management

Herdonia GIS represents not only a system to visualise geo–referenced maps, but also a basis of archaeological information linked to spatial data (Teodor 2014). The software we used for this is Quantum GIS; free and open source software is often used in many subjects, including archaeology (Fig. 7-1).

We used QGIS to categorise the geometric entities of all the vector layers of the trenches in order to allow users to search for information by asking certain questions. After a preliminary subdivision, we created three main categories: year of excavation, topographic context and chronology. In this way it is possible to visualise different thematic maps of

[1] Eleven volumes of the series 'Ordona' have been published. There are also a short book about the history of the Roman city, many scholarly articles and many MA and PhD theses.

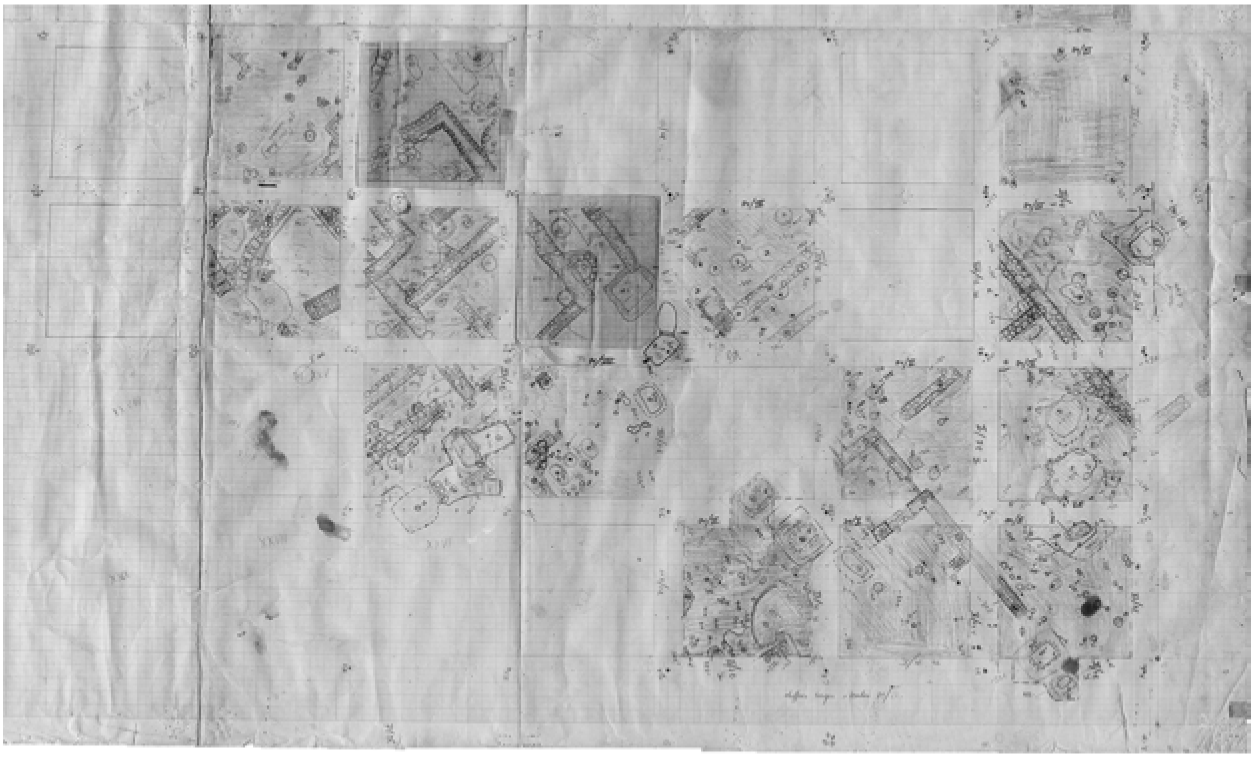

fig. 6.

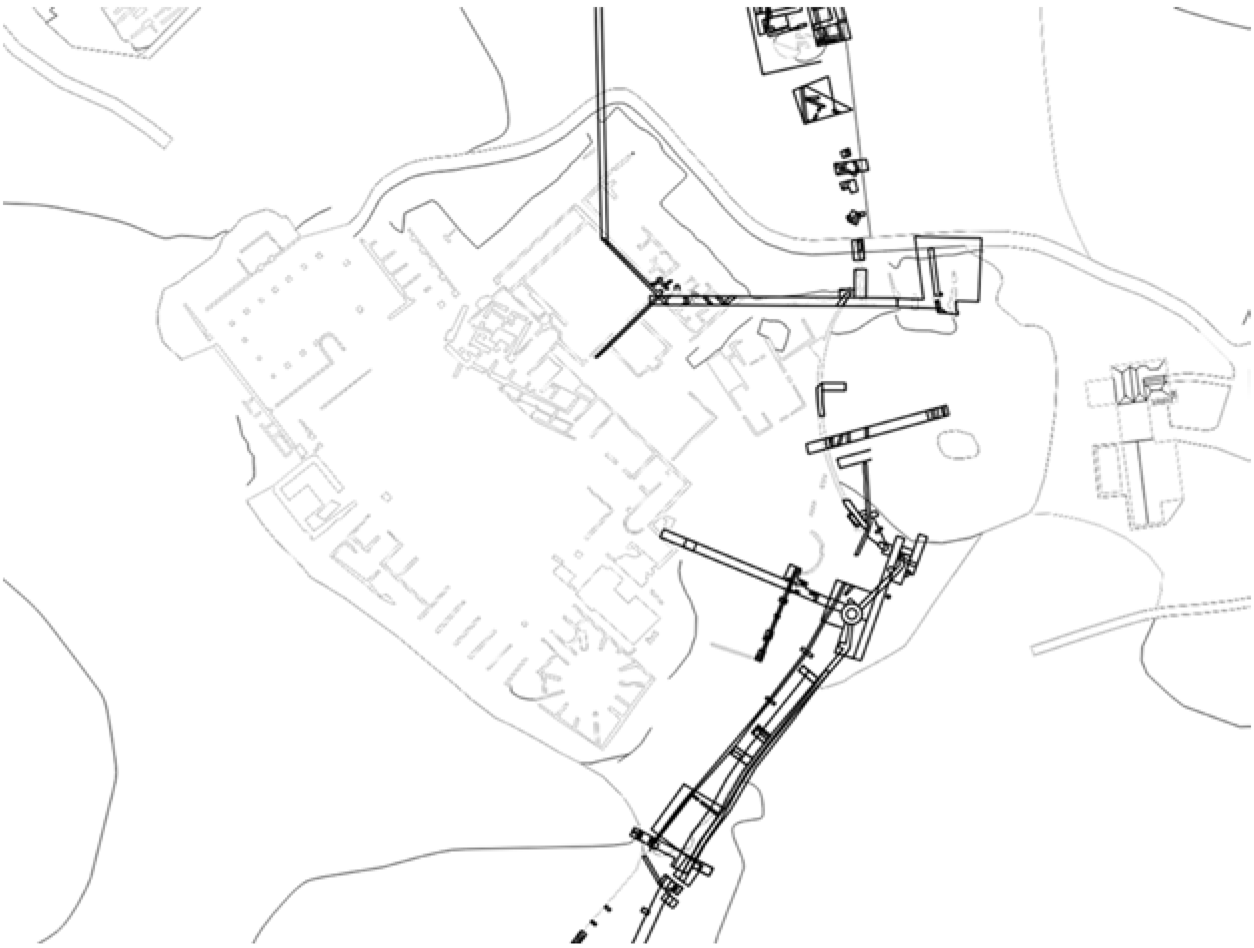

Fig. 7.

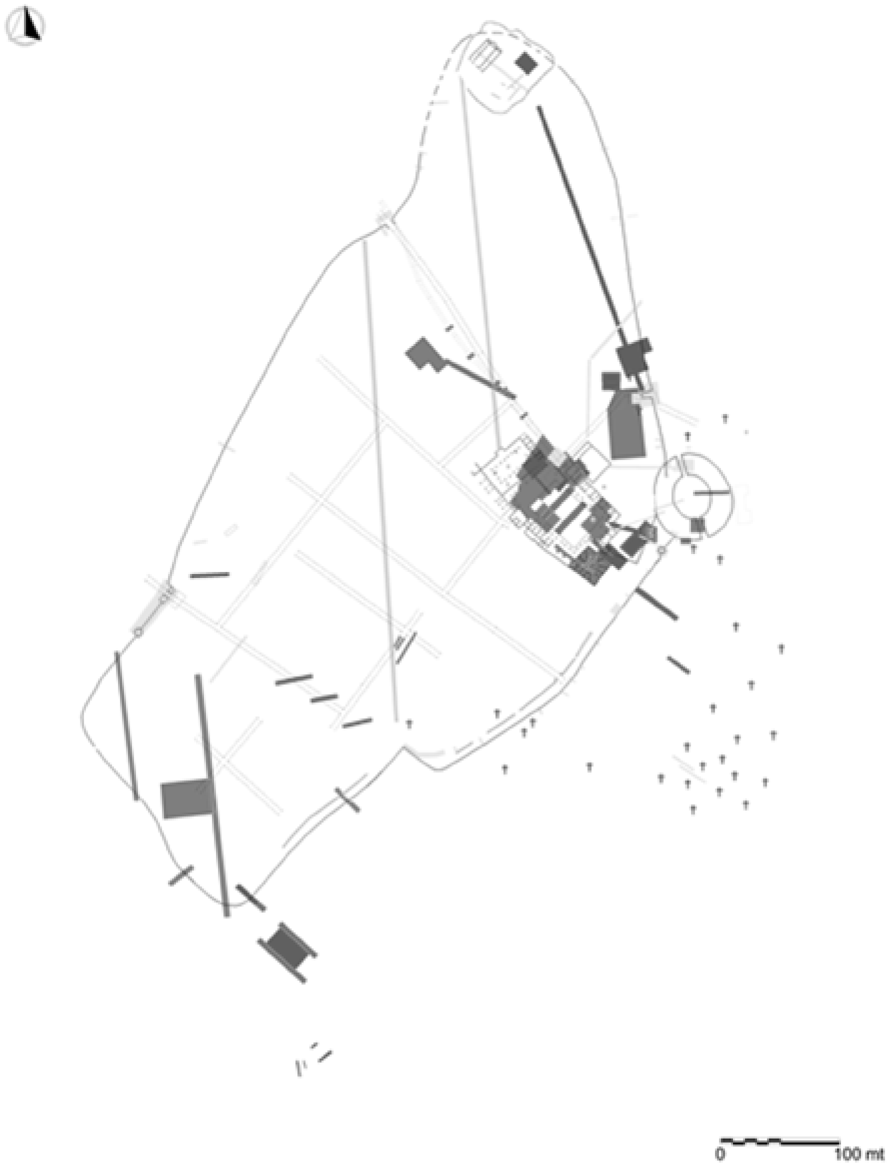

FIG. 8.

Herdonia, where layers can be labelled depending on the year of excavation or the chronological phase (Fig. 8-1).

Of course, it is possible to create a more detailed information system, and to do so, a more in-depth study of the individual trenches is required. In any case, we consider as a first, important goal the realisation of a global digital cartography of *Herdonia*, which still does not exist. More than 200 maps have been acquired, vectorised and imported to the *Herdonia* GIS. Moreover, a future step we're working on is the integration of other documents in the geographical system. In particular we aim to add the enormous quantity of pictures taken during the excavations and link them to vector data thanks to very useful plugins such as eVis (QGis 2009). Apart from GIS, we also used a MySQL database to organise all the raster data. Users can easily browse maps and sections and easily find them in the real archive.

4 Next steps – Merging new and old data and sharing

Sharing data and interactive visualisation. If the main idea of this project is the disclosure of data from Mertens' archives via a WebGIS where users can quickly find legacy data related to geometric entities in a digital geo-referenced cartography, there is also a second goal that we would like to achieve: the creation of a 3D environment in order to understand better the chronological sequence of a part of the ancient forum, the area of the Basilica (Fig. 9-1).

Belgian excavations reported a very complex stratigraphic sequence on the northern side of the forum, and in this area we can notice the profound changes that modified the urban layout throughout the centuries: from the Daunian defensive moat surrounded by chamber tombs to the different phases of the Roman forum with underground rooms and the construction

fig. 9.

of important public buildings, such as the Basilica; from the reuse of part of the Roman walls in the Early Christian era to the Medieval village and then ultimate abandonment (Mertens 1971; Mertens 1997).

We also carried out a photogrammetric survey in order to obtain a high quality 3D model of the area through a low cost processing system, like Autodesk 123DCatch (Autodesk 123D 2015). Our idea is to model all the geometric entities from paper to screen and put them in a common system with 3D models of the area of the Basilica in its present state. So users can scroll through the archaeological layers and learn about the history of the ancient city and the archaeological methodology of the excavations. In other words, we'd like to let users 'dig in a virtual scene. In this application we'd like to show not only the documents, maps and photos we used to reconstruct the stratigraphic sequence, but also the archaeological way of thinking. In other words, we're writing a short story to illustrate the urban evolution of *Herdonia*.

3D surveying has been one of the main activities of the Digital Archaeology Lab since its foundation. We use TOF laser scanning to acquire point clouds of buildings or archaeological sites; a low cost laser scanner for small objects, such as particular finds (De Felice *et al*. 2012), and also 3D photogrammetry. We believe that 3D data can be very useful not only for spatial and morphological analyses, but such data can also be implemented as 3D objects in different 'viewers' for communication (Fig. 10-1, Fig. 11-1).

fig. 10.

In the first phase of our project we had to test whether 3D data acquired by laser scanning or photogrammetry could fit in a virtual interactive environment or in a common web browser. Scanned data processing is not easy and a lengthy procedure is imperative for many reasons: data are too heavy and generally real–time engines impose a maximum value of vertices. Moreover, meshes generated from point clouds might

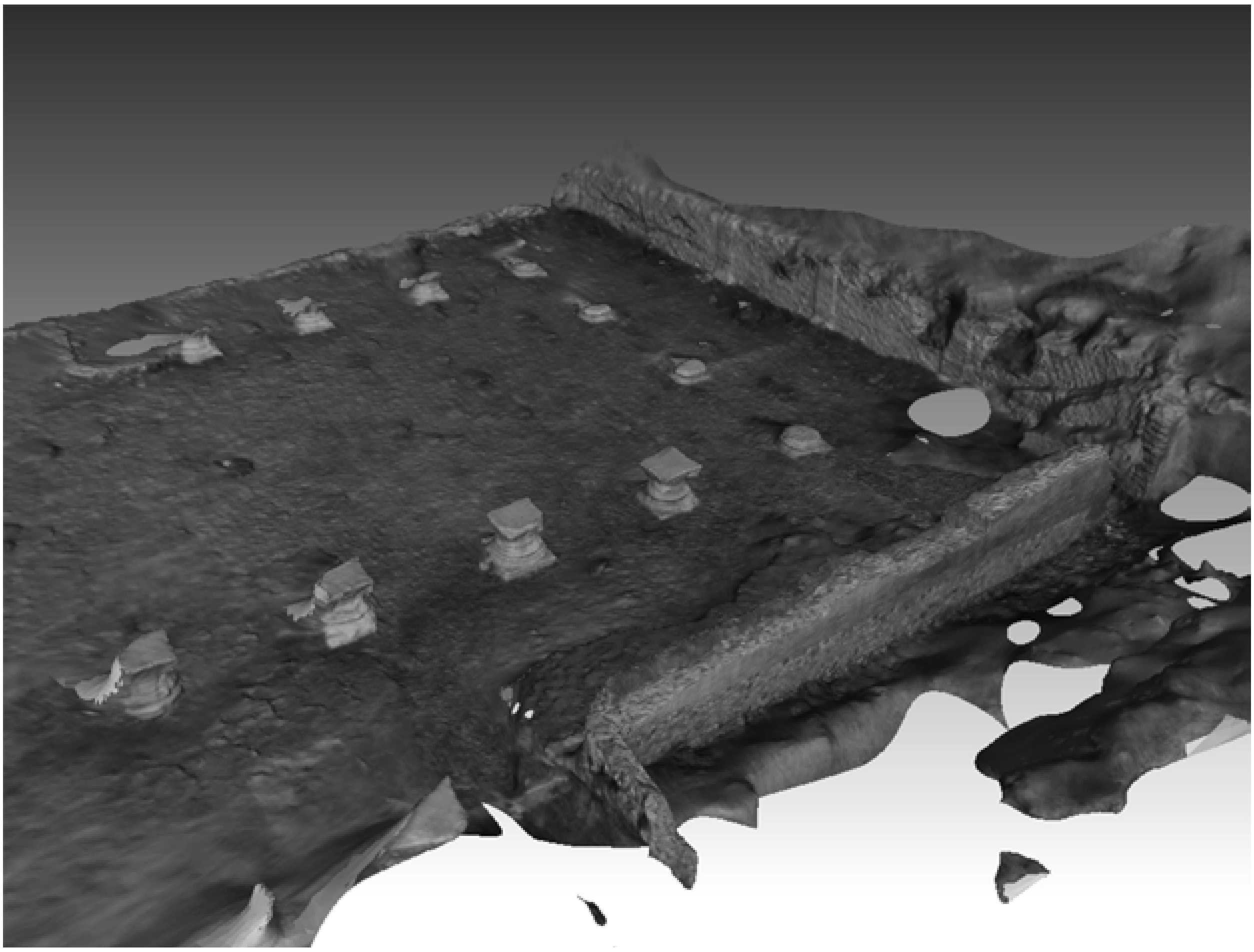

FIG. 11.

have several non–manifold components and so they could not be imported into these scenes. Meshes generated from 3D surveying techniques can be conveniently processed in order to reduce the number of geometric primitives, delete eventual errors in the 3D surface and transfer attributes such as colour.

Before starting the project, we carried out a process to elaborate raw 3D data until they were ready to be embedded in frameworks for interactive visualisation (Guidi *et al*. 2010). It doesn't matter that we are working with real–time engines or 3D viewers for browsers: complex 3D meshes need to be reduced and optimised (Scopigno 2006). But how can we do this? Will we lose the high level of detail of the original mesh?

The general workflow we employed for data processing consists of two main phases: the first one concerns the geometry of the model, and the second one the layout. In MeshLab (Meshlab 2015) we made copies of the original mesh using its powerful remesh algorithms that allow us to generate a new mesh usually with no non–manifold components. After that, it is possible to state the number of the triangular faces thanks to decimation tools. In this way we can control the number of vertices and respect the limits imposed by real-time engines.

For the second phase we preferred working with Blender (Blender Foundation 2015). This software offers the possibility to transfer attributes from one 3D object to another, if they are imported in the same scene. Thanks to 'baking' tools it is possible to generate raster maps of attributes from a hi-poly to a low-poly mesh, and transfer chromatic information or normal face in order to make textures and normal or displacement maps. In this way, even if the 'destination' model has a very simplified geometry, it still looks very detailed. Thanks to this procedure we successfully imported meshes to online 3D viewers (LAD 2012) such as Sketchfab or p3D.in and even to virtual interactive games (Comune di Deliceto 2014).

Tests on 3D data confirmed the effectiveness of these processes in order to import complex 3D meshes to interactive scenes. We consider 3D data as an essential part of archaeological documentation, along with legacy data and 2D outputs, such as ground plans, overlays and stratigraphic sections. Now our question is: can we use this documentation to spread archaeological knowledge? (Fig. 12-1).

5 Conclusions

In the first two years of activity about 300 maps had been acquired in raster format, georeferenced and vectorised and 90 trenches had been added to the global cartography of *Herdonia*. For the first time we have a digital and complete map that can be easily used by all kind of users. Furthermore other typologies of data, such as pictures, journals and inventories of archaeological finds can be linked to *Herdonia* GIS.

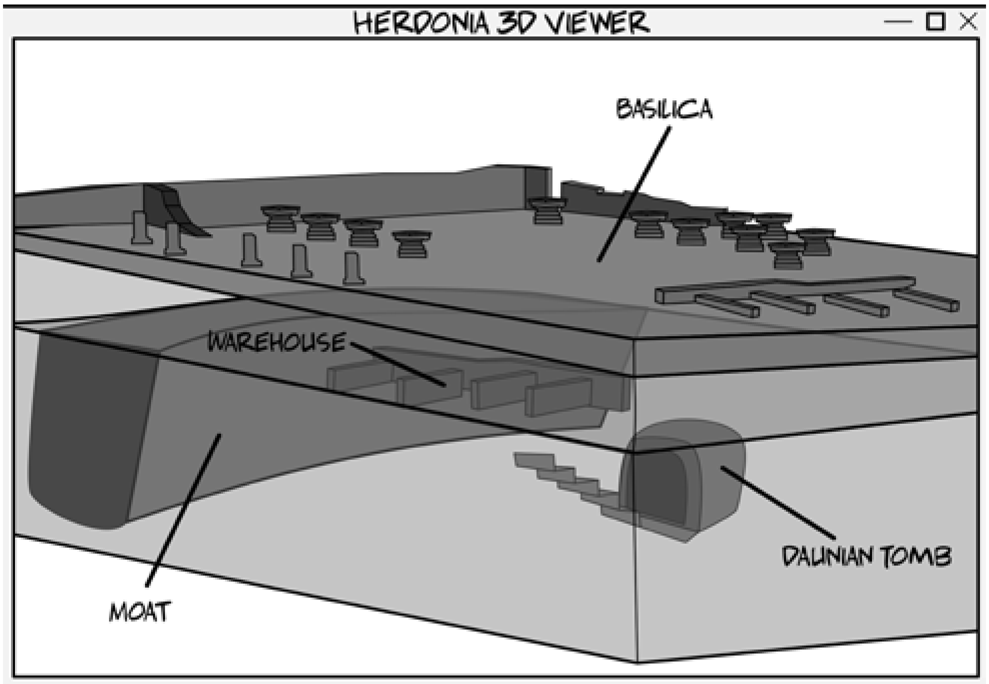

fig. 12.

The 'dig in the archive' project is just at the beginning. Many other 'digs' could be done and many other paths could be trodden, but we are sure the direction we have taken is the right one.

A strong relationship between archaeology and communication occurs, and Mertens' archives are the proof: 40 years of excavations and only the central area of *Herdonia* is visible today. Most of the archaeological ruins are still buried, but information about them is stored in the archive. Our purpose is to continue investigations in *Herdonia*, making interlocutors – both specialists and the general public – more interested.

Opening an archive means spreading knowledge. This is our attempt to make access to the archives easier. We began to work on topography since, thanks to GIS, we are able to link different information to geographic data and we can share a complete digital cartography of *Herdonia* with the community of archaeologists for the first time.

But we can do something more. Many people do not want to read all the documentation related to a site. They just prefer to understand its history. This may not be the right place to talk about effective communication in museums or archaeological sites, but we strongly believe that 'translating' archaeological data into something that people can better understand is the archaeologist's task. That explains why we would like to propose a 3D interactive application to make users aware of the archaeological stratifications of *Herdonia*: layers are the facts with which archaeologists write the story of a site. And 3D is just *one* way, not *the* way. We need to find the solutions that best fit our communication purposes. Technologies do not work without contents: a good tale is what people are looking for.

Bibliography

Arches Project 2012. *The Standard and Guide to Best Practice in Archaeological Archiving in Europe.* http://archaeologydataservice.ac.uk/arches/Wiki.jsp?page=INTRODUCTION [Accessed: 18 June 2015]

Bonacchi, C. (ed.) 2012. *Archaeology and Digital Communication: Towards Strategies of Public Engagement*, London, Archetype Publications.

Callieri, M, Corsini, M., Ranzuglia, G., Cignoni, P. 2009. Scanner 3D con hardware low cost e strumenti free/open source. *Archeologia e Calcolatori. Suppl.* 2: 175-82.

Comune Di Deliceto 2014. *HistoryHub* http://www.comune.deliceto.fg.it/Default.aspx?frame=CittaTerritorio\HistoryHub\Scarica.ascx [Accessed: 25 june 2015]

De Felice, G., Fratta, A., Moscaritolo, C. 2013. Il progetto 'Archeo3D' per una gestione tridimensionale dei dati archeologici. Una prospettiva open?. *Archeologia e Calcolatori. Suppl.* 4: 194-201.

Gianattasio, C., Grillo, S. M., Vacca, G. 2014. The Medieval San Francesco Convent in Cagliari: From the architectural. Materical and Historical-Stratigraphical Analysis to the Information System. *International Journal of Heritage in the Digital Era* 3, 3: 413-29.

Guidi, G., Russo, M., Beraldin, J. A. 2010. *Acquisizione 3D e modellazione poligonale*. Milano, McGraw-Hill.

Kansa, E., Whitcher Kansa, S., Watrall, E. (eds.) 2011. Archaeology 2.0: New Approaches to Communication and Collaboration. *Cotsen Digital Archaeology 1*, The Cotsen Institute of Archaeology at Ucla. Available from: https://escholarship.org/uc/item/1r6137tb [Accessed: 23 july 2015].

Lad - Laboratorio Di Archeologia Digitale. (2012) ArcheO3D http://www.archeologiadigitale.it/progetti/a3d/a3d/a3dmet.php [Accessed: 25 june 2015]

Mertens, J. 1965. *Ordona 1. Rapport provisoire sur les travaux de la mission belge en 1962/63 et 1963/64.* Roma.

Mertens, J. 1971. *Ordona 3. Rapport et études.* Roma.

Mertens, J. (ed.) 1995. *Herdonia, scoperta di una città.* Bari, Edipuglia.

Mertens, J. 1997. *Ordona 9. Rapport et études.* Roma.

Mohan Das, V., Garg, Y. 2011. Digital reconstruction of Pavilions described in an Ancient Indian architectural treatise. *Journal on Computing and Cultural Heritage* 4, 1-4: 1-16. New York, ACM.

Scopigno, R. 2006. Gestione efficiente dei dati prodotti dai sistemi di scansione tridimensionale. In: Campana, S., Francovich, R., (eds.), *Laser Scanner e GPS, Paesaggi Archeologici e Tecnologie Digitali*: 41-68. Firenze, All'Insegna del Giglio.

Selden, R., Means, B., Lohse, J., Koenig, C., Black, S. 2014. Beyond Documentation: 3D Data in Archaeology. *The Newsletter of Texas Archaeological Society* 58, 4: 20-4. Available at: http://www.txarch.org/Publications/newsletters/index.html. [Accessed: 23 june 2015]

Simon, K. M., Payne, A. M., Cole, K., Smallwood, C. S., Goodmaster, C., Limp, F. 2009. Close-Range 3D Laser Scanning and Virtual Museums: Beyond Wonder Chambers and Cabinets of Curiosity?. *Making history interactive. Papers from the 37th Annual Conference of Computer Applications and Quantitative Methods in Archaeology, Williamsburg 22-26 March 2009*. (Online Proceedings). Available at: http://www.caa2009.org/articles/ Simon_Contribution368_a (1).pdf [Accessed: 23 june 2015]

Teodor, A. 2014. 2D topographic data mangement: a Case study on Callatis' general site plans. *International Journal of Heritage in the Digital Era* 3, 3: 501-29.

Volpe, G., Goffredo, R., Di Zanni, A. 2007. Herdonia e l'archeologia dei paesaggi della Valle del Carapelle. Per un museo archeologico diffuso. In Longo, L, Vecchionii, V., Sistemi locali e sviluppo. Lineamenti per un piano strategico: 109-24. Foggia, Claudio Grenzi Editore.

Volpe, G., Leone, D. 2008. *Ordona XI. Ricerche archeologiche a Herdonia.* Bari, Edipuglia.

Archaeological and Physicochemical Approaches to the Territory: On-site Analysis and Multidisciplinary Databases for the Reconstruction of Historical Landscapes

Luisa Dallai[(1)]
luisa.dallai@unisi.it

Alessandro Donati[(2)]
alessandro.donati@unisi.it

Vanessa Volpi[(2)]
volpi13@student.unisi.it

Andrea Bardi[(1)]
andreabardi71@gmail.com .

[1] Department of Historical Sciences and Cultural Heritage, University of Siena
[2] Department of Biotechnology, Chemistry and Pharmacy, University of Siena

Abstract: The 'Colline Metallifere', a wide territory located in the south-west of Tuscany, has been characterized by a great development of mining activity over the centuries; this is due to the presence of a large mineral deposit, mainly constituted by mixed sulfide ores, that were exploited since Eneolithic age for the extraction of copper, silver, lead and iron.

The territory has extreme relevance for the study of pre-industrial mining and smelting processed. Here, archeological research has been developed since '80 through archaeological digs and surveys. The project and the results we are going to briefly present are the result of an established collaboration between archaeologists and chemists of the University of Siena. It implies the comprehensive study of ancient mining sites, combining classic historical and archaeological observations with physical-chemical measurements and statistical methods, as well as the development of a multidisciplinary-relational database.

Keywords: Interdisciplinary methodology, Archaeological surveys, Smart Database, Physical-chemical analysis, Mining territory

1 Aims of the project (L.D., A.D., V.V., A.B.)

The research project we are going to present has been developed and is still going on over a wide territory located in southern Toscana, the 'Colline Metallifere' district (Fig. 1). The area is very well known for the presence of a large mineral deposit, mainly constituted by mixed sulfide ores, that were exploited for the production of copper, silver, lead and iron. As a consequence, the area has known a great development of mining activity, that has left outstanding remains (mining shafts, galleries, slag heaps) dating back to a long range of time. Beside this, considerable alunite deposits underwent to a systematic extraction activity historically recorded from Late Middle Age to early 19th century, even though archaeological research is discovering a much longer exploitation tradition. In the Colline Metallifere district, the University of Siena has undertaken archeological researches since 1980 through excavations and surveys, covering a territory of more than 145km^2, recording and describing over 2500 sites (about 50% of these were ancient mining and/or smelting sites). The data collected both from digs and fieldworks have contributed to produce a general understanding of the mining exploitation techniques and ore transformation and commercialization over time (Dallai 2013; Bianchi *et al*. 2013). From an environmental point of view, the area offers many research suggestions; among these, the presence of arsenic and heavy metals contamination associated to the relevant remains of the long-

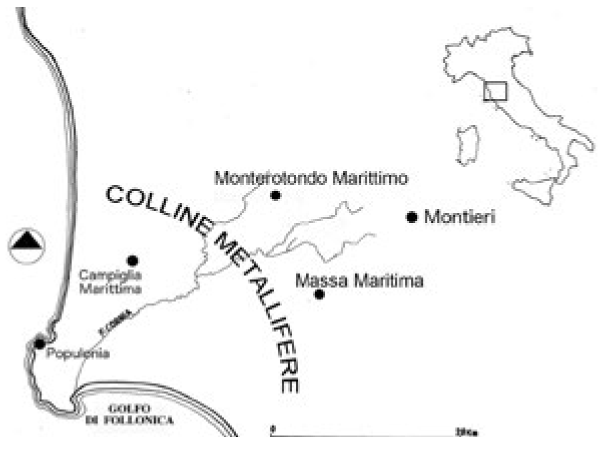

Fig.1. Location of sites referred to in the text.

standing tradition of ore mining and processing has addressed the development of a multidisciplinary project, in which a combination of archaeological and physicochemical analyses and the statistical treatment of the data are used to describe and interpret this peculiar historical landscape (Dallai *et al*. 2013). A number of scientific techniques applied on environmental matrices (i.e. soil, stream sediments, water, plants) have been used with both predictive and descriptive goals. In particular, high throughput techniques have been used in multi-scale investigations (*intra-situ* and medium-large territorial scale) in order to obtain detailed chemical and/or geochemical maps. The merging of these data with archaeological maps will give a more accurate interpretation of the historical context and can be very advantageous in the excavation planning of a site. This model need a specific care in the classification, storage and recovering of the data. Consequently the production of a 'smart database' is mandatory in order to have a correct inter-exchangeability of the data and flexibility in the data-mining.

In the present work the methodological approach of our research is reported together with key studies demonstrating its validity and robustness.

2 The territory of the southern Colline Metallifere: historical mining, metallurgical tradition and archaeological investigations (L.D.)

Investigations in the Colline Metallifere Grossetane, specifically the southern part of the hill-chain that stretches from the province of Livorno (north of Populonia), to Grosseto, began in the mid-1990s, with the planning of a series of topographic campaigns in sample areas that have a strong connection with mining. During the years, several archaeological digs in key sites (i.e. fortified settlements and productive structures) have been undertaken as well. Since the very beginning, the aim of the project has been to propose a reconstructions of changes through time in settlement patterns and exploitation techniques (both mining and metallurgical ones), stressing the existing relations between natural resources and settlements, with a special focus on the Medieval time. The reach mineralization was crucial in addressing the gradual increase in the importance of inland areas, such as the hilly ones, compared with coastal plains. This phenomenon is documented in the archeological record ever since the later Roman time, reaching a peak in the medieval period (Marasco 2013). Polymetallic deposits in the Massa Marittima and Montieri area became of primary importance in the medieval period, for the productions of so-called 'coinable metals'; in this same period, together with intensive mining, specific regulations, the so called *Ordinamenta super artem fossarum rameriae et argenteriae civitatis Massae,* drafted at the end of the 13th century, were produced and included within the statute of the Comune of Massa Marittima (1311-1325). The *Ordinamenta* constitute one of the oldest examples in Europe of mining regulations, and represent a rich source of technical information relating to the management and control of mining activities (Dallai 2014). In the same area, out of the many different research in-depths proposed by the project, some of the mines of Massa Marittima have become the terrain for a pilot study that has produced a better understanding of both mining techniques, productive steps, and the environmental impact of ancient tips on the surrounding area. Underground surveys and explorations have revealed a number of technical characteristics used at these mine-workings as well (Aranguren *et al*. 2007). Chemical analyses carried out on waste material have revealed that, in the presence of marked differences in the nature of the mining deposit in question, initial selection operations at the mine head were capable of eliminating minerals regarded as useless for the purposes of production (e.g. calamine) which is clearly a sign of skill, specifically in the systematic setting aside of zinc minerals from the extraction and metallurgical process (Dallai *et al*. 2013).

The project is still going on, with a special focus on multidisciplinary approaches to the territory. In some cases (a good example is the territory of Montieri), new inspections are currently being planned, to increase the amount of information available. In particular field-surveys on the hill of Montieri have revealed a very large number of mine openings that are now filled in. Although it is not possible to establish a definite date for these, it is known that there were many profitable mines active here in the medieval period (there are also references to these in the well-known *Brevi* of Montieri, written documents dated to the first quarter of the 13th century), which were mined for silver.

Access to the underground areas in the Montieri district has been possible thanks to the presence of mine-workings datable to the early years of the 19th century (in the Poggio area), or to the second half of the 18th century (in the area known as Le Carbonaie), which used parts of older workings. The more recent mine-workings, often intended for the production of green vitriol, have revealed the existence of older tunnels and chambers, probably dug by miners seeking copper and silver minerals, and the presence of waste rock stored within the chambers themselves (Fig. 2) (Dallai *et al*. 2012).

In the majority of the sampled areas of the Colline Metallifere, where researchers have identified ancient mines features and the remains of industrial structures related to metallurgical production, these have become a very good 'data sets' on which the project team could perform combined archaeological and physicochemical analyses. A statistical interpretation of chemical analyses on residues of mineral processing has made it possible to add new pieces of information to our understanding of economic exploitation in the pre-industrial era.

2.1 Data base structure and data collection: physico-chemical, archaeological and geological data (A.B.)

Given the multidisciplinary nature of the project, the storage and management data system has to deal with data originated from different sources: archaeological, chemical and geological in particular. Moreover, it has to be taken in account that the aim of the database is not merely limited to a data consultation, but fosters an interaction between the different sections in order to obtain extra information.

The data base structure is summarized as follows:

- disciplinary sections designed to store information derived from different sources: geological, historical, chemical and archaeological in particular.
- possible interactions between the different sections.
- geographic data management.
- tools for data analysis in each disciplinary section and through the different ones.

The construction of this archive has started with the choice of the RDMS software (*https://it.wikipedia.org/wiki/Relational_database_management_system*), that allows us to build a quite complex relational structure with the possibility to organize geographical data. The next step has been the selection of the Open source MySQL software, as well as MsAccess and

Fig. 2. Ancient mines located in the study area: underground inspections (LTTM, University of Siena).

LibreBase softwares, with the aim of allowing data viewing and consulting. For the construction of the database structure the choice has privileged the open source software Workbanch, which allowed us the development of a conceptual model.

Regarding the three main sections of the database (the geological, chemical and archaeological ones), the 'state of the art' was quite different from one section to the other; as an example, considering the archaeological data, the project could profit of an already existing storage structure which required only a general revision, according to the new needs of the research and the interaction with the others sections. On the contrary, as regards to the chemical and geological sections, the structure had to be completely built up. The final conceptual model of this storage system can be define as a 'star', at whose centre we have the so called 'localization', that is a couple of geographic coordinates. In order to clarify this concept we can use the example of the on-site handheld XRF analyses; once the data have been acquired, they will be stored in a separate table containing the site coordinates; through internal relations, the table is linked to the rest of the database structure.

The nature of data acquired to the project can vary a lot, depending on the different needs of each discipline; if on the one hand for the archaeological and geological sections we deal with descriptive alphanumeric information, which must be digitized by an operator, on the other hand the chemical analyses produce only numeric data. It is clear that this different nature of data turns to be a problem both for their management and comparison. In order to obtain comparative analyses and spatial analysis developed with the GIS software, that is one of the main goals of this project, it is therefore mandatory that the nature of data, even if originally very different, became similar. For this reason we have defined a 'conversion field' voice that enable the translation of alphanumeric values into numbers by giving a value, where possible, to each descriptive definition.

This method can obviously produce errors; therefore the 'weight' of the field may vary, according to the different contexts.

For the statistical analysis, we have chosen the so called 'Cube OLAP methodology' (*https://it.wikipedia.org/wiki/Cubo_OLAP*); the OLAP cube is defined as a multidimensional spreadsheet where the values stored in each face can interact in a virtually unlimited way with the values of the other faces (Fig. 3). Through the use of Pivot Tables, this methodology is capable to analyze a large amount of data in a short time, and can also deal with values of different nature.

Finally, the database scheme is designed to follow three different steps: data input; management and consulting and data processing. This last final step runs partially outside the structure itself and interacts with other software for data exchange. The database can be query in order to obtain a selection of information; thanks to the query, we can obtain sets of data ready to be analyzed by other programs, such as the spreadsheet that supports the function OLAP (i.e. Excel or LibreCalc) and GIS software for spatial analysis. This goal is obtained with a mechanism of data import in which an external spreadsheet regularly updated can developed OLAP queries, graphs and statistical analyses. This sheet can also generate a point file based on geographic coordinates, ready to be imported into GIS software.

Mentioning geographical data storage, the database has also a part dedicated to this aim. MySql software allows us to create specific tables for the geographical data storage that can be related to other tables for data management and interrogation. DBMS bridges between the queries required from the client and the DB storage; this can be particularly useful when managing large volumes of queries. One of the possible goals in the use of this database is also the identification and selection of key areas that satisfy given characteristics (Fig. 4). This process, which is typical of predictive archaeology, follows standardized procedures. The availability of chemical and geological data expands the possible combinations of information, usually limited to the geomorphological ones.

To conclude, the structure that we have designed can also deal with a difficult aspect of data management, the so called indexes. The term index identify the 'weight' assigned to a particular feature, or to a particular combination of elements, in addressing or modifying the development of a given area. The definition of this 'weights' is complex and strictly related to the territory in which they are identified. It is hard to imagine or to employ similar indexes to read different territories; even if possible biases have to be taken in account, we think that they can be a powerful tool for reading homogeneous contexts, especially for predictive analysis.

3 A key study area: Montieri and the medieval silver production

3.1 An archaeological and historical overview (L.D.)

Archaeological investigation in the Montieri district, one of the most relevant silver, lead and copper mining area of the Colline Metallifere, began in 2007, with archaeological digs (emergency excavation works and archaeological digs undertaken both in the town center and in the parish church named 'La Canonica'); surveys on crucial territorial samples, such as the Poggio of Monteri itself and other main mining areas; physico-chemical analysis performed both on wide areas (such as on sediments sampled along the streams of the Poggio itself), as well as on archaeological digging sites (i.e. La Canonica, mentioned above) (Benvenuti *et al*. 2014). The

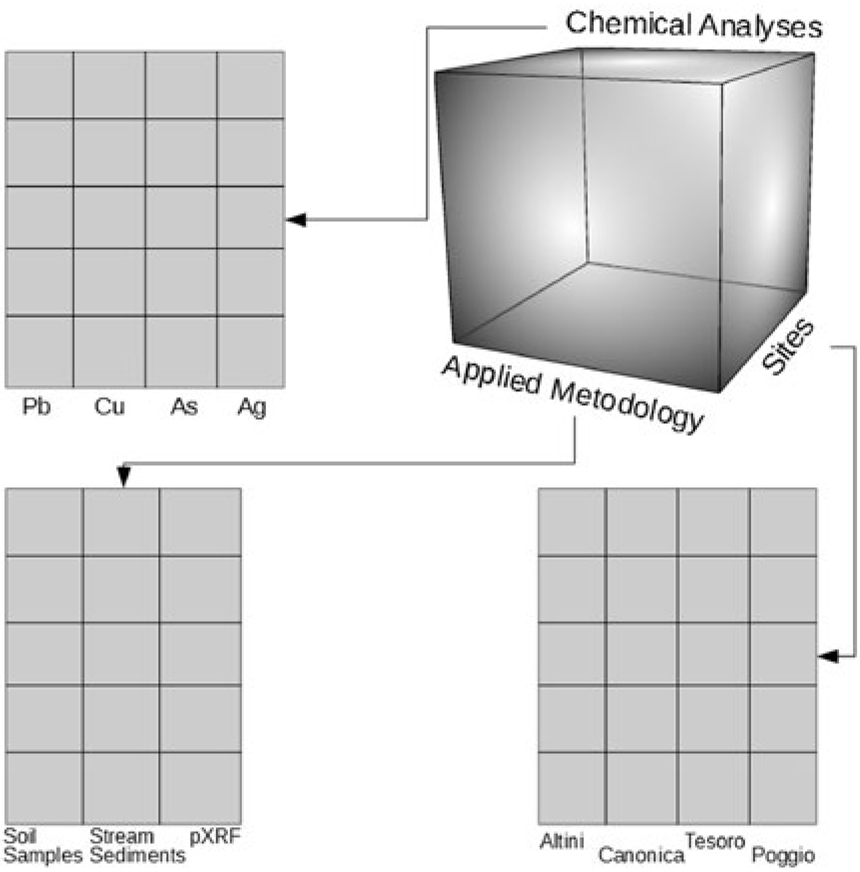

Fig. 3. OLAP cube structure: an example from the project.

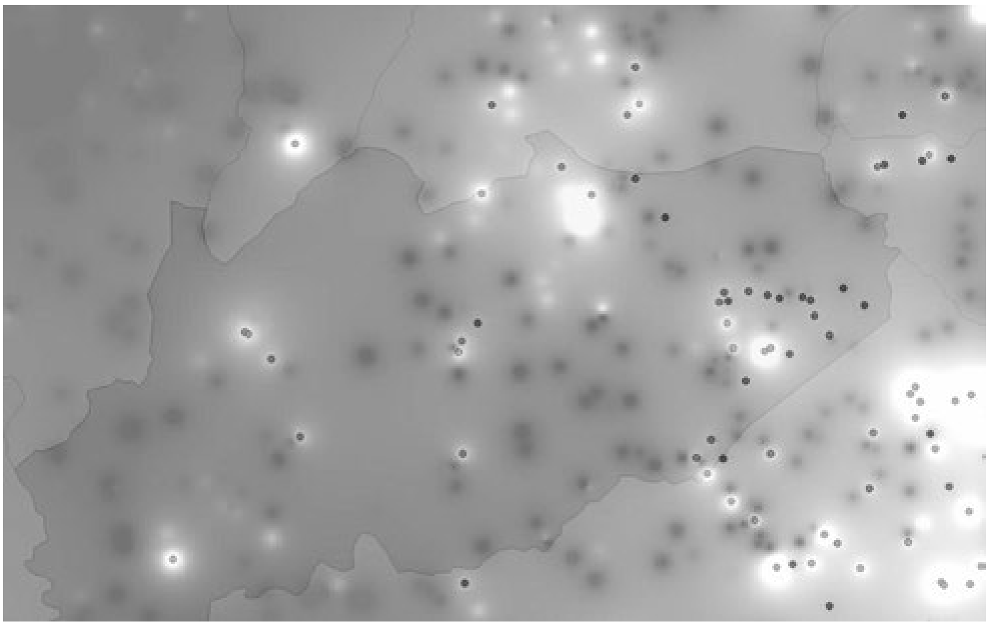

Fig. 4. In white: areas with high values of antimony, arsenic and silver.

bishop of Volterra was the main political figure in this area, and it is due to his influence if the castle of Montieri developed as one of the main mining centers in the Colline Metallifere. The castle was the core of a complex system of ore exploitation and mineral production sites and its economical importance is testified by the building quality and by the presence of a mint which struck coins on behalf of the bishop between the end of the 12th century and the first half of 13th (Bianchi *et al*. 2013).

The multidisciplinary research chose this area as a key one in order to perform multi-scale environmental analyses. In this territory, mineral processing for silver production has led to the accumulation of a significant amount of slag, partly positioned where the modern-day town center stands. A series of test analyses have been recently conducted, relating to both the settlement area and the surrounding territory, as well as on-site physico-chemical analyses realized on the site of La Canonica, a religious complex linked to the bishop of Volterra, attested from written documents since 1133. The church with its extremely peculiar central plan surrounded by six apses and the fine stone architecture, shows the economical effort sustained by the bishop in the mid-11th century. Modifications went on in the next centuries, until the final abandonment of the site, occurred just before the 15th century. At La Canonica site, a very large-scale sampling grid of 1 x 1 m was applied to two different digging areas; the analysis results revealed a marked presence of anomalies (in particular Fe, Pb and Cu) in an area where archaeological research discovered the presence of archaeo-metallurgical structures (specifically: forges, and the remains of a bell furnace). The integrated approach, involving scientific analysis and a historical-archeological input, has made it possible to get very significant results also on a larger scale; the distribution of the geochemical anomalies of trace elements has enabled the study of extensive extraction or transformation sites from the pre-industrial era.

3.2 Environmental data collection: on-site and territorial strategies (A.B., V.V.)

From an environmental point of view, the Montieri territory turned out to be ideal to define a standard methodology of sampling that could allow a coherent and statistically reliable data collection.

After some tests, we could define a standard method in order to identify the areas which were matching given criteria, and therefore were suitable to collect significant measurements directly on the field, as well as ideal to sample soils and stream sediments. The identification of these areas is finalized to perform predictive analyses as well. As said, the predictive methodology used in archaeology is based mainly on the definition of morphological parameters: i.e. slope, exposure, asperity index.

Regarding the Montieri area, the agricultural resource availability introduces a single powerful variable capable to call in question all the others based on geomorphological parameters. For a proper map construction, it is therefore necessary to consistently reduce the weight of the most common parameters and to identify new ones, in order to design predictive maps more coherent and effective.

Once that the areas of interest were selected we were able to establish a field analysis and sampling strategy; obviously, the

Fig. 5. Montieri: on-site XRF analyses (LTTM, University of Siena).

methodology is different dealing with a single archaeological site or with a large territory (Fig. 5). In the first case, as mentioned before, the data (XRF measurements) have been collected following a grid of 1 x 1 square m; inside each square we have collected from a minimum of 3 to a maximum of 4 XRF measures or more, if necessary. When possible, 1 or 2 samples of soils have been collected as well. In the case of territorial analyses, we have proceeded with a systematic soil and stream sediments sampling; in fact, in a wooden territory, as the Montieri one, streams are particularly useful both as natural paths to cross the vegetation, and, moreover, as heavy metal collectors. From the samples, which are normally taken every 50m, the laboratory analyses and the different techniques applied (i.e. X-ray fluorescence, Atomic Absorption Spectroscopy (AAS) and ICP-MS spectrometry) could extract interesting physicochemical details to produce territorial maps highlighting the main concentration of given elements (Fig. 6).

3.3 Slags and heavy metal contamination: using environmental data for a historical reconstruction (V.V., A.D.)

Regarding the large scale investigations, arsenic (As) has been fruitfully used as tracer elements to study not only the environmental contamination but, as we will see, even the historical landscape: indeed, this can be considered a very good example of the effectiveness of a multidisciplinary approach to the study of the territory.

Arsenic is ubiquitous in mixed sulfide mineralization and it was proved that its soil concentration is closely related to the extraction and processing of these minerals (Donati *et al*. 2005).

The concentration of arsenic and other heavy metals in soil and sediments is usually measured with purpose of environment monitoring. In fact, part of our data concerning the distributions of trace elements was originally used for their 'natural mean ground level' determination in the Colline Metallifere territory. However, this kind of analysis has proved to be also very interesting from the historical and archaeological perspective, particularly to determine the production 'vocation' of the

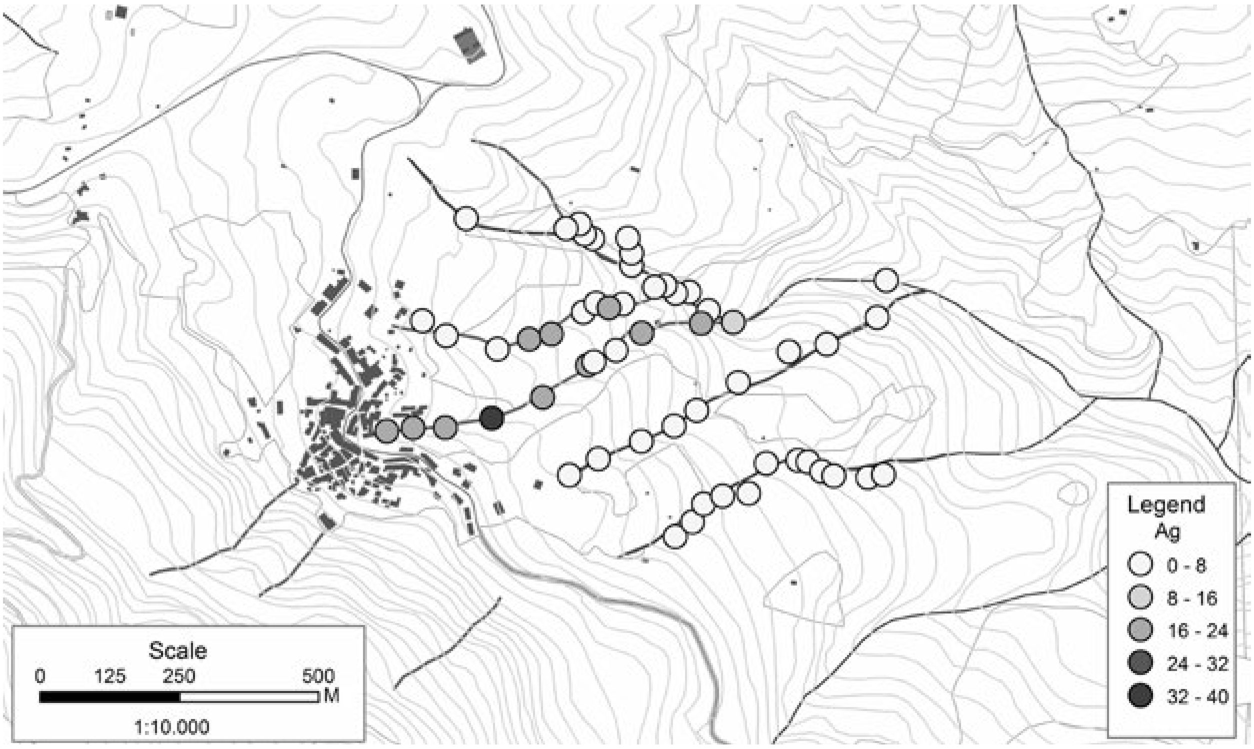

Fig. 6. Montieri's vector topographic map. It shows the results of Atomic Absorption Spectroscopy (AAS) analysis of silver distribution in the river sediments. In the legend, the concentration ranges considered.

individual mining sites, setting out from an analysis of the minerals present in the waste dumps.

Therefore this protocol could also become a valuable instrument for monitoring the local area, with a view to safeguarding the cultural heritage; to this end, the case study of the Tesoro site, in the municipality of Massa Marittima is significant: here, the major anomaly of arsenic levels indicates the probable location of an extraction area and/or mineral processing area that has never been described before (Donati *et al*. 2004, 2007).

Regarding the intra-site scale approach, an early analysis of archaeological database was done together with an assessment of other environmental parameters. After this preliminary work, a number of model sites in the 'Colline Metallifere' territory were chosen.

Among the others, one of the most interesting cases was the Altini site. This mine was located very close to Massa Marittima and it was cyclically exploited in the past. Now only few traces of the ancient activity are visible. The analysis of arsenic distribution revealed a non-homogeneous anomaly indicating the different location of the productive elements (extractive sink, mine tails deposit, processing area) and their functional connection (Fig. 7).

The environmental data collection described in the previous paragraph helped to define, on a smaller scale, the topographic limits of a large slag area, very well known from historical descriptions, nowadays partly covered by the standing town of Montieri. In fact the 18th century descriptions indicate that the mass of waste visible at that time in the city center reached exceptionally large proportions. The slags are the result of the ore extraction and metallurgical processes that went on around Montieri's village during the Medieval period. The place, as said above, was in that historical phase in fact an important mining and metallurgical center, and numerous silver mines are still partly visible in the surrounding hills and have been identified by the archaeological surveys.

To estimate the extent of this pile of slag with an initial level of topographical approximation, a large-scale screening was conducted on the river sediments, using the natural leaching process of contaminated soil as a guide. In the case in hand, lead was used as the 'tracer' element; indeed, lead is very closely connected with silver extraction (production from silver-bearing galena). Five gullies (seasonal streams), that begin lower down the town of Montieri, have been chosen for the analysis. The first four are located just below the slag heap while the fifth, named 'Madonna's river' is positioned to the east. Along the streams it was made a systematic stream sediment sampling for the laboratory analysis through the Atomic Absorption Spectroscopy (AAS) technique.

Results from the analyses showed high concentrations of lead (Pb) on the central rivers compared with the peripheral ones. This indicates that the contamination originated from an area approximately definable. The subsequent level of refinement has included chemical measurements of the soil; this has led us to define with greater precision the area where the slag probably accumulated, as detailed in Benvenuti *et al*. (2014)**.** The area that can be calculated on the basis of these figures is around 7,500 m^2. with a depth of around 4m in the southern extremity to a few dozen cm in the northern extremity (Fig. 8) (as in Fig. 3, Dallai *et al*. in press). This research has been important to determine some important chemical feature for

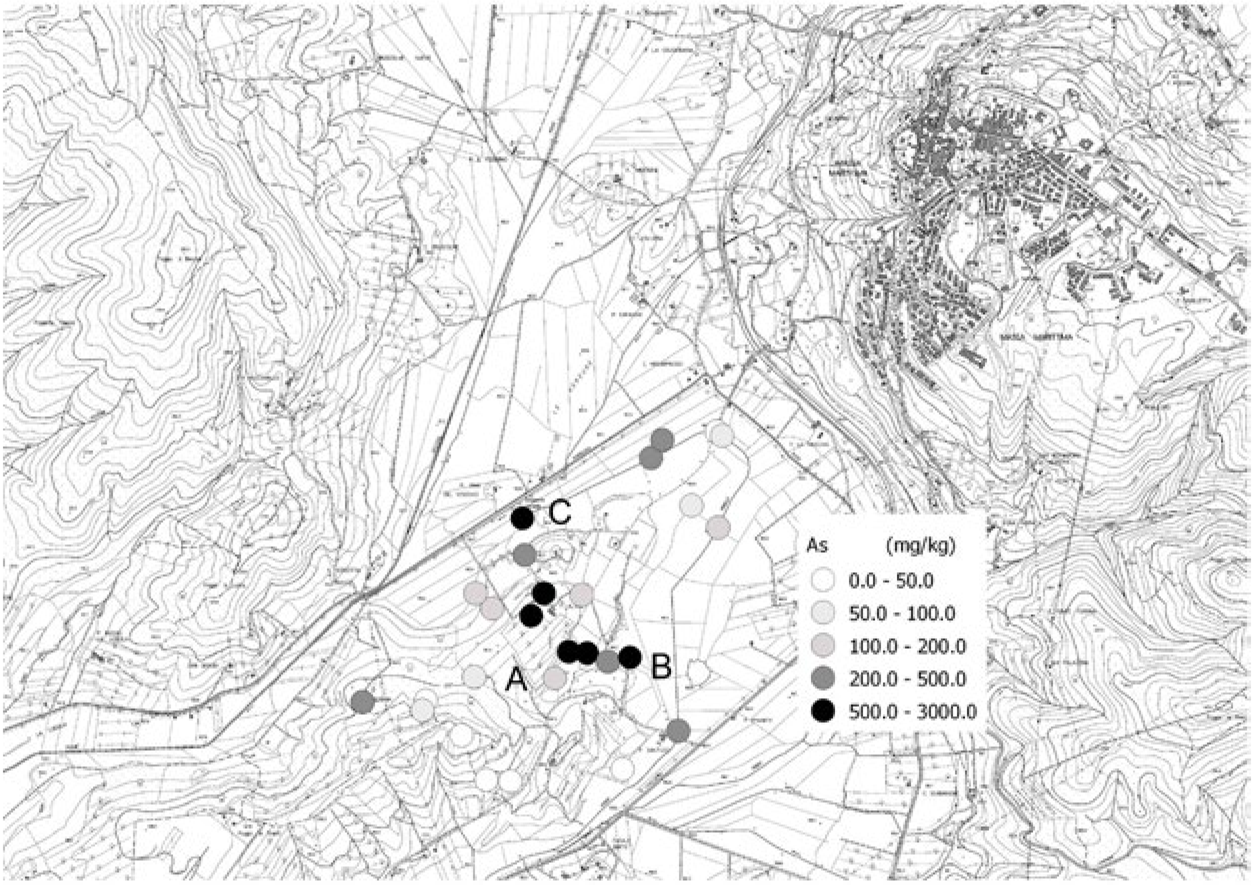

Fig. 7. Arsenic concentration in soil samples collected in the Altini site (Massa Marittima – GR). The distribution of As was non-homogeneous and with a clear north-south direction reflecting the location of the main elements of the mining activity: extraction sink (A), mine tails deposit (B) and processing area (C).

a better understanding of the local historical mining context. In particular it is crucial to find out on the one hand some productive characteristics that can help in defining the amount of mineral worked and, consequently, of metal produced. On the other hand, behind the archaeological aspect, it is useful to verify the spread of contamination and to understand to what extent the presence of metallurgical slags has affected the local environment, providing general indications on the toxic elements speciation in the area.

4 Conclusions (L.D., A.D., A.B., V.V.)

As described in the paragraphs above, the proposed research approach was applied to a context, the Colline Metallifere territory with strong peculiarities; an important mining field in the south-west of Tuscany where silver, copper, lead, iron and alum have been cyclically exploited for centuries contributing to the economic development that characterized the area through the centuries. This mining field was also recently exploited (the last pyrite mine was dismissed in 1995 year) and it is predictable that in the future mixed metal sulfides will be extracted again.

As we have seen, the territory can be properly studied by the proposed multidisciplinary approach, gathering together documental information, archaeological surveys and physico-chemical data in a smart database. Using this database, merged maps were produced and cross-correlations between ancient mining and smelting sites and the distribution of metal contamination were obtained.

This approach can be used at different scales: a context (large/medium) or local (intra-site) scale, as seen in par. 3.3. Both of them give accurate information about the localization of sites and their main use and about the mineral exploited. The difference between them resides in the respective level of detail that can be reached.

Moreover, the proposed methodology also has a great potential as predictive analysis. Indeed, it is possible to use chemical and environmental data in synergy with the databases already available for the local area, to highlight the possible consistency between the presence of geochemical anomalies, and the location of archaeo-mining and archaeo-metallurgical sites that have not yet been documented.

Once again, the Montieri area and the so called 'Poggio' (see par. 2), can offer good examples of cross-data management,

After a careful analysis that has evaluated historical and cartographic data, and a preliminary on-site fieldwork described above, we could define significant differences between three

Fig. 8. The concentration of lead in soil slag heap. The polygon represent the waste area.

main areas. The first one is located on the East slope of the hill; here, the combination of archaeological evidences related to mining exploitation and metallurgical activities, as well as the historical record, testify the existence of a long archaeo-mining tradition. The chemical analyses in particular have stressed the presence of high concentrations of lead (Pb), copper (Cu), silver (Ag) and arsenic (As) all over the territorial sample, with specific peaks recorded closed to possible ancient mines and metallurgical structures (i.e.: Pb 2271 ppm; Ag 38 ppm; Cu 477 pm; As 435 ppm).

The same analyses could discriminate a much lower concentration of heavy metals in a second sampled area, south of Montieri village, where the historical record again describe the existence of ancient mines. Nevertheless, their impact on the environment appears to be of less importance (i.e.: Pb 103 ppm; Ag4 ppm; Cu 67 ppm; As 100 ppm). The third and final key area of the 'Poggio' is located on the western slope, where 'La Canonica' stands. Here, the chemical values evidence, once more, only very low concentrations of heavy metals (i.e.: Pb113 ppm; Ag 1,5 ppm, Cu 30 ppm; As 118 ppm). From all the data collected in the area we could finally establish in which area of the Poggio the mining activities went on and where, on the contrary, this cannot be assess on a scientific base, although the written sources suggest the contrary.

High throughput physico-chemical data were collected (from 2002 to 2015) by using classic geo-referenced sampling of soil and/or sediments (analyzed by laboratory techniques: GF AAS; ICP-MS; XRD; FESEM – EDX) or by using on site pXRF technique. Data arising from previous geochemical prospecting and exploring activity and from environmental monitoring were also used. This gave the possibility to carry out an extremely detailed screening of the areas under investigation, and to get a very precise picture of the distribution of tracer (indicator) elements, both within an individual site and across larger geographical areas. Further comparison with data gathered during archeological monitoring, still under way, will certainly be useful to specify with even greater precision the conclusions that the analytical data are already suggesting.

Bibliography

Aranguren, B., Bagnoli, P., Dallai, L., Farinelli, R., Negri, M. 2007. Serrabottini (Massa Marittima, GR): Indagini Archeologiche su un antico campo minerario. *Archeologia Medievale* 34: 79-113.

Benvenuti, M., Bianchi. G., Bruttini, J., Buonincontri, M., Chiarantini, L., Dallai, L., Di Pasquale, G., Donati, A., Grassi, F., Pescini, V. 2014. Studying the Colline Metallifere mining area in Tuscany: an interdisciplinary approach. IES Yearbook 2014: 261-87.

Bianchi, G., Bruttini, J., Dallai, L., Grassi, F. 2013. Nuovi dati dalla ricerca archeologica per la ricostruzione del paesaggio storico delle Colline Metallifere massetane. In Galeotti, G., Paperini, M. (eds.), Città e territorio. Conoscenza, tutela e valorizzazione dei paesaggi culturali: 80-5. Livorno, Debatte Editore.

Dallai, L. 2013. Archeologia delle attività produttive e metallurgiche. Il caso toscano: le Colline Metallifere grossetane. In García Porras, A. (ed.), *Arqueología de la produccion en época medieval*, Nakla 15: 291-304. Granada, Alhulia.

Dallai, L. 2014. Massa Marittima nell'età del Codice: una rilettura dei dati archeologici e minerari. In Farinelli, R., Santinucci, G. (eds.) 2014, *I codici minerari nell'Europa preindustriale: archeologia e storia*, *Biblioteca del Dipartimento di Archeologia e Storia delle Arti, Università di Siena* 19: 71-83. Firenze, All'Insegna del Giglio.

Dallai, L., Bardi, A., Donati, A., and Trotta, M. 2012. Indagini archeominerarie sul comprensorio montierino: le miniere di Giovanni Arduino in Val di Merse. In Redi, F., Forgione, A. (eds.) 2012, *V Congresso Nazionale di Archeologia Medievale (L'Aquila, 12-15 Settembre 2012)*: 271-277. Firenze, All'Insegna del Giglio.

Dallai, L., Donati, A., Bardi, A., Fanciulletti, S. 2013. Archeologia e chimica per il patrimonio minerario (Ar.Chi. Min.). Un nuovo approccio multidisciplinare allo studio dei contesti archeominerari del comprensorio massetano. In Galeotti, G., Paperini, M. (eds.) 2013, *Città e territorio. Conoscenza, tutela e valorizzazione dei paesaggi culturali*: 86-91. Livorno, Debatte Editore.

Dallai, L., Bianchi, G., Donati, A., Trotta, M., Volpi, V. 2015. Le analisi fisico-chimiche territoriali ed 'intra-sito' nelle Colline Metallifere: aspetti descrittivi, 'predittivi' e prima interpretazione storica dei dati. In Arthur, P., Imperiale, M. L. (eds.), *VII congresso nazionale di archeologia* Medievale: 389-94. Firenze, All'Insegna del Giglio.

Donati, A., Protano, G., Riccobono, F., Dallai, L., Francovich, R., Rossi, F., Tiezzi, E. 2004. Influence of ancient mining settlements on arsenic pollution in the southwest of Tuscany. In *Brownfields Sites II. Assessment, Rehabilitation and Development*: 183–9. WIT press, Southampton.

Donati, A., Pulselli, F. M., Protano, G., Dallai, L., Francovich, R., Tiezzi, E. 2007. With Arsenic On The Etruscans' Footprints**.** *International Journal of Ecodynamics* 2: 24–6.

Donati, A., Pulselli, F. M., Riccobono, F., Dallai, L., Francovich, R., Tiezzi, E. 2005. Origin of arsenic pollution in southwest Tuscany: comparison of fluvial sediments. *Annali di Chimica* 95: 161-6.

Marasco, L. 2013. La Castellina di Scarlino e le fortificazioni di terra nelle pianure costiere della Maremma settentrionale. *Archeologia Medievale* 40: 57-68.

Interdisciplinary Methods of Data Recording, Management and Preservation

Marta Lorenzon
m.lorenzon@sms.ed.ac.uk
University of Edinburgh, School of History, Classics and Archaeology.

Cindy Nelson-Viljoen
c.nelson-Viljoen@sms.ed.ac.uk
University of Edinburgh, School of History, Classics and Archaeology.

Abstract: One of the challenges faced by archaeologists in multidisciplinary research is the successful integration of different datasets. This paper aims to open a discussion on some of the inconsistencies that researchers must face when working with diverse records in recording, preserving and managing archaeological data. How do researchers overcome obstacles in the adoption of interoperable and interdisciplinary datasets? What methodologies and approaches are incorporated in the design and management of databases that can integrate different datasets, in addition to be used as interpretative tools? What steps are taken in securing the preservation of archaeological contexts, its factual interpretation and dissemination among the academic and non-academic community and its ultimate use in public outreach as a key instrument in preserving archaeological heritage?

Keywords: Data recording, Database management, Interdisciplinary, Interoperability, Data management, Accessibility

Introduction

The integration of different archaeological datasets is becoming more challenging as new types of data including linked open data are increasingly being used in archaeological investigations. Thus, the need arises to preserve and efficiently combine different typologies of data, compelling archaeologist and computer scientist to work together to find new solutions. Data collected in the field and during laboratory analysis are not always compatible or easily associated into one database or management system. When different datasets are combined, various aspects must be considered, such as the interdisciplinary nature of archaeological research, the interoperability of database systems, the long-term preservation of the results, its accessibility, accuracy and future dissemination.

In the last two decades the introduction of computer application and quantitative methods in archaeological research has clearly effected our approach to archaeology, leading to new ways in addressing problems such as data reliability and quality control. In addition, the quantity of information that can be analyzed is often misleading to archaeologists if not interpreted through a well-designed and interoperable system. Archaeological data management is, however, often hampered by the disassociation between computer science and archaeology due to the variability of research aims and questions in the respective fields. Therefore it is not always instinctive or possible to effectively collect different sets of archaeological data into one recording and interpretive tool. Nonetheless, the application of quantitative computer methods to archaeological problems has led to new approaches in answering research questions. New methods in database design, GIS, 3D reconstruction and spatial analysis, have all greatly contributed to the study of archaeology (Smith *et al*. 2014; Levy *et al*. 2010). However, as innovative computer applications have been applied to archaeological database management and research it has also become more pressing to resolve issues of data preservation, accessibility and communication. Archaeological research and data must be accessible; firstly between specialists to facilitate collaboration and progression; and secondly to the public, to engage the wider audience in cultural heritage in a friendly and accessible format.

1 Archaeological data management

With archaeological data management and database design, one of the key obstacles to overcome is the range of data that can be collected, the methods in which the data is collected and the subsequent reliability of that data. It is the authors' opinion that the discipline need controlled methods in collecting, recording and management of data in the field and laboratory. This session showcased some interesting and variate case studies, where innovative methodologies have been implemented by researchers to record and interpret their data (i.e. Maguet, Barreau and Leroyer's presentation on the incorporation of paleoenvironment data on an online bioarchaeological database). Even with regional and cultural variation in fieldwork styles and methodology, similar research questions could be answered and interpreted in different ways, sometimes resulting in the predilection of one type of data or methodology over another. There are, however, some common denominators in the type of data collected, for instance the classification and description of stratified layers. As Gidding *et al.* (2013: 2118) states, artefacts are 'silent records of humanity', it is the archaeologists who give them meaning through their analysis and interpretation.

At its simplest form data can be managed in three main phases:

- 1st phase: raw field work and laboratory data collection
- 2nd phase: analysis and interpretation of data
- 3rd phase: dissemination and preservation of data

Tab. 1. Data Recording.

Data type	Examples
Stratigraphical	Harris matrix- and Munsell descriptions, section drawings, photographs
Ethnoarchaeological	Oral and written histories, multimedia
Biological and Osteological	Species identification, seasonality, diets, disease, mortality rates, forensics
Geochemical	XRF, XRD, SEM, EBSD
Geospatial	GIS, maps
Architectural	Photographs, monument drawings, CAD
Artefacts	Drawings, typology classification, matrix, residue analysis
Photographical	Aerial, elevation photos

Tab. 2. Analysis Type.

Analysis type	Examples
Conservation	Type of intervention, chemicals used
Qualitative data interpretation	Typological analysis
Quantitative data interpretation	Statistical analysis
3D modelling	Virtual excavations, tours, 3D printing

The quantity of data collected from each phase is directly proportional to the type of data analysed. The first phase, therefore, has the highest quantity of data relative to the number of subfields in field and laboratory research. Whereas the third phase produces the least amount of data, yet poses the highest complexity in data management and has to present a global view of the final results. In this session researchers focused on these three phases of the archaeological process, in an effort to combine them together into one manageable database.

1.1 The first phase, raw field work and laboratory data collection

Archaeological investigations must consider and overcome the challenge of an ever growing discipline, where in the best case scenario the type of data produced during the excavation could be summed up as follows:

During this phase of research one of the more challenging problems is the large quantity of data created by new technologies and subsequent data selection process through quantitative methods and data modeling (i.e. laser scanning, XRF/XRD data set, GIS).

1.2 The 2nd phase, analysis and interpretation of data

The 2nd phase of archaeological research focuses on elaborating on raw data and developing possible interpretations of the past through analysis, interpretation and integration of different data sets. The interpretative tool and database design must consider the multi-dimensional nature of archaeological sites and associated artefacts.

1.3 The 3rd phase, dissemination and preservation of data

The 3rd stage of data management is perhaps the most challenging phase in archaeological research. Archaeological interpretations and possible future analysis with improved methods are reliant on the multiple interpretations already established, the methods of data collection and its subsequent preservation, dissemination and storage. Outside disciplinary (ADS, tDAR, MOD) and interdisciplinary (DANS, Dataverse, etc.) repositories with long-term preservation, one of the main problems remains the viability and applicability of one tool, which can combine data management and its long-term preservation (e.g. storage security, durability and longevity).

Tab. 3. Preservation and Dissemination.

Preservation type	Examples
Physical Storage	Storage Unit, Museum
Digital storage	Data cloud, on site server
Digital management	Design and updating of databases
Dissemination	Open source accessibility, public outreach, exhibitions, publications

Fig. 1. The archaeological process.

2 Discussion

As illustrated, the large quantity of data created requires new systems of management and analysis. In the past there have been some well-known case studies that have attempted to solve problems in developing systems that can integrate the various phases of archaeological research with new technologies, i.e. preserving and publishing (Witcher Kansa and Kansa 2014), analysis and recording (Moir *et al*. 2012) or the implementation of field data and analysis (Smith *et al*., 2014). The most comprehensive case study being the ArchaeoSTOR platform (Gidding *et al*. 2013), where the authors' approach is based on combining field and laboratory data as well as analysis and publishing in one unique interoperable platform (Gidding *et al*. 2014). Although their efforts are admirable, it is based on the assumption of having internet connectivity in the field and laboratory. With excavations often taking place in remote areas, internet connectivity cannot be guaranteed. Their combination of three phases, recording, analysis and preservation, is however implemented and easily accessible.

Nonetheless one must consider whether a database can handle all the complexity of a discipline with so many sub-disciplinary boundaries? Should a different, more interactive and more interconnected system be created? Can onsite servers allow more freedom in programming interoperable databases? Should we not consider the level or reliability of archaeological data and the eventual progressive modifications in software development and its effect and use in database design and management? We need to refocus the interaction between computer applications and archaeology. In a field such as archaeology, where context plays a key role in defining the meaning of artefacts and architectures, computer applications should be used from the earliest phases of the excavation to understand and be able to represent all the subtleties of archaeological contexts, which provide essential information for the interpretation of scientific datasets. Finally, should we not have a universal system of classification, thesauri and interpretation to add objectivity to the discipline as a whole? The need to mainstream the archaeological record in a globalized world is becoming a pressing issue where archaeologists from different backgrounds and sub-disciplines within archaeology need to have a globalized system in which to compare and discuss data.

3 Conclusions

With this short introductory paper we aimed to highlight problems in the field of interdisciplinary data collection, preservation and management. Presenters in our sessions tried to answer these problems through thought-provoking case studies from around the world, working in different sub-disciplines such as archaeobotany and public archaeology, in which they dealt with these issues in unique ways, moving forward and creating a more globalized interoperable system, which takes into consideration the constraints of the discipline. Follow-up discussions were often ground to compare different approaches utilized to find innovative solutions for archaeologist faced with multidisciplinary research and the successful integration of different datasets.

Bibliography

Gidding, A. B., Matsui, Y., Levy, T. E., Defanti, T., Kuester, F. 2013. ArchaeoSTOR: A data curation system for research on the archeological frontier, in *Future Generation Computer Systems 29*: 2117–27.

Gidding, A., Levy, T. E., Defanti, T. A. 2014 Archaeostor: The development and utilization of a web-based database for the Field and Lab. *Near Eastern Archaeology* 77, 3: 198-202.

Levy, T. E., Petrovic, V., Wypych, T., Gidding, A., Knabb, K., Hernandes, D., Smith, N. G., Defanti, T. 2010. On-site digital archaeology 3.0 and cyber-archaeology: into the future of the past–new developments, delivery and the creation of a data avalanche, in M. Forte (ed.), *Cyber-Archaeology*: 135–153. Oxford, Archaeopress.

Moir, A., Wild, R., Haddlesey, R. 2012. An internet-accessible building Archaeology research database (BARD). *Vernacular Architecture* 43, 1: 1-6. Routledge.

Smith, N., Passone, L., Al-Said, S., Al-Farhan, M., Levy, T. 2014. Drones in Archaeology: Integrated Data Capture, Processing, and Dissemination in the al-Ula Valley, Saudi Arabia, *Near Eastern Archaeology* 77, 3: 176-81.

Whitcher Kansa, S., Kansa, E. 2014. Data publishing and archaeology information ecosystem. *Near Eastern Archaeology* 77, 3: 223-7.

Driving Engagement in Heritage Sites Using Personal Mobile Technology

Thom Corah
tcorah@dmu.ac.uk
Interactive and Media Technology Research Group, De Montfort University, UK

Douglas Cawthorne
dcawthorne@dmu.ac.uk
Digital Building Heritage Group, De Montfort University, UK

Abstract: The use of smartphone and tablet devices is now becoming more common in heritage and museum settings. The aim is often to further develop public engagement with tangible and intangible cultural heritage, explain and explore existing information about artefacts, sites and cultures and present new information in engaging and accessible ways to a range of audiences. Community archaeology groups are becoming alert to this trend and wish to engage with it too, particularly for 3D exploration of built archaeology and the artefacts associated with it. This poses a number of challenges that differ from those for artefacts and documents in museum settings alone. It also poses contextual challenges in relation to specific and highly engaged user groups like community archaeologists. This paper describes completed apps which have been designed to address some of these unique challenges of interpreting and exploring 3D digitally reconstructed historic buildings for community heritage groups.

Keywords: Community heritage, Public Engagement, Mobile Technology

1 Introduction

Public interest in archaeology has been increasing rapidly in the UK and both professional and community archaeologists find it useful to present their work to public audiences, often on site, to show how exciting finds can inform understanding of the communities and landscapes where we live. Presenting individual artefacts can help bring the past back to life but complex archaeological sites, with many artefacts, trenches, masonry, test pits and piles of earth can often make the ancient buildings in and around which they are found difficult to visualise for the non-expert. Furthermore recent finds are often processed and stored off-site and may not be available to the visitor so the connection between the artefact, the meaning behind where it was found and the process of archaeology can often be lost.

In order to help overcome these limitations, De Montfort University's Digital Building Heritage Group has recently completed a UK Arts and Humanities Research Council (AHRC) funded research project (Grant Ref AHL0132901) in collaboration with colleagues from the University of Nottingham and the University of Durham and two community heritage groups to produce two innovative new mobile device apps which allow finds and other information to be uploaded by users to 3D representations of archaeological and historical sites and explored in an intuitive way. The idea behind this was to give community heritage groups greater opportunities to interpret their own finds and present them in a way which would allow these groups to shape the stories about the archaeology they are involved with. In doing so the project and the applications are intended to address particular issues surrounding the use of mobile digital technologies for co-production of community heritage interpretation in community archaeology and to examine how the explanatory and interrogatory potential of mobile device software can be used to build community led interpretive paradigms for post excavation analysis, presentation and education in community archaeology projects. The problems of digital curation by community heritage groups has been previously recognised, with propositions to use the connected nature of the web to develop a sustainable method of data collation and organisation (Beel *et al*. 2015). This project adds a public facing aspect, allowing a community heritage group to not only organise and interpret their work, but to also present it in a meaningful and accessible way to the public.

Two specific archaeological projects in England were used for the purpose of this study: a Roman bathhouse in Northumberland and an historic urban fabric in Southwell, Nottinghamshire. For each of these two sites a community heritage group exists: These are associations of enthusiastic amateur historians and archaeologists who have worked hard to uncover much about their respective sites and have created and collected a rich tapestry of documentation about them. This community-produced media including content such as documents, images, videos and audio forms a persuasive body of constantly evolving evidence and knowledge. The core problem of this project was to produce a system that would allow these community heritage groups to collate and present their work and the content they had gathered to the world. The strength of the system would be in its ability to make the experience of interpretation social and collaborative, thereby leveraging the power of cross-media interaction (Giaccardi & Palen 2008).

Tablets were chosen as the delivery medium for this content for a number of reasons. Their growing market penetration means they are now familiar to a large proportion of the audience for this project. Tablets easily allow the presentation and manipulation of a range of media from text documents to three-dimensional models. The cross-media capacity of the application is an important step towards producing a solution that will both serve the public interest and the needs of the

Fig. 1. The excavations of a Roman bath-house at Binchester Roman Fort in the UK being supervised in 2015 by Dr David Petts of the Department of Archaeology at the University of Durham and conducted by volunteers including members of the Architectural and Archaeological Society of Durham and Northumberland.

Fig. 2. Part of The Burgage in Southwell, UK. This is a medieval urban fabric centred on a village green with a long and complex history of re-use. Studies of the area are being led by Dr David Petts of the Department of Archaeology at the University of Nottingham with substantial research being carried out by members of The Southwell Community Archaeology Group.

community group, helping to establish the relationship between the human and non-human worlds and avoid dislocation from the physicality of the heritage site (Giaccardi 2007). Their portability means that they can be taken 'into the field' by the user, and provide access to site-specific content whilst actually on-site. This mobility has been seen as a key factor in the suitability of mobile devices such as smartphones and tablets for presenting context-specific locational information as they can do so more instantaneously and opportunistically that any other technologies (Han *et al*. 2014).

2 The Community Heritage Groups

This project involved working with two UK community heritage groups: The Southwell Community Archaeology Group (SCAG) whose interests have focussed on a medieval area called the Burgage in the village of Southwell in Nottinghamshire which includes a 19th Century House of Correction (a form of prison), and the Architectural and Archaeological Society of Durham and Northumberland (Arc & Arc) whose interests in this project are focussed on a bathhouse in the Roman fort of Binchester. Both of these groups have been active for some considerable time in archaeological excavations on their respective sites as well as carrying out archival work and public engagement. Through these activities they have built up a wealth of expertise and documentation about their sites, with work shared amongst the groups' members according to their individual interests and availability. What these groups often lack is a way to persistently organise and present the information they have gathered and present it efficiently to the world. Many groups like these have in the past turned to the Internet to produce web pages to act as repositories. Without specialist technical knowledge these websites are typically not well suited to the needs of those who wish to explore the archive. There is often little in the way of search or filtering capability. The medium itself does not lend itself well to the exploration of anything beyond text. The construction of such sites is often conducted by 'hard-coding' links and references to the various assets, missing the opportunity for the generation of an organised and systematic store that would be useful as a cataloguing mechanism for the community group in question.

These limitations often lead community heritage groups to look at tablet applications created for other, larger and national heritage institutions and to conclude that the technology could benefit their own causes if they could access it. However it is rare for a community heritage groups to have the skills and resources within its membership to develop a mobile device app from the ground up entirely without external assistance. Furthermore the alternative of bespoke app development by a commercial supplier can often place the technology out-with the funding and maintenance capabilities of these groups, in ways that may not be the case for larger organisations, museums and other heritage institutions. In addition to this there are also issues associated with the interpretation of the content. A museum has access to a wealth of expertise in order to arrive at an interpretation of an artefact and there is a large, multidisciplinary and very active international academic community publishing and discussing artefact interpretation. The degree to which community archaeology and heritage groups can / do / should access this body of opinion varies very widely and there are respected points of view which hold that local communities may be the most appropriate interpreters of their own heritage, irrespective of their degree of alignment with 'experts' from elsewhere. Whether or not one agrees with this viewpoint, there is a substantial and growing appetite amongst these community groups to be able to shape the narratives of the heritage assets with which they are involved. Moreover, there is growing recognition that participants in an exhibition can make as valid a contribution as professionals, with some noting how 'even low-technology strategies for engagement can be successful in making visitors active contributors to heritage sites' (Ciolfi 2012: 58). The process of collating a shared digital story can also have positive effects beyond the direct, it can be seen as a 'transformative tool for personal, professional, organisational, and community development' in its own right (Freidus and Hlubinka 2002: 26). However, within these groups there are often conflicting views on meaning and interpretation, and indeed ownership or monopolisation of ideas, originality and points of view, just as there are in the academic world.

'Communities are run through with divergent interests, anger, boredom, fear, happiness, loneliness, frustration, envy, wonder and a range of either motivating or disruptive energies. Added to this are thick seams of power that structure any given collection of people.' (Waterton and Smith 2010: 8)

Just as in the academic world the key to overcoming these is transparency in evidence-based processes of evaluation. One of the key aspects of developing the paradigms underpinning the new apps for this project was to provide the means to allow individual group members not only to present evidence in the ways they saw as most appropriate but to be able to have discussion threads associated with the process of doing so that would provide a vehicle for working through alternative or divergent points of view. In this it was intended that the effect, for example, of a leadership position within the group, a position that may not be bestowed simply on the basis of their expertise in the area, did not overly colour the interpretation of evidence and that other voices in the group might be afforded equal weight by means of access to this on-line technology. We believe this approach can theoretically encompass multiple and divergent viewpoints as well as providing the opportunity for consensus should the group dynamic lead in that direction. Furthermore, by definition, a community heritage group is a constantly evolving entity albeit one united by its members' interests around a particular local site, area or subject. Just as the concept of community itself can be 'renegotiated so that it fits the purpose for which it is being used' (Crooke 2010: 17), so too can the composition and outlook of the community change over time. The Binchester and Southwell apps, as they have been developed by our team, are intended as a means of recording the views and interpretations formed by the groups' members as these changes take place and form a vehicle for their potentially permanent record. Potentially this may help to ameliorate the fragmentation of recording and documentation that tends to occur in and by community heritage groups over time as membership and interests change.

3 The Proposition

This project therefore focussed on developing the means to allow community heritage groups not only to present but also to curate their research content in their own tablet application. In doing so it was hoped that a number of the issues faced by these groups could also be overcome. Key aims therefore were to:

- Provide a low-cost way of creating a tablet application for public use.
- Provide a tool set for the group to update the contents of the app that is accessible, flexible, and easy to use.
- Allow for documented discussion around the interpretation of articles.
- Develop a central repository for the group's articles that doesn't rely on any single individual.

It was decided that any system that was developed should have two primary components, the tablet application and a web-based administration tool through which the group members could control the content of the application. One route would have been to collect all the documents from the group and build an application based on that. However, if the group then wanted to add to the content at a later date they would need to bring in external expertise again to work directly on the source code of the app and go through the process of submitting an updated version to the app store. A web-based administration tool however gives the opportunity to have a portal that is accessible to anybody with a PC and an Internet connection. It also reduces the application source code updates to just those required to keep the app up to date with new developments in the technology of the tablet such as the operating system and the interface.

Apple's iPad was selected as the target for the tablet application. This choice was based on a number of factors including:

- The popularity of the platform.
- Existing expertise within the academic team.
- The lack of divergence amongst targeted devices. An application for Android tablets for example would add extra complexity due to the wide range in screen size, resolution, and technical capabilities.

The total system therefore involved an iPad application that can communicate with a content management system based on a web server. This is a popular paradigm for content-based applications as it allows for updates to be pushed to application users without the need for a full-scale application update.

Community heritage groups collect and produce a wide range of media, so the system had to be capable of supporting that. As well as documentation relating to the site and the artefacts uncovered, the production of a public facing application is intended to lead the group to produce well-formed content designed to explain aspects of the history of the site to the public. This requires a system that can support videos and free-form text entry as well as images and scanned documents. In doing so the system also had to promote group discussion around individual documents to better inform debate and multi-vocal and / or consensual approaches to the interpretation of the site data and how this should be presented in the app.

It was important that the system be easy to repurpose for new groups. While the creation of the initial system for two specific community heritage groups in the first instance might require a large level of expertise in both application and web development, the effort necessary to reproduce the system for a new purpose should be minimal in order to reduce the cost for new groups to produce their own application.

It was also vital that the tablet application present a meaningful way for the user to navigate the range of documents produced by the group. A simple list based approach would do little to convey the context of the information, nor for instance the important spatial relationships between the find locations of archaeological artefacts for instance. A navigable three dimensional model approach was therefore adopted whereby the user would be able to explore the documents through their location-based relationship with the site. This led to the development of a novel 3D datapoint paradigm, whereby any number of documents can be associated with one of a number of datapoints located within the three-dimensional environment of the site. In many cases the group's interest extends beyond the limits of the primary site or building into the surrounding environment. This is particularly the case with SCAG where the House of Correction is part of the rich historical fabric of the Burgage area of Southwell that covers an area of several hectares with the village itself approximately a square kilometre in extent. The application therefore ideally also needed to have a map view with a similar datapoint system operating over a potentially unlimited geographically area.

The proposed method of communicating site and find details to interested users is not new. Examples of iPad applications that present users with a richly detailed 3D virtual tour have been a valuable tool in enabling institutions to open themselves up in some regard to the public. 'A Window On The Past' is a prime example, developed by Luma 3D Interactive (2014) in collaboration with The University of Edinburgh, it presents users with an interactive view of the university's Old College in such a way that they can interrogate the changes to the fabric of the building through the course of history. Similarly, 'The Bank of England Virtual Tour' app for iPad uses the same 3D model paradigm along with a system of 'data-points' in order to allow the user to explore the history of the Threadneedle Street building in a contextual way (The Bank of England 2014). This project however builds on such ideas by using the 3D virtual tour presentation as a malleable front-end, with content supplied and controlled dynamically by the community group themselves.

4 The Content Management System

The web-based Content Management System (CMS) was developed on a standard php/mysql stack in order to allow it to be straightforward to setup for new groups. Visual styling and layout was utilised using the Bootstrap library in order to have a CMS that would adapt its layout based on screen size and therefore aid accessibility. This means the CMS can be used on devices from a full desktop PC down to a web-enabled smartphone (see Figs. 3 and 4).

The CMS provides for secure access for registered group members using a login system. It also uses the concept of permission levels in order to give controlled access to a range of members. In doing so the group are able to accept contributions from members of the public, but maintain control over what is actually presented in the application. This enables widened participation in the curation and development of material, as well as discussion around the interpretation of documents.

4.1 Defining Data Points

The CMS allows the group to define datapoints on both the map and the 3D model in the app. The database stores the location of each datapoint as a set of numerical data. In the case of a map point, this is the latitude and longitude. In the case of a model point this is the x, y, and z coordinates. Although members of the group could use a tool such as Google Maps to discover the latitude and longitude of a particular point on a map this is far from ideal in terms of accessibility. The system therefore presents a map view, using Google Maps, allows the user to place a marker on the map at the required location, and from this derives the latitude and longitude (see Fig. 5). Using Google Maps presents an interface and interaction paradigm that will be familiar to many allowing for quick navigation and manipulation of the map.

Defining a point in the model is more problematic. The coordinates used for each model are never externally visible, leading to a trial and error method of discovery in order to accurately place a datapoint. In order to overcome this the Three.js JavaScript library was used to display a version of the model used and allow the user to place a datapoint within it. Rudimentary object slicing is achieved through manipulation of the near plane of the projection. A set of three sliders allow the user to accurately place the location of the datapoint (see Fig. 6). While not ideal in terms of usability, this does function as a much improved method of point localisation.

4.2 Managing Documents

A document can be added using a simple form. The information recorded for each document includes:

- The name. This is the name that will appear in the list of documents for a particular datapoint, alongside an icon representing the type of document.
- The document type, selected from a list defined elsewhere in the CMS.
- The datapoint the document is associated with.
- A short description, with options for simple formatting including the ability to add a hyperlink to a web page.

The user must also acknowledge that they have the legal authority to make the document publicly viewable.

The CMS then allows users to edit or delete a document, subject to the permissions that have been setup. They must also then choose to publish the document, again subject to the permissions that have been established by the group. This means that the CMS can act as a store for a range of document beyond those displayed in the app. A single document therefore can go through a process whereby its content or meaning is discussed until a suitable interpretation has been arrived at before publication in to the application. This process is supported through the use of document-specific discussion threads. In a similar fashion to an online forum, a discussion thread is associated with each document allowing for a dialogue to emerge that can be traced. This discussion is purely internal, and therefore not a part of what is published to the application.

5 The iPad Application

The application has two main views: Model View, and Map View. The Model View presents a three-dimensional model of the building in question in such a way that the user can scale, rotate, pan and slice it (see Fig. 7).

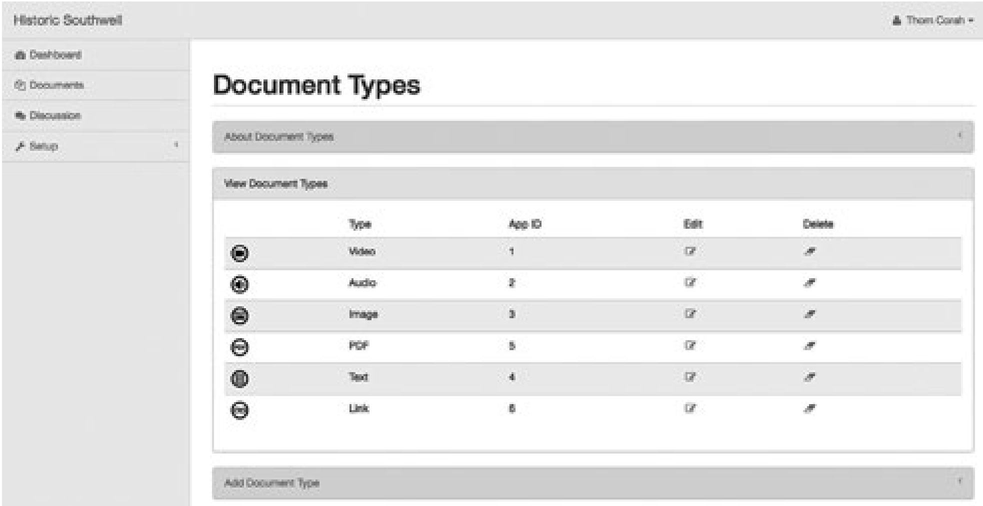

FIG. 3. A VIEW OF THE CMS AS DISPLAYED ON A FULL DESKTOP PC.

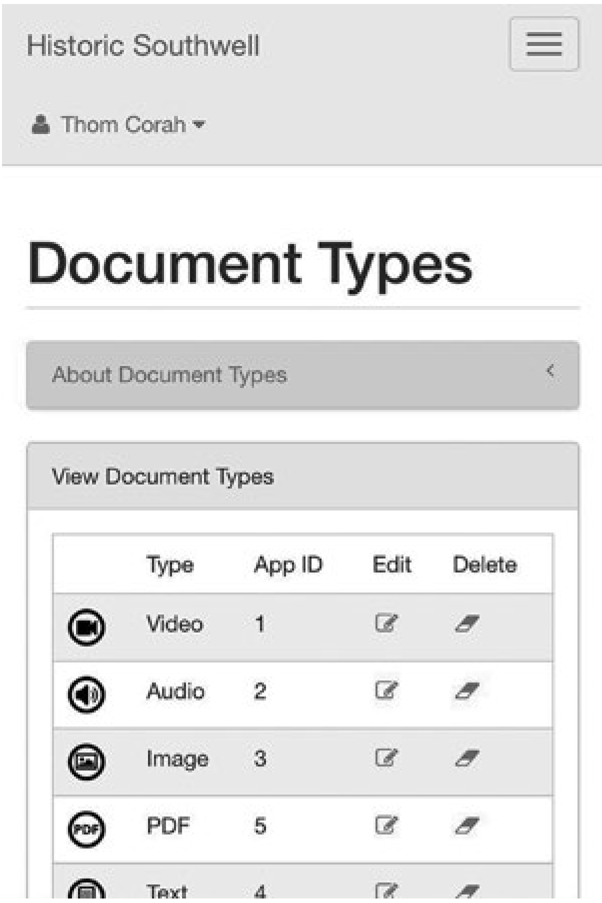

FIG. 4. THE SAME CMS VIEW DISPLAYED ON AN IPHONE SHOWING HOW BOOTSTRAP ELEGANTLY HANDLES ELEMENT REPOSITIONING TO SUIT THE SIZE OF THE SCREEN BEING USED.

The concept of ‘slicing’ or more accurately sectioning the model (see Fig. 8) is we believe novel within mobile device heritage apps at this time. It is a particularly effective method of exploration as it allows the user to cut through the model along any of the three x, y or z axis and reveal not only the interior of rooms but also the interiors of walls, floor, roofs and the ground. It is controlled by a quarter-circle thumb slider on the right of the screen combined with the rotating axis selector on the left which are both placed in these positions to allow for ease of operation when holding the iPad in both hands in a landscape orientation. This ability means that data points can be placed within structures such as walls and floors (as well as elsewhere) and not just on their surfaces and can be revealed as the section is slid through the model. In the z (up and down) axis the analogy in doing so is remarkably similar to the process of digging the site, with the structure and finds emerging in an intuitive way that visually parallels the actual process of archaeological excavation.

The user can update the contents of the application using the button in the top-left of the interface. This opens a tab that informs them of the size of the download from where they can choose to either download the update or close the tab. The update facility has been added as an all or nothing facility. Rather than allow the user to manage the update on a document-by-document basis it was decided to simply update all data in the app. This leads to a simpler method of interaction for the user. It is recognised that the user may often take their iPad to the actual location of the building or site where there may be no Internet connection. To overcome this there is the facility to update everything in the application beforehand when they do have an Internet connection so that they have a complete set of all the media that is available in the system when on-site.

The Map View presents datapoints in a similar way, allowing the user to tap a datapoint to display a list of all documents associated with it (see Fig. 9). It uses Apple’s default Map View therefore presenting a map that the user will likely know how to interact with already. It also displays their current location on the map should they be exploring on-site which allows the user to navigate in real-time between the datapoints. There are

FIG. 5. THE MAP VIEW USED IN THE CMS FOR PINPOINTING THE LOCATION OF A MAP BASED DATAPOINT. THE USER IS ABLE TO PAN AND SCALE THE MAP, AS WELL AS DRAG THE MARKER TO THE REQUIRED LOCATION.

obvious uses here for archaeological geo-tagging and other forms of in-life game-play using this feature that offer potential social interactivity benefits to the use of the apps.

6 Conclusion

The development of this system was highly collaborative, involving archaeologists, local historians, architects, computer programmers, graphic artists and 3D digital modellers. The ongoing success of a community based technology project such as this relies upon the sustainable engagement of the community groups which in part comes from the sense of ownership they take from being involved in the conception and running of the project (Balestrini *et al.*, 2014). Initial meetings with both community heritage groups led to the establishment of a robust set of requirements that were largely adhered to during the development of the apps. The groups tested progress in the development of both the CMS and the iPad Application in order to produce a system that was fit for purpose. The end result is a system that allows the members of a community heritage group to curate a set of documents for presentation to the public through an engaging iPad application that is truly multimedia. In addition to this two key new concepts have been developed in these apps which make them different from other data-based archaeology apps that are available and which make a significant advance in the functionality and usability of apps on archaeological sites for heritage interpretation.

1. The first is the ability for registered users to upload finds data to an on-line database. This is done over the Internet using the CMS in a normal web-browser. Information to upload can be text, images, video and audio. This finds data can be geo-located in three dimensions to precise points on the archaeological site by the user during the upload. When the user then looks at the app on their iPad, they will see new datapoints on the 3D and 2D views of the site and by pressing an update button on the app screen, the new finds data will be uploaded from the server and become clickable hot-spots on the datapoints which will show the finds data.

2. The second innovation in these apps is the use of 3D reconstructions of the buildings associated with the finds and the way they are presented. The hot-spots appear in three dimensions in the buildings. In order to reveal ones inside structures or in walls and floors or underground there is a 'section slider' which allows the user to see inside the buildings and their walls and floors. In this way it really is like digging down and through the building to reveal the locations of finds so that you can click on them.

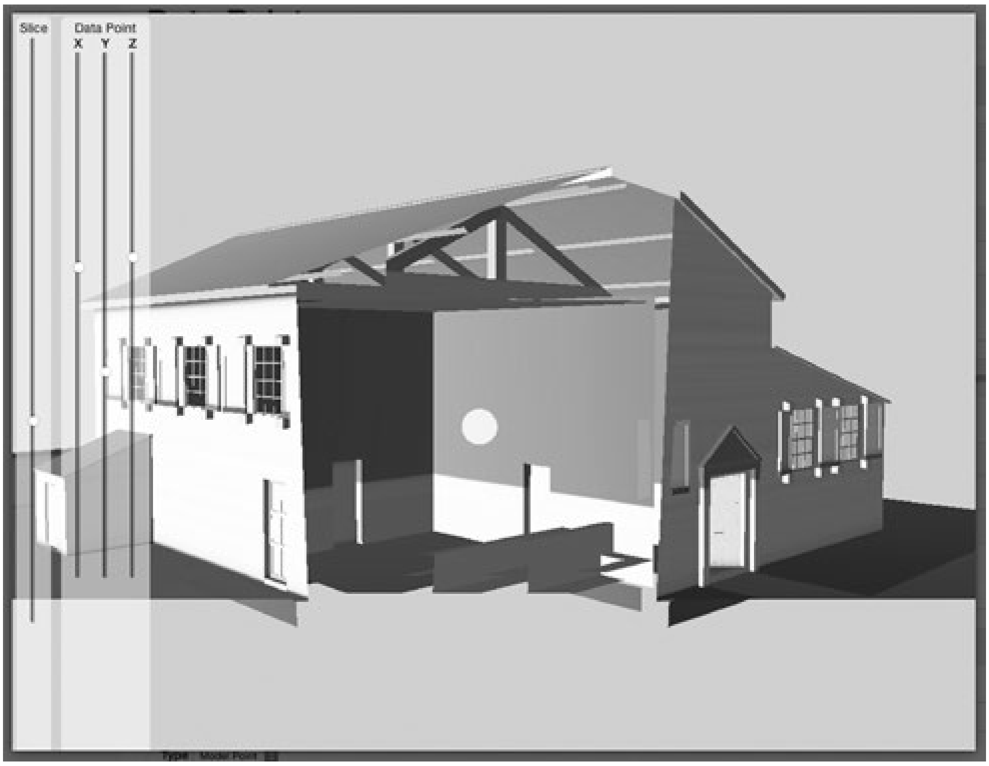

Fig. 6. The slider bar method of defining the 3D (x,y,z) location of datapoints, shown in this case within the 3D reconstruction of the Binchester Roman bath house app. This method is common to both apps that have been developed

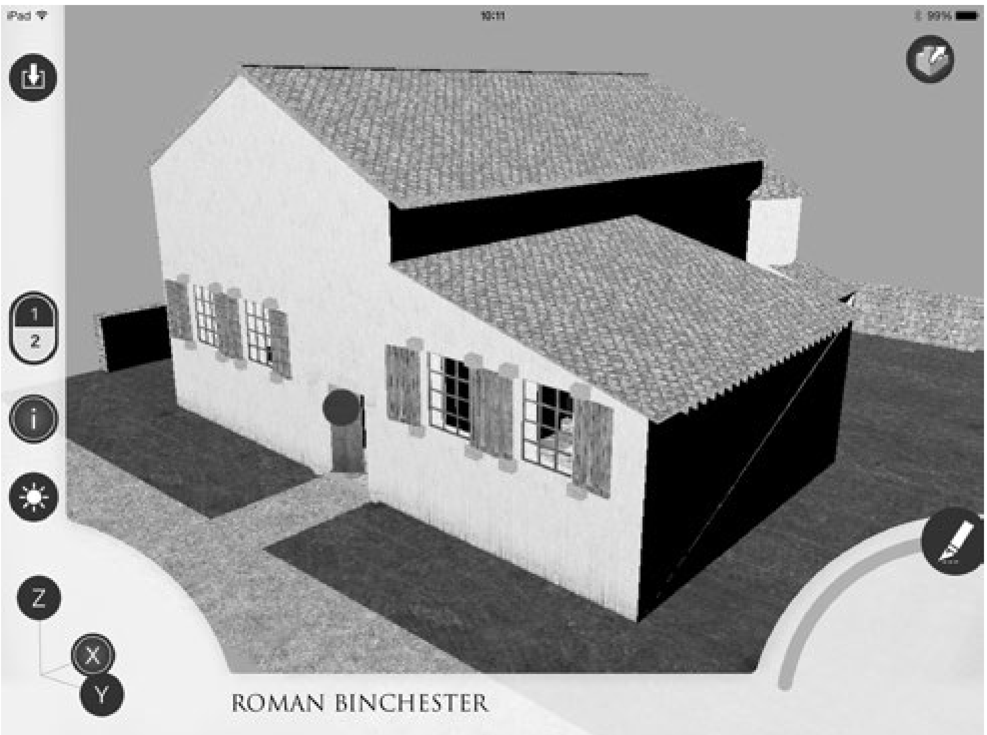

Fig. 7. The 3D reconstructed digital model of the Binchester Roman bathhouse building within the app interface. The reconstruction is deliberately elementary so as to omit detail that might change substantially on later interpretation and is intended merely as a 3D visual armature or placeholder on which to place the datapoints and to allow visitors on site to develop a mental picture of the full overall form the building from the foundation and wall remains. The stars on the datapoints indicate that they have new data that has been uploaded to them.

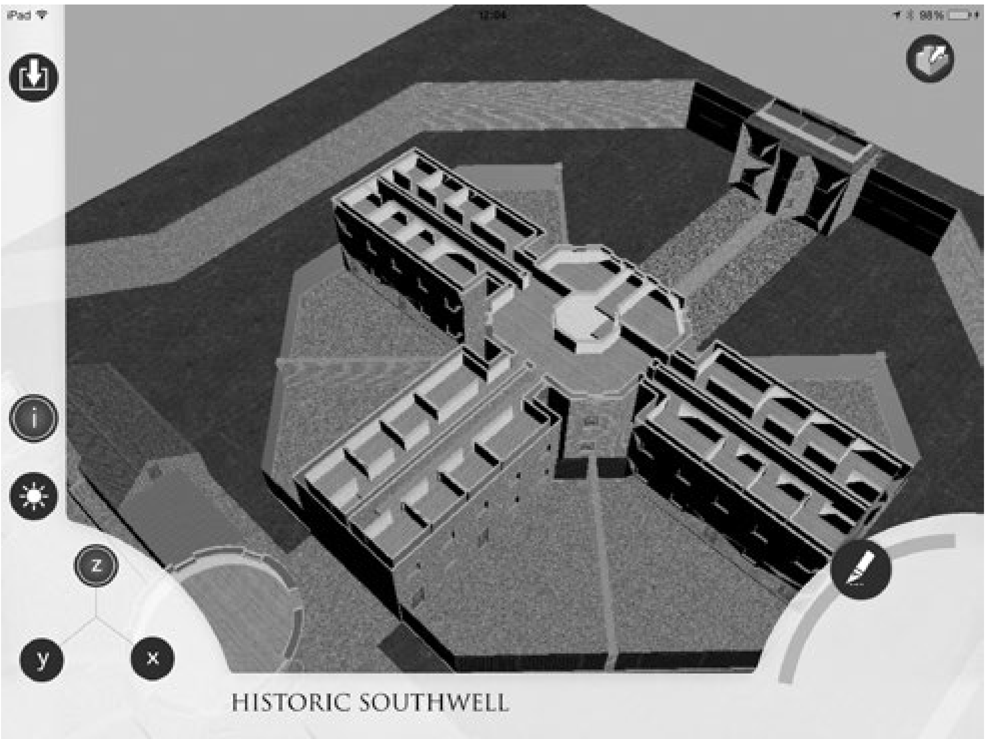

Fig. 8. The section function of the apps make exploration of the interiors of and the fabric of the buildings and sites intuitive and allows data points to be revealed that lie within the fabric of structures.

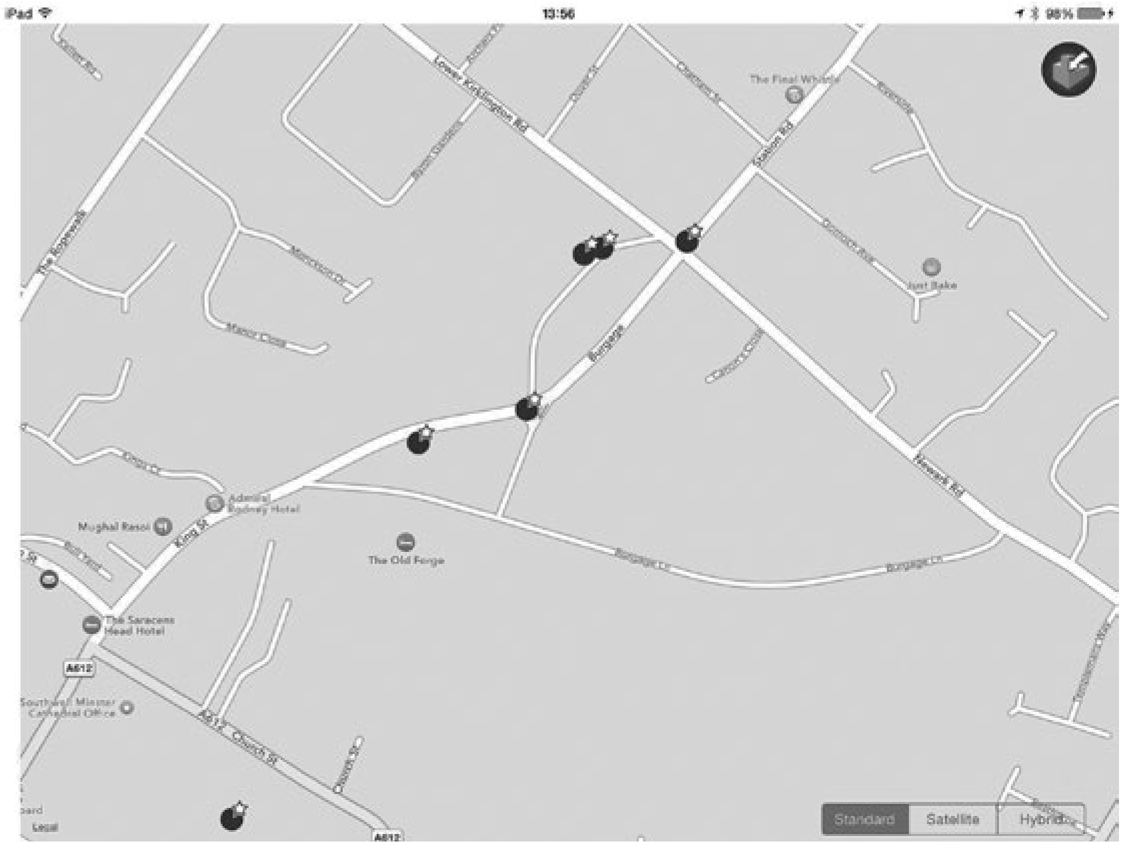

Fig. 9. The map view using Google Maps allows users to place datapoints at positions that are not restricted to the small area represented in the 3D digital reconstruction model of the Roman Bath-house alone.

Finally, these are prototype apps developed as part of ongoing research to bring better, self-directed heritage interpretation to wider audiences and archaeology enthusiast as well as professionals. The apps are free to download from Apple's App Store and at present are available for Apple's iPad only. There is scope for further development here. The system can be further refined on the basis of usage metrics collected by analytics tools embedded in both the CMS and the application. Further consultation with both of the community heritage groups involved in this project and other users of the apps can yield fresh insights in to the effectiveness of this technology in the wider context of community heritage, archaeology and public engagement.

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Bibliography

Balestrini, M. *et al*. 2014. Understanding sustained community engagement: a case study in heritage preservation in rural Argentina. *CHI 2014*: 2675–84.

The Bank of England 2014. *The Bank of England Virtual Tour* [Software] iOS. Version 1.1. London: The Bank of England.

Beel, D. *et al*. (2015) CURIOS: Connecting Community Heritage through Linked Data. *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing*: 639–48. New York, ACM.

Ciolfi, L. 2012. Place-centred interaction design: situated participation and co-creation in places of heritage. In: M. Ballarin and M. Dalla Mura (eds.), *Museum and design principles, Proceedings of the conference*: 57-68. Venezia.

Crooke, E. 2010. The politics of community heritage: motivations, authority and control. *International Journal of Heritage Studies*, 16, 1-2: 16–29.

Freidus, N. and Hlubinka, M., 2002. Digital Storytelling for Reflective Practice in Communities of Learners. *ACM SIGGROUP Bulletin*, 23, 2: 24–6.

Giaccardi, E. 2007. Cross-media interaction for the virtual museum. *New Heritage: New Media and Cultural Heritage*: 336. Routledge.

Giaccardi, E. and Palen, L. 2008. The Social Production of Heritage through Cross-media Interaction: Making Place for Place-making. *International Journal of Heritage Studies*, 14, 3: 281–97.

Han, K. *et al*. 2014. Enhancing community awareness of and participation in local heritage with a mobile application. *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing - CSCW '14*: 1144–55. Available at: http://dl.acm.org/citation.cfm?doid=2531602.2531640.

Luma 3D interactive 2014. *The University of Edinburgh, Old College: A WINDOW ON THE PAST* [Software] iOS. Version 1.01. London: Luma 3D Interactive

Waterton, E. and Smith, L. 2010. The recognition and misrecognition of community heritage. *International Journal of Heritage Studies*, 16, 1-2: 4–15.

A Conceptual and Visual Proposal to Decouple Material and Interpretive Information About Stratigraphic Data

Patricia Martin-Rodilla
patricia.martin-rodilla@incipit.csic.es

Cesar Gonzalez-Perez
cesar.gonzalez-perez@incipit.csic.es

Patricia Mañana-Borrazas
patricia.manana-borrazas@incipit.csic.es

Institute of Heritage Sciences (Incipit), Spanish National Research Council (CSIC)

Abstract: Stratigraphic information is an important basis on which archaeologists infer conclusions about past events. Thus, the conceptualization and visual representation of stratigraphic information plays a fundamental role in generating archaeological knowledge.

We have performed a deep analysis of the conceptual and visual approaches applied to stratigraphic information over time, with an emphasis on how archaeologists conceptualize and construct stratigraphic sequences. We have found that most approaches make no conceptual or visual separation between the material aspects (i.e. how strata are physically disposed) and the outcomes of the interpretations based on the former (i.e. the functional or chronological conclusions inferred from them). This situation creates ambiguities and conflicts, so the decoupling of material and interpretive aspects is needed.

In order to support this decoupling necessity, we present a conceptual proposal and a subsequent visual design. The proposed approach allows a more precise documentation, processing and displaying of stratigraphic information that differentiates between the material and interpretive aspects.

Keywords: Stratigraphy, Conceptual modelling, Information visualization, Interaction patterns, CHARM

Introduction

Stratigraphic data constitutes one of the main sources on which archaeologists document and infer conclusions about past events. The conceptualization and subsequent use of the stratigraphic information has been studied at least for decades, constituting an important research corpus in the discipline. However, most of the more innovative representations presented in this corpus are only used to communicate results or disseminate archaeological knowledge to non-professionals, while research tasks employ only the more traditional approaches. However, it is research, which usually presents the most demanding needs for information conceptualization and visualization, and stratigraphic information, as shown in the literature, may benefit from new approaches.

In order to tackle this issue, a deep review of the representation and visualization techniques applied to stratigraphic information over time has been performed, with particular emphasis on how archaeologists conceptualize, visualize and interact with stratigraphic sequences during research processes. This review allowed us to identify some underlying conceptual problems in the visual strategies adopted that make the use of more innovative visualization techniques very difficult or impossible. In particular, we found that there is a lack of a conceptual and visual separation between the material aspects of stratigraphy (i.e. the physical arrangement of strata) and the outcomes of the interpretations that are based on the former (such as the functional or chronological conclusions inferred from them). Instead, material and interpretive aspects are usually dealt with as a whole, both at conceptual and visual levels. This creates ambiguities and conflicts as some authors have pointed out (Adams 1992; Yule 1992). Besides, it is easy to argue that decoupling these two aspects would greatly improve their modular treatment; for example, an approach where these aspects were separate (but related) would make data reuse much easier, since third parties would be able to adopt the datasets describing the materiality of the stratigraphy and reuse them to overly a new interpretation that does not need to coincide with that of the original authors. If the two aspects are collapsed into one, scenarios like this become extremely difficult.

In this paper, a clear and unambiguous conceptual and visual proposal for stratigraphic information is presented. This proposal has been developed as a joint effort between archaeologists and specialists in information modelling and visualization. By using the proposed approach, the two aspects of information – material and interpretive – can be documented, processed and displayed separately but in a strongly interconnected fashion, giving the researcher the power to view only one aspect, the other, or both at the same time. This means that stratigraphic information can be handled with better precision and more ease, and communicated with less ambiguity, thus improving the archaeological research process.

The paper is structured as follows: the first part below describes the literature analysis performed in terms of existing conceptual and visual proposals for stratigraphic information. The second part describes the conceptual problem of non-separation, how other authors have pointed out similar ideas, and our vision of it. In addition, the proposed solution is presented, based on a strong conceptual-oriented approach and a visual design based on interaction and presentation principles. Later the proposed solution through a prototype implementation is illustrated. The last section presents some conclusions, discussing the possible applications of the approach, as well as some benefits and limitations.

1 Existing Approaches to Stratigraphic Information

As a methodological construct, the conceptualization, management and visualization of stratigraphic information has traditionally been linked to the origin of stratigraphic documentation methods (Harris 1975; 1989), keeping notations and visualization techniques that emerged all at once. Thus, prior to the advent of information visualization techniques by computational methods, the graphic representation of the stratigraphic data is linked to the origins of the Harris matrix as a methodological paradigm for the stratigraphic record. The Harris matrix representations at this time displayed all stratigraphic units, uniquely identified by a number, in a sequential diagram representing their temporal succession. However, the technological limitations did not allow for the representation of other important aspects of the stratigraphic units, such as their type (deposit, interface, etc.) or related information. In addition, and for the first time, it collapsed the materiality of the stratigraphic units and the temporal interpretations about them into a single element.

1.1 First Uses of Computing visual techniques

The development of the first computer visualization techniques allowed the emergence of stratigraphic information representations. Good examples are the BASP suite (Scollar 1994), which in 1994 incorporated a tool to create Harris matrices, or the standard GUI-based Arched (Pouchkarev 1998). These first approaches adopted the Harris matrix paradigm explained above. Regarding visual strategies, BASP only allowed the definition of stratigraphic units and the creation of relations between them, through text-based commands. In other words, direct visual manipulation of the stratigraphic sequence was not possible. Arched improved on some features of BASP, allowing direct manipulation of the stratigraphic sequence and distinguishing between types of stratigraphic units (deposit or surface), but maintaining the conceptual mixing of materiality and interpretive information inherited from the first approaches.

Simultaneously to BASP and Arched, the literature shows other visual representations of stratigraphic sequences, mainly using commercial tools such as AutoCAD or similar drafting software tools (DoA 2011). These initiatives tried to cater for some of the visualization needs, such as the management of different types of stratigraphic unit or the need to arrange stratigraphic units into meaningful interpretive groups. However, the ad hoc nature of these implementations did not allow the generalization of a visual proposal based on a deep conceptualization of the stratigraphic information.

1.1.1 Current tools

More recently, software engineering principles and current visual strategies have been applied to the representation of stratigraphic information. Some examples are the 'Stratify' (Herzog 2006) or 'HMC' (Traxler and Neubauer 2008). 'Stratify' (Herzog 2004; 2006), for instance, applies sophisticated layout techniques, allowing the direct manipulation of the representation and the grouping of stratigraphic units following time-related criteria. The conceptualization underlying 'Stratify' is based on a graph approach where all nodes –i.e. all stratigraphic units in the visual representation— conceptually belong to the same category. This situation prevents the distinction between types of stratigraphic units —such as interfaces and deposits— and between material evidences and time-oriented interpretations.

'HMC' (Traxler and Neubauer 2008), on the other hand, incorporates some improvements in terms of usability and interaction. For instance, it allows the definition of temporal phases with a collapse-expand mechanisms to visualize them. Other improvements are in terms of application scope, since it incorporates mechanisms to connect GIS software to the tool's interface. In addition, some needs described above such as the support for different types of stratigraphic units and grouping functionalities are also present in 'HMC'. However, material description and temporal interpretation are still merged in the visualizations offered by 'HMC' (Traxler and Neubauer 2008).

All the mentioned approaches are based on the Harris matrix paradigm, and all maintain the material and interpretive dimensions merged. As an additional problem, all of them are mainly used for the production of Harris matrix diagrams in their final form and their subsequent dissemination. Thus, archaeologists usually develop draft stratigraphic diagrams by hand and then, once a final version is ready, use the software tool to create a 'pretty picture' that can be used for publication or circulation. This means that these tools are not being used to assist archaeologists during the research process itself, e.g. to explore and reason about alternative interpretations of the stratigraphic realities.

1.1.2 Alternatives approaches

All the approaches mentioned above follow visual representation strategies designed to adapt or improve the Harris matrix paradigm. However, there are other alternative approaches that deviate from this. Good examples are Cosmas (Cosmas *et al*. 2003) or Day (Day 2005), which includes 3D representations of stratigraphic units; or Bobowski (Bobowski 2007), which presents a 3D environment in which a stratigraphic sequence is represented by a graph schema. These approaches focus on improving the reasoning capabilities of the archaeologist while interacting with stratigraphic data. Interestingly, the need for a material and interpretive separation has been pointed out by them as well (Day 2005; Bobowski 2007). The next section describes this in depth.

1.1.3 A conceptual problem

As we can see in the previous section, the tools and strategies for a visual representation of the stratigraphic information have incorporated the available technological advances, but maintain a clear legacy of a conceptual assimilation between the material and interpretive aspects.

This problem was identified from a theoretical point of view (Adams 1992; Yule 1992) years ago, and theoretical discussions about interpretations of the stratigraphic sequences continue today (Roskams 2011). In these works, the theoretical implications of the lack of separation for the archaeological practice are deeply studied. However, there is still another implication, which is the focus of the present work: the visual representation of stratigraphic information is influenced for this non-separation, preventing in most cases that visual representations are used for research purposes rather than the production of final results. Other authors, based on their experience developing software for stratigraphic information representation, point out the same idea: it is necessary to decouple the material information (physical aspect) and the interpretive details of the stratigraphic data. The authors of HMC, for instance, state that any Harris matrix is constructed in two distinct phases: a first stage based 'entirely upon the analysis of the topographical record and topology by defining the stratigraphic relations' and a second one, corresponding to 'the division of the sequence into so called phases and periods' (Traxler and Neubauer 2008). This second phase 'depends on additional information based on structural (phase) and temporal (period) analysis of the stratigraphic record when the units of stratification are grouped' (Traxler and Neubauer 2008). In this scheme, the first phase corresponds to the physical (i.e. material) description of the stratigraphy, while the second phase corresponds to its interpretation.

According to this, it seems that the actual practice of the Harris matrix method allows for the gradual incorporation of material and interpretive aspects to stratigraphic information. However, conceptual and visual approaches connecting these two aspects prevent this decoupling from being present in the final results (i.e. completed matrices). We argue that a blended conceptualization of stratigraphic information is the major reason for this. An example of this blended conceptualization is the treatment of temporal phases – associated to specific stratigraphic units – and materiality itself as a whole.

To deal with this problem, we take one step back and start from a conceptual level: we propose a conceptual model for stratigraphic information that decouples these two dimensions, which is described in the next section. Then, specific visual strategies are proposed based on this conceptual model.

2 Conceptual proposal

The main goal of the conceptual model here proposed is the faithful representation of the archaeological stratigraphic reality in such a manner that the material and interpretive dimensions are kept separate but strongly connected. Since stratigraphic entities are connected to others, such as finds, features or places, this model is not stand-alone, but a part of the large Cultural Heritage Abstract Reference Model (CHARM, www.charminfo.org) (Gonzalez-Perez and Parcero Oubiña 2011; Incipit 2013). CHARM represents anything that may be the recipient of cultural value ascribed by any individual, plus the associated valorisations ascribed to said things, plus the representations of these things that may exist; in this manner, CHARM is based on two core concepts: Evaluable Entity (an entity that has been, is or may be culturally evaluated) and Valorisation (abstract entity of a discursive nature that adds cultural value to other evaluable entities through interpretive processes that have been agreed upon within a group or discipline) (Incipit 2013).

CHARM is expressed as a ConML (Gonzalez-Perez 2012; Incipit 2013) type model. This means that concepts are represented as *classes* having *attributes*, and connected to other classes through *associations*. A complete description of ConML is out of the scope of this paper; please see (Incipit 2013) for full details. Also, CHARM is not intended to be used 'as is', but provides a common shared abstract reference model that must be extended for each particular organization, project or task (Gonzalez-Perez *et al.* 2012; Incipit 2013). This means that the model presented here can be adapted to your needs if it does not match them perfectly.

The following sections describe the different elements of CHARM that conceptualize stratigraphic information.

3 Material aspect

Most material concepts in CHARM are subtypes of a class named Tangible Entity, and which is defined as an evaluable entity that is fundamentally perceived in a direct fashion and through its materiality. Relevant subtypes of Tangible Entity are:

Structure Entity: a place having boundaries with material characteristics that distinguish it from its surroundings and, also, material entity that shapes the space where it is located, influencing visibility and/or mobility over it. Examples of structures include a house, a cave or the remains of an old canal.

Object Entity: a material entity that does not shape the space where it is located, not influencing visibility or mobility over it. Examples of objects include a clam shell or a fragment of a ceramic pot.

Deposit: a material entity corresponding to matter that has deposited gradually through accumulative processes.

Stratigraphic Entity: a tangible entity that corresponds to one or more stratigraphic units (as methodologically determined during the practice of archaeology).

Figure 1 shows a diagram containing these classes.

The Stratigraphic Entity class is especially interesting, since multiple relevant subtypes specialize from it:

Stratigraphic Sequence: a stratigraphic entity composed of a collection of stratigraphic units that are physically interrelated.

Stratigraphic Unit: a stratigraphic entity made of matter or the trace of removed matter, arranged as a layer with regard to others, reflecting a specific order of deposition, construction or destruction.

Stratum: a stratigraphic unit consisting of a material volume.

Stratum by Deposit: a stratum comprising matter from a deposit.

Stratum by Object: a stratum comprising matter from an object entity.

Interface: a stratigraphic unit consisting of a material surface.

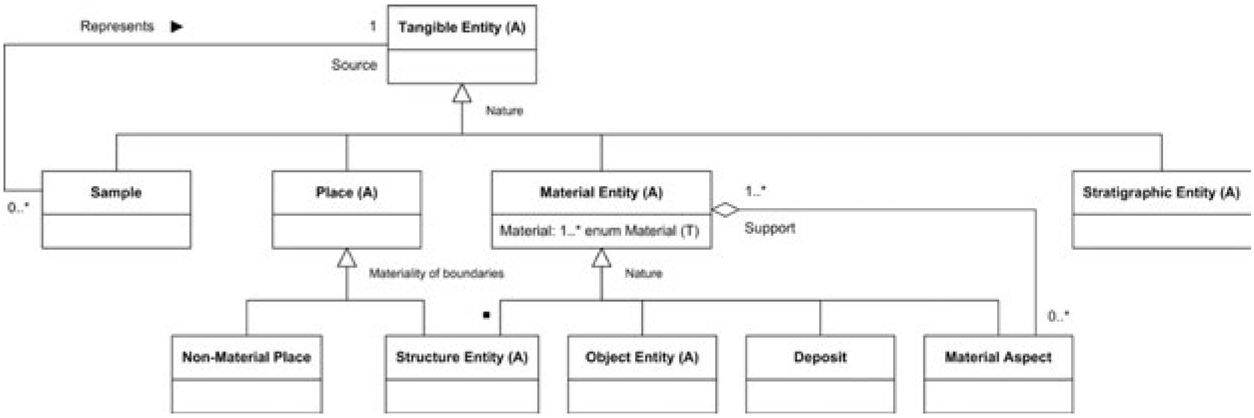

Fig. 1. Fragment of CHARM showing relevant classes related to material entities.

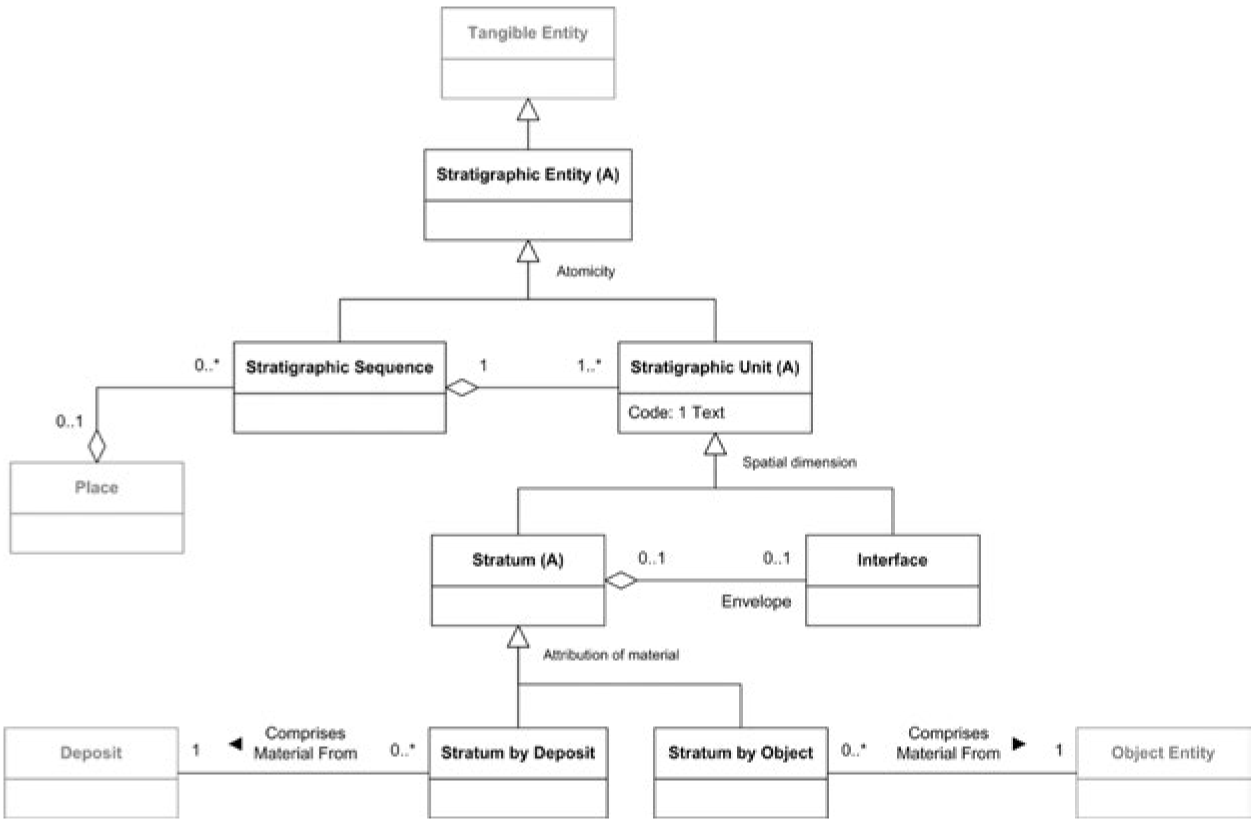

Fig. 2. Fragment of CHARM showing relevant classes related to stratigraphic units and associated concepts.

Figure 2 shows a diagram containing these classes.

The diagrams and definitions in figure 2 show that the physical reality of stratigraphy is captured through the Deposit and Object Entity classes, whereas the methodological decisions on how to excavate or where to dig a trench are captured by classes specializing from Stratigraphic Entity. For example, a site may be excavated on different areas, each one having its own set of stratigraphic units recorded and documented. However, two or more stratigraphic units belonging to different trenches may correspond to the same actual underlying deposit. Having different concepts to model each of these two aspects (physical and methodological) constitutes the first step towards our goal.

Stratigraphic units must be related. A number of relationship kinds are defined, as follows:

Stratigraphic Relationship of Joining: a three-dimensional stratigraphic relationship consisting of a source stratum that horizontally touches the destination stratigraphic unit without fusing with it. This stratigraphic relationship is symmetric; that is, if A joins B, this implies that B joins A.

Stratigraphic Relationship of Abutment: a three-dimensional stratigraphic relationship consisting of a source stratum that horizontally fuses with the destination stratigraphic unit. This stratigraphic relationship is symmetric; that is, if A abuts B, this implies that B abuts A.

Stratigraphic Relationship of Support: a three-dimensional stratigraphic relationship consisting of a source stratum that touches the destination stratigraphic unit vertically and from above, resting on it. This stratigraphic relationship is anti-symmetric; that is, if A is supported by B, this implies that B cannot be supported by A.

Stratigraphic Relationship of Coverage: a three-dimensional stratigraphic relationship consisting of a source stratum that attaches tightly to the surface of the destination stratigraphic unit, covering it. This stratigraphic relationship is anti-symmetric; that is, if A covers B, this implies that B cannot cover A.

Stratigraphic Relationship of Filling: a three-dimensional stratigraphic relationship consisting of a source stratum that fills a concavity of the destination stratigraphic unit. This stratigraphic relationship is anti-symmetric; that is, if A fills B, this implies that B cannot fill A.

Stratigraphic Relationship of Cutting: a two-dimensional stratigraphic relationship consisting of a source interface that establishes a removal of matter from the destination stratigraphic unit. This stratigraphic relationship is anti-symmetric; that is, if A cuts B, this implies that B cannot cut A.

Stratigraphic Relationship of Equivalence: a non-physical stratigraphical relationship that indicates the material and interpretive equivalence of the involved stratigraphic units. This stratigraphic relationship is symmetric; that is, if A is equivalent to B, this implies that B is equivalent to A.

Note that, although the Harris matrix (Harris 1989) usually employs an above/below schema of relations between stratigraphic units –as well as equivalences between these–, we have conceptualized all possibilities of relations between stratigraphic units that we have found in the field according to our experience throughout the years. The proposed conceptualization allows us to use only the above/below schema if needed –by using the Support relationship only–, but also a higher level of detail when necessary. Figure 3 shows a diagram containing these classes.

4 Interpretive aspect

Interpretive concepts in CHARM are mostly related to the Valorisation class, which was discussed above, as well as the Derived Entity class, i.e. an evaluable entity that is not understood in an immediate and implicit manner when perceived, but requires an explicit reception process; derived entities are the outcome of valorisation processes, which involve interpretation. Relevant specific classes are:

Research Valorisation: a scientific-technical valorisation produced with the purpose of generating new knowledge about the valorised object. Research valorisations allow us to interpret raw material evidences (such as stratigraphic entities and relationships) and construct derived entities from them, especially stratigraphic groups.

Stratigraphic Group: a simple scientific-technical derived entity corresponding to a set of stratigraphic units that jointly work towards a common structural and/or functional goal. Stratigraphic groups may have sub-groups. Examples of stratigraphic groups include ‘access corridor’ (in a mound) or ‘abandonment level’ (in an excavated settlement).

Figure 4 shows a diagram containing these classes.

In addition, the interpretation if stratigraphic data usually employs a strong temporal component. For this purpose, CHARM uses the Circumstance class, which is defined as a relative occurrence that happens inherently to one or more evaluable entities; in other words, a circumstance is something that occurs to an evaluable entity such as a stratigraphic entity or a stratigraphic group. There are some specific subtypes of this class, as follows:

Phase: a circumstance that takes a relatively long time and that corresponds to a stable period of the associated entities. Examples of phases include ‘in construction’ or ‘first occupation’ (regarding a construction); or ‘abandoned’ (with regard to a site).

Change: a circumstance that takes a relatively short time and that corresponds to an instable moment of the associated entities. Examples of changes include ‘destruction by fire’ or ‘abandonment’.

Figure 5 shows a diagram containing these classes.

In summary, valorisations, stratigraphic groups and circumstances allow us to capture the interpretive details that may be added to the material description of the relevant stratigraphic entities.

4.1 Interaction and Visual Proposal

Any implementation of a conceptual model implies the selection of a set of criteria to guide the implementation process. In this case, the implementation of the conceptual model described above is in form of a visual and interaction proposal. Thus, we establish the following implementation principles:

We maintain the correlation introduced by the Harris matrix between the vertical disposition of the visual representation and the vertical disposition of the actual stratigraphic units in the territory.

The material and interpretive aspects of the stratigraphic information will be visually separated, matching the concepts in the conceptual model. In order to implement this, we have chosen the black colour to depict concepts belonging to the material aspect, and colours other than black for concepts belonging to the interpretive aspects of the information.

A range of features must be visually represented. This includes distinguishing between the different types of stratigraphic units defined in the conceptual model, a mechanism to group stratigraphic units based on the concept of stratigraphic group, and the visual distinction of the different stratigraphic relationships types defined in the conceptual model.

With regard to interaction, a drag and drop mechanism is necessary in order to support the direct manipulation of the stratigraphic elements displayed. Also, a zoom and pan mechanism is needed to allow the user to display as much or as little information as needed, and selectively change the focus.

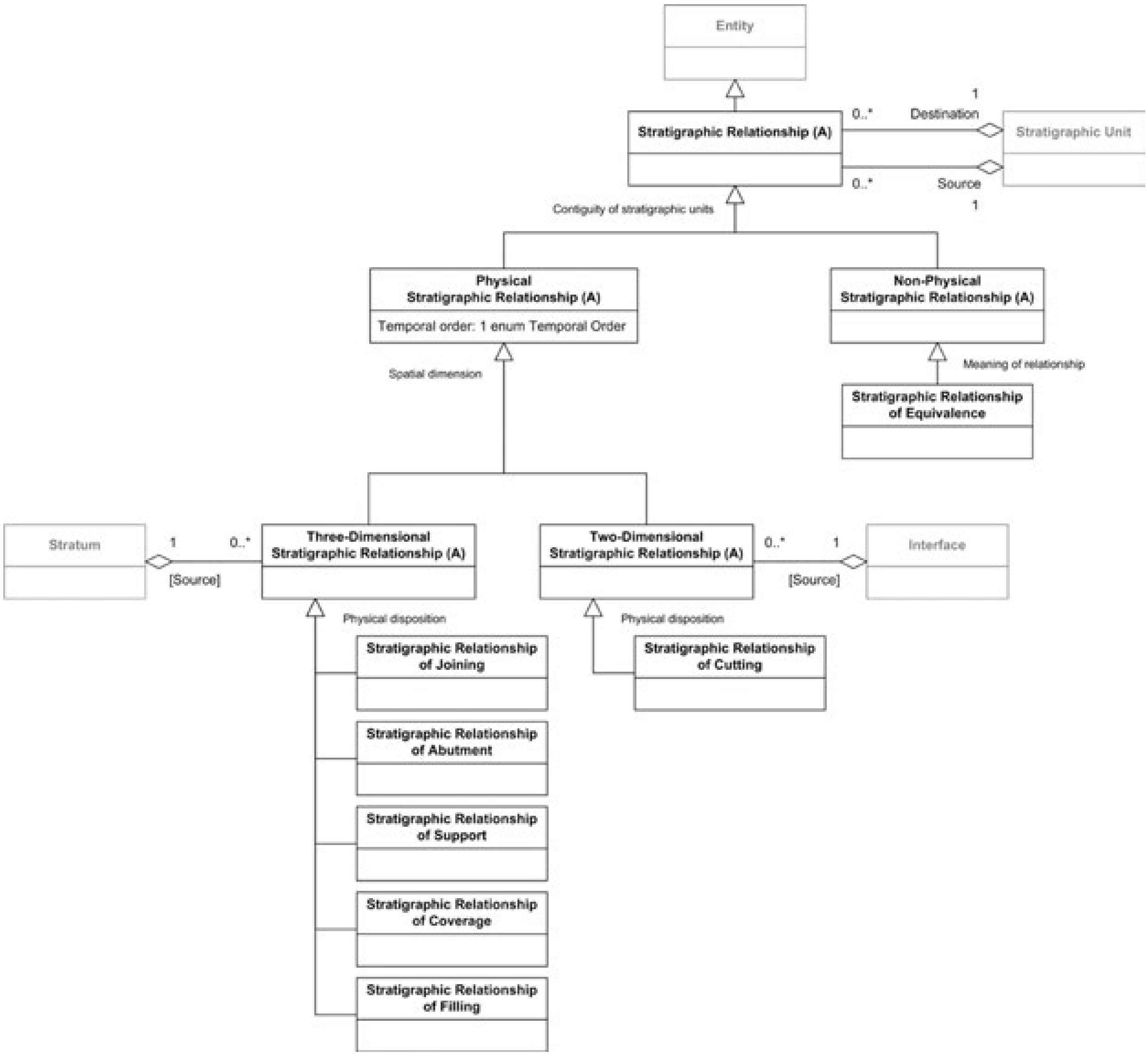

Fig. 3. Fragment of CHARM showing relevant classes related to stratigraphic relationships.

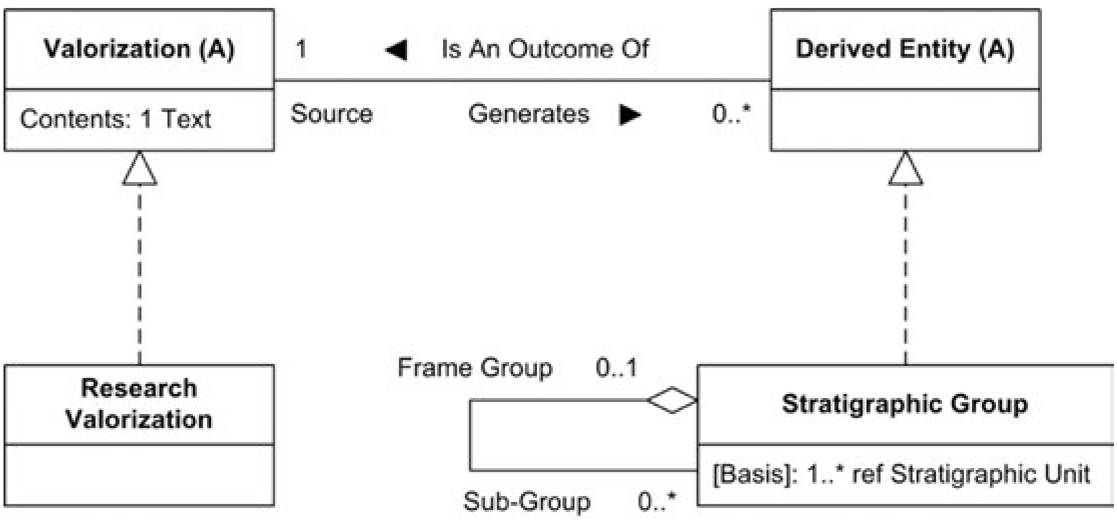

Fig. 4. Fragment of CHARM showing relevant classes related to the interpretive aspect.

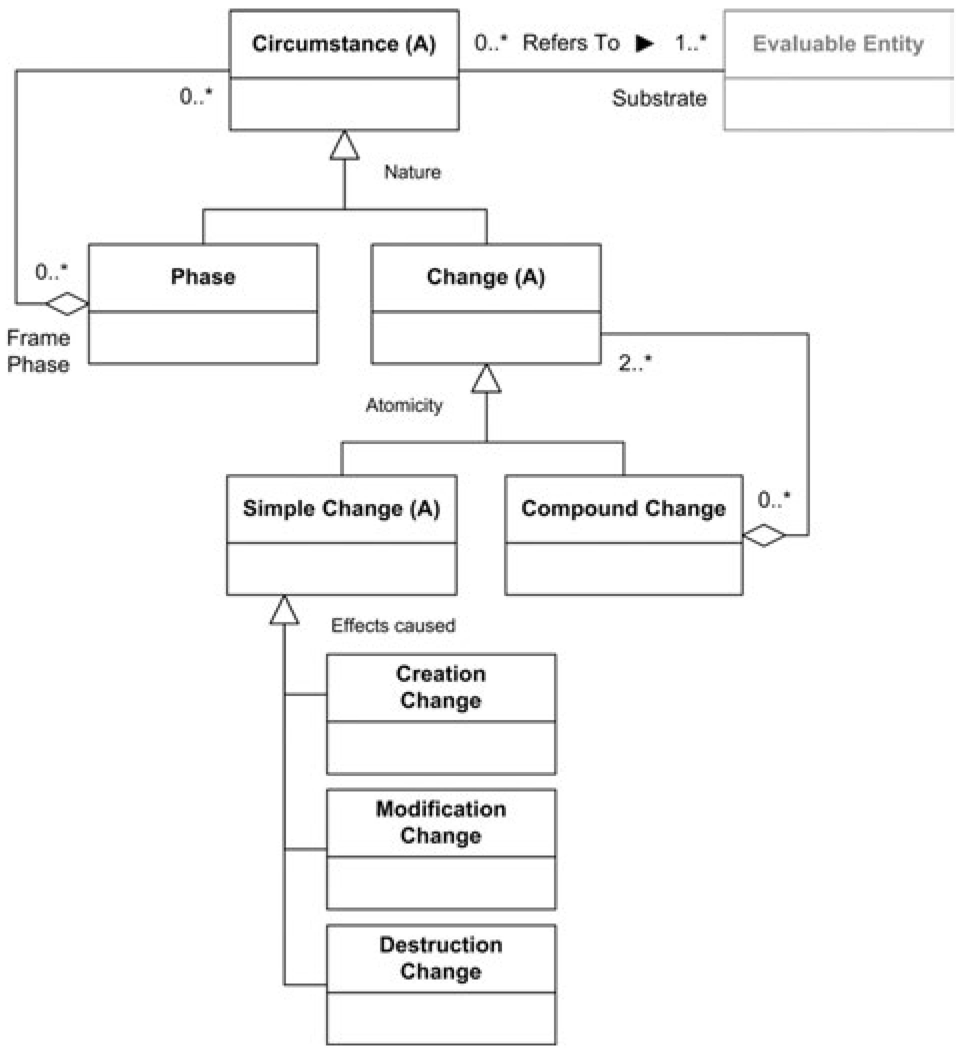

FIG. 5. FRAGMENT OF CHARM SHOWING RELEVANT CLASSES RELATED TO TEMPORAL CHANGE.

In addition, the selection of preferred colours for interpretive aspects is interesting, in order to facilitate the user's reasoning according to different facets of the information, such as functional, temporal or methodological.

Following these principles and based on the conceptual model created, we have implemented a prototype system, which will aid in validating the proposed approach. The next section describes this.

4.2 Implementation and Initial Validation

The prototype uses a dataset from the real-world archaeological excavation project in A Romea (Criado-Boado *et al*. 2014), an Iron Age barrow in Galicia (Spain), which was excavated in 2003. The complete stratigraphic information for the excavation and the related data is shown in the prototype. The prototype was implemented on the Apple iOS platform for iPad tablets. This choice was made due to the good potential of iOS environments to manage interaction and representation with clear user interfaces. However, it should be possible to implement the proposed approach in any technological platform by following the conceptual model and the visual and interaction principles provided in previous sections.

Firstly of all, the prototype implements the conceptual model proposed and an instance of this model for the data of A Romea. This means that it contains an information structure that directly supports the needed decoupling of aspects. Secondly, the prototype implements a user interface that follows the provided visual and interaction principles, and which are described below. A screenshot of the prototype is shown in figure 6.

In general, the prototype allows the user to freely interact with the stratigraphic representation. A typical view is shown in figure 7. Note that all the symbols displayed are painted black, because all the underlying concepts belong to the material aspect of the information.

The user can activate optional views in the left-hand side menu, namely timeline and valorisation groups. These two views correspond to the interpretive aspects described in previous sections. Thus, both views are displayed in colours other than black. The valorisation groups view overlays a layer on top of the stratigraphic units that allows the user to create and interact with groups of the existing stratigraphic units. Figure 8 shows an example. Note that this grouping mechanism is criterion-independent, i.e. it can be used to represent groupings at

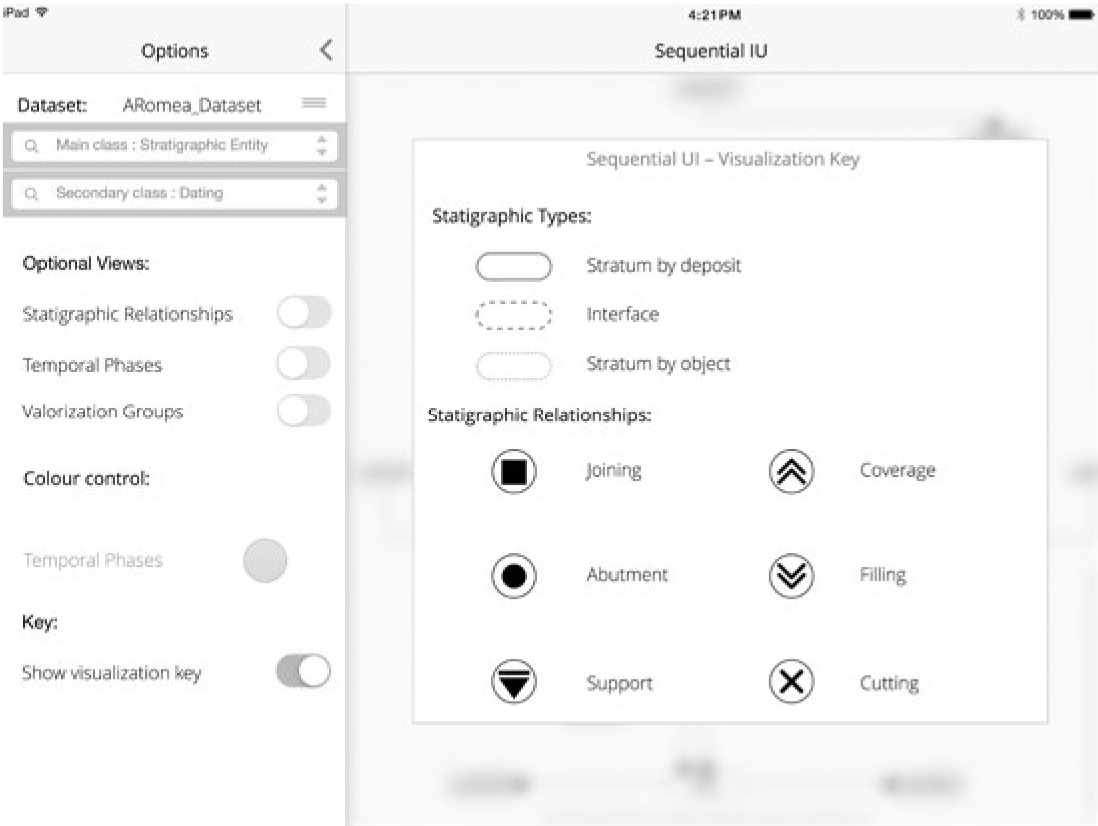

Fig. 6. Prototype screenshot displaying a legend with the different symbols used

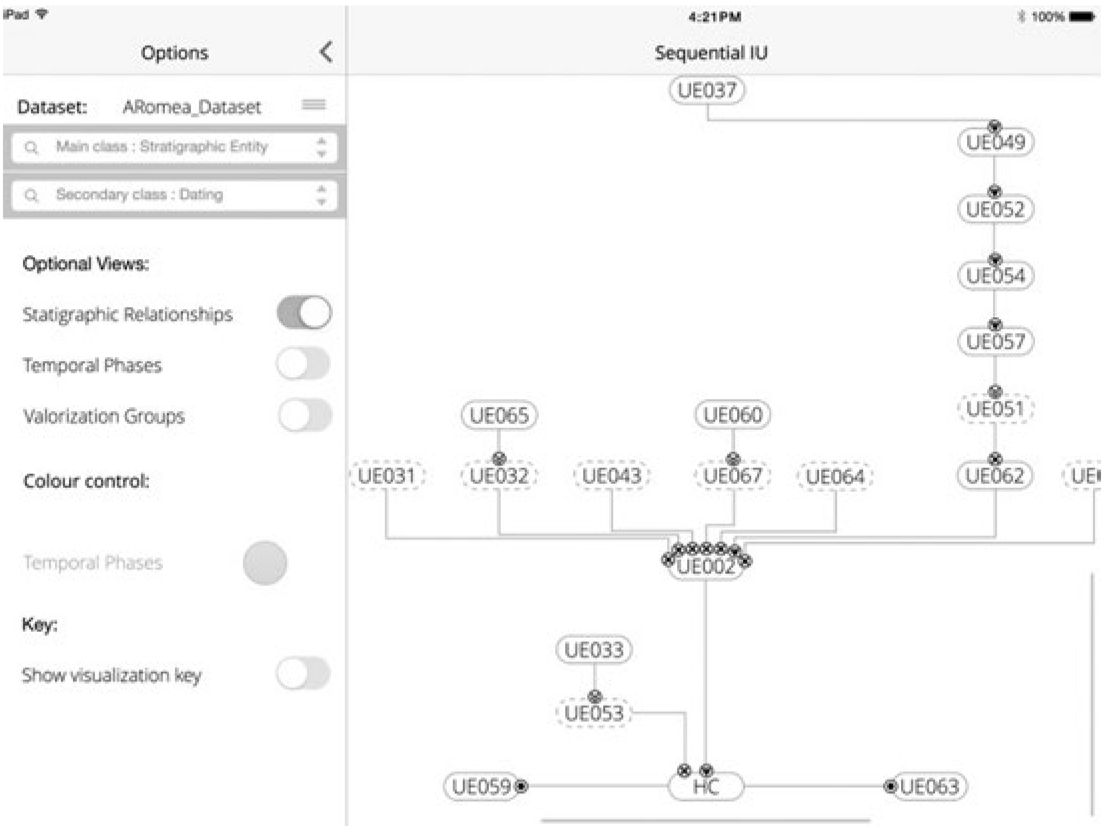

Fig. 7. Prototype screenshot displaying the material aspects of a stratigraphic sequence

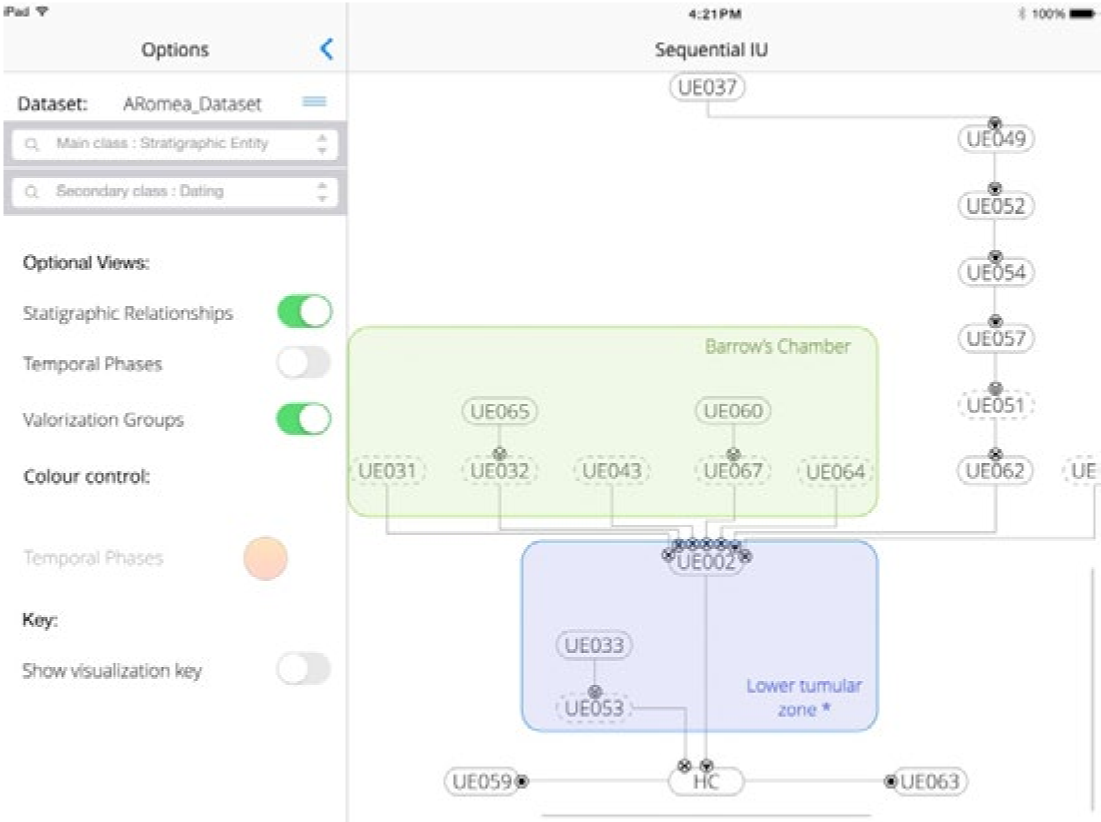

Fig. 8. Prototype screenshot displaying valorization groups overlaid on the material aspects of a stratigraphic sequence.

different facets (temporal, functional, methodological, etc.) of the interpretive aspect of the stratigraphic information.

Regarding the timeline view, it is based on the Valorisation class and also uses the Circumstance class and its subtypes. Enabling the timeline displays a vertical bar on the right-hand side of the screen that depicts the different time-related valorisations and their mappings to the stratigraphic units. Figure 9 shows an example. An interesting utility of this feature is the detection of irregularities in the stratigraphic sequence, mainly when the physical order of the stratigraphic units differs from the temporal order as interpreted by the archaeologist.

As an initial validation, the complete stratigraphic dataset of A Romea excavation was loaded into the prototype, and the archaeologists who participated in the excavation (among them, one of the authors of this paper) asked to exercise it. The prototype is fully functional, allowing the user not only to interact with the information but also to create, edit and remove elements in order to facilitate the exploration of stratigraphic hypothesis. Initial validation was achieved through the joint development of the prototype; a full report of the archaeologists' feedback on its adequacy is beyond the scope of this paper and left for future research.

5 Conclusions

In this paper we propose a conceptual and visual approach to solve the need to decouple the material and interpretive aspects of stratigraphic information. This approach is based on conceptual modelling techniques that permit the representation of the archaeological stratigraphic reality in such a manner that the material and interpretive dimensions are kept separate but strongly connected. The most important implications of this decoupling are:

The decoupled conceptualization facilitates the reuse of the material descriptions in the context of different interpretative approaches.

The decoupled conceptualization supports that different authors develop separate interpretations or the material evidence, and even that the one author maintains multiple interpretations about a given material reality, perhaps as different interpretative hypotheses.

The decoupled conceptualization is better aligned with two-step research archaeological methodologies, in which the first step entails a material description of the evidence and the second one involves the interpretation (or the multiple interpretations) of the former.

In addition, we have defined a set of principles to implement this proposal as an interactive user interface. The proposed approach and the visual principles defined allow that the two aspects of stratigraphic information –material and interpretive– can be documented, processed and displayed separately but in an interconnected fashion, giving the researcher the power to view only one aspect, the other, or both at the same time. In addition, we present here an initial validation of the

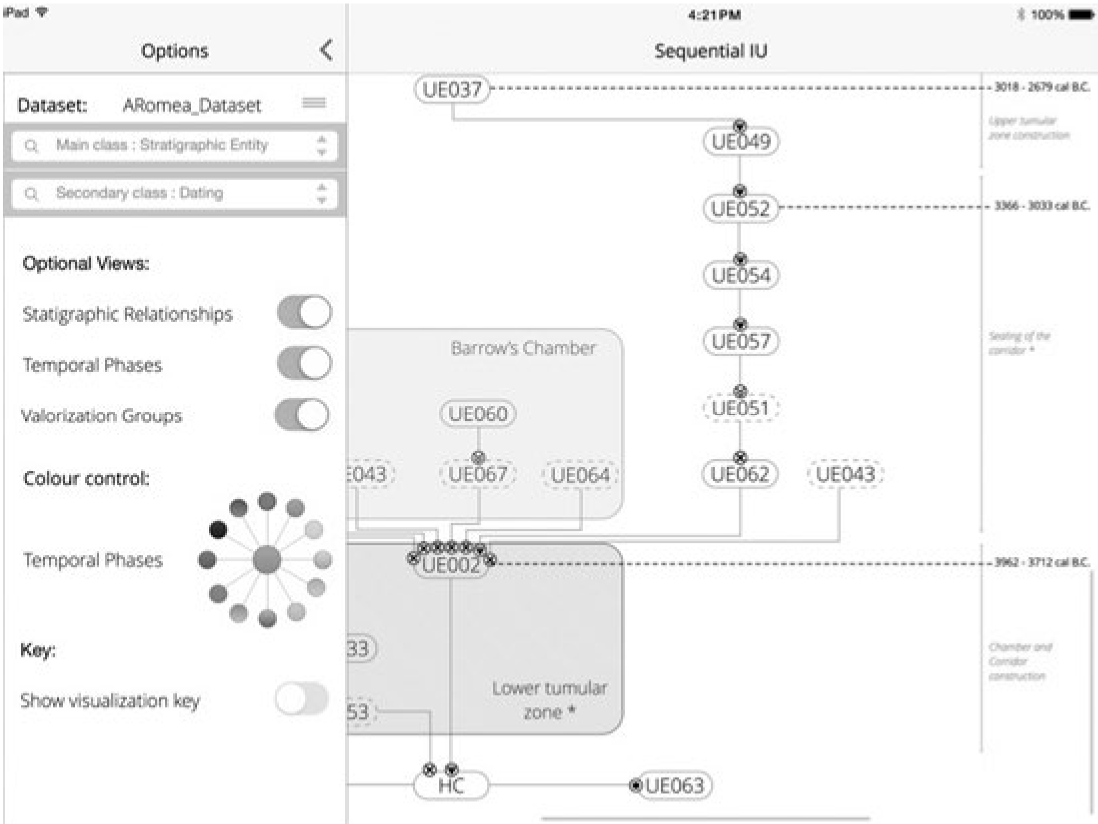

Fig. 9. Prototype screenshot displaying an interpretive temporal timeline (right-hand side) and its correspondence to other elements in the stratigraphic sequence.

approach through an implementation of a prototype based on the stratigraphic information of the A Romea excavation. The implementation has allowed us to test the conceptual proposal with a real dataset and validate the feasibility of the visual principles defined.

Adopting the proposed approach in commercial tools would allow archaeologists not only to create nice-looking diagrams for publication, but also to explore hypothesis based on the stratigraphic information in an easier way, facilitating the reasoning based on stratigraphic data. In this regard, we conceive our solution as an exploratory tool for the daily work. In addition, the approach may be useful in educational contexts, where students have to learn and continuously evolve stratigraphic sequences.

As future work, we plan to extend the validation of the proposal through a range of case studies with more complex stratigraphic sequences and needs than the one presented here. In addition, we plan to conduct a set of empirical studies with archaeologists in order to evaluate other theoretical implications that this decoupling may have for archaeological practice and that we have not addressed in this work.

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Bibliography

Adams, M. 1992. 1992, Stratigraphy after Harris: Some Questions. In K. Steane (ed.), Interpreting Stratigraphy: a Review of the Art. *CLAU Archaeological Report* 31: 13-6. Lincoln 1993.

Bobowski, B., Walczak, K., Stawniak, M. 2007. 3D Visualisations of Archaeological Sites: Dynamic 3D Visualisations of Harris Matrix Data for Rescue Town Excavations Gdańsk / Szafarnia Site, Poland. *Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA) Berlin, Germany, 2–6 april 2007*. Available at: http://proceedings.caaconference.org/files/2007/03_Bobowski_et_al_CAA2007.pdf [Accessed: 1 july 2015]

Cosmas, J., Itegaki, T., Green, D., Joseph, N., Van Gool, L., Zalesny, A., Vanrintel, D., Leberl, F., Grabner, M., Schindler, K. 2003. Providing Multimedia Tools for Recording, Reconstruction, Visualisation and Database Storage/Access of Archaeological Excavations. In D. Arnold, A. Chalmers, F. Niccolucci, *The 4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*: 165-74. The Eurographics Association.

Criado-Boado, F., Ferro Vázquez, C., Martínez Cortizas, A., Mañana-Borrazás, P. 2014. Punctuated stages of megalithic construction: from barrows chronologies to sediments. Megalithic biographies: cycles of use and closure, the XVII World UISPP Congress, Burgos, september 2014 (Oral communication) Available at: http://hdl.handle.net/10261/101378. [Accessed: 1 july 2015]

Day, W., Cosmas, J., Ryan, N., Vereenooghe,T., Van Gool, L., Waelkens M., Talloen, P. 2005. Linking 2D Harris Matrix with 3D Stratigraphic Visualisations: an integrated approach to archaeological Visualisations. In A. Figueiredo and G. Leite Velho (eds.), *The world is in your eyes. CAA2005. Proceedings of the 33rd Conference of Computer Applications and quantitative methods in Archaeology (CAA 2005), Tomar Portugal, 21-24 march*: 155-60.

Gonzalez-Perez, C. 2012. A Conceptual Modelling Language for the Humanities and Social Sciences. Sixth International Conference on Research Challenges in Information Science (RCIS 2012). In C. Rolland, J. Castro, O. Pastor (eds.), *Sixth International Conference on Research Challenges in Information Science*: 396-401. IEEE Computer Society.

Gonzalez-Perez, C., Martín-Rodilla, P., Parcero-Oubiña, C., Fábrega-Álvarez, P., Güimil-Fariña A. 2012. Extending an Abstract Reference Model for Transdisciplinary Work in Cultural Heritage. In J. M. Dodero, M. Palomo-Duarte, P. Karampiperis (eds.), *Metadata and Semantics Research*: 190-201. Cádiz (Spain), Springer.

Gonzalez-Perez, C., Parcero Oubiña, C. (2011). A Conceptual Model for Cultural Heritage Definition and Motivation. In M. Zhou, I. Romanowska, Z. Wu, P. Xu, P. Verhagen, Revive the Past Proceeding of the 39th Conference on Computer Applications and Quantitative Methods in Archaeology: 234-244. Beijing (China), Amsterdam University Press.

Harris, E. C. 1975. Stratigraphic analysis and the computer. Computer Applications in Archaeology 3: 33-40.

Harris, E. C. 1989. Principles of Archaeological Stratigraphy. Second edition. London and San Diego, Academic Press.

Herzog, I. 2004. Group and Conquer – A Method for Displaying Large Stratigraphic Data Sets. In K. Fischer-Ausserer, Börner, W., Goriany, M., Karlhuber-Vöckl, L. (eds.), Enter the Past. The E-way into the four Dimensions of Cultural Heritage. Proceedings of the 31st Conference of Computer Applications and quantitative methods in Archaeology, British Arcaheological Reports Internation Series 1227: 423-6. Oxford, Archaeopress.

Herzog, I. 2006. No News from Stratigraphic Computing*? Workshop 10 'Archäologie und Computer. Kulturelles Erbe und neue Technologien'*, Vienna 2005. PDF file on CD. . Vienna, Phoibos Verlag.

Pouchkarev, I., Thome, S., Mutzel, P., Hundack, C. (1998). 'Arched website at Vienna University of Technology.' Available at http://www.ads.tuwien.ac.at/arched/. [Accessed: 1 july 2015]

Roskams, S. 2001. *Excavation*, Cambridge, Cambridge University Press.

Scollar, I. (1994). The Bonn Archaeological Software Package for Windows 5.0, The Unkelbach Valley Software Works, Remagen.

Traxler, C., Neubauer, W. 2008. The Harris Matrix Composer, A New Tool To Manage Archaeological Stratigraphy. Proceedings of the 14th International Conference on Virtual Systems and Multimedia, Cyprus: 13-20.

Yule, B. 1992. Truncation horizons and Reworking in Urban Statigraphy. Interpretation of Stratigraphy: A Review of the Art. In K. Steane (ed.), Interpreting Stratigraphy: a Review of the Art. *CLAU Archaeological Report* 31: 20-3. Lincoln 1993.

Websites

DoA (2011). 'Day of Archaeology. Roman and Early Medieval Crickley: Matrices and Contexts.' from http://www.dayofarchaeology.com/6-roman-and-early-medieval-crickley-matrices-and-contexts/.

Incipit 2013. ConML Technical Specification, Incipit, CSIC.

Incipit 2013. ConML Web Site. Available at http://www.conml.org.

Incipit 2013. CHARM Extension Guidelines, Incipit, CSIC.

Incipit 2013. 'CHARM Web Site.' Available at http://www.charminfo.org.

Incipit 2013. CHARM White Paper, Incipit, CSIC.

Recording, Preserving and Interpreting a Medieval Archaeological Site by Integrating Different 3d Technologies.

Daniele Ferdani
daniele.ferdani@itabc.cnr.it
CNR-ITABC Institute for Technologies Applied to Cultural Heritage, National Research Council, Italy,

Giovanna Bianchi
giovanna.bianchi@unisi.it
Department of Historical Sciences and Cultural Heritage, University of Siena

Abstract: In recent years, the University of Siena has been involved in studying the archaeology and architecture of the medieval castle of Montieri (Grosseto, Italy). The castle was built by the Bishop of Volterra, and, thanks to its metal-bearing ores, it was the focus of a complex history. The most recent field campaign was focused on excavating 'La Canonica', an ecclesiastical complex dedicated to St. Niccolò. The excavations revealed the existence of a church characterized by an unusual plan, having six apses (the only example of its kind in Italy), and a number of buildings pertaining to a large residential area and artisans' zone. During the field research, an innovative system of 3D documentation and analysis was tested, in order to produce digital data for different research purposes: 3D documentation, monitoring, preservation, interpretation and 3D reconstruction. This paper expands on the workflow system, techniques, and software used, and the results they led to.

Keywords: 3D modelling, dense image matching, 3D reconstruction workflow, dreservation, dnterpretation.

Introduction

Montieri is a small medieval site situated in southern Tuscany, between Siena, Grosseto and Volterra (Fig. 1). Although the settlement is not well known, because of the nearby presence of the better-known sites mentioned above, it has several high-status medieval buildings in such a good state of preservation. These buildings have rare, ornate features, and embellished architectural elements, such as the so-called 'Cassero' (the fortified headquarters of the Bishop), the 'Foundries', and towers. These buildings are wonderful examples of private fortified residences, characterized by the stylistic and architectural influence of Siena and Volterra, and they reflect the economic wealth of their inhabitants. Indeed, between the 12th and 13th centuries, Montieri was an important castle town built close to silver mines and administered by the Bishop of Volterra. It was used to operate the productive cycle of silver: from mine-workings to silver working, and the minting of coins (Aranguren *et al*. 2008).

Over the last few years, the University of Siena, in collaboration with local authorities, has been involved in studying the medieval architecture of Montieri, using techniques and methodological tools of the Archaeology of Architecture. Within this discipline, developed in the context of Italian medieval archaeology, methodological tools have been developed which borrow the principles of stratigraphic sequencing from traditional archaeology, with the aim of identifying, in the fabric of walls, the traces and relationships of the main actions and transformations involving construction and destruction which have taken place over time (Brogiolo 1998). This allows different phases in the life of the building itself to be identified. The architectural survey was supported by excavation campaigns that have brought to light new, important information about the role of some of these buildings. This is the case of the 'Foundries', a large building which once housed the local mint. During excavation inside the ground floor, several braziers and furnaces for smelting metal were discovered, along with small channels cut into the ground for mixing the molten metal. Another important case relates to the San Niccolò ecclesiastical complex, called 'La Canonica'.

The site was discovered during recent campaigns. The complex stands on the north-eastern side of Montieri hill, outside the castle walls. It was known from written documents as of 1133, but the excavation revealed the existence of architecture belonging to an earlier period. The most important building in the overall complex is the Church of S. Niccolò, which had six apses. Archaeological investigation has made it possible to establish that the church was built in the first 40 years of the 11th century, before the rest of the buildings that make up the complex. It was found that its construction was linked to a burial, an inhumation in a stone coffin.

During the 12th century, and especially in the first few decades of the 13th century, variations were made to the existing system of structures, and it was only in the later 14th century that a new, residential building was added to the original structures. The presence of an extensive burial area, both inside and outside the enclosed area, which has so far yielded more than 300 inhumations, suggests that the main function of this site was connected to worship, rather than to mining. The creation of this important centre of worship can be seen as a successful attempt, by the bishop of Volterra, to combine control of mineral resources with religious and social control over the Montieri community (Fig. 2).

1 Goals

During the most recent campaign, our efforts were focused especially on the architecture of the church. The architectural complexity of the church, and the necessity to obtain a thorough metric analysis of the building, required the use of three-dimensional survey technologies. The main goal of the

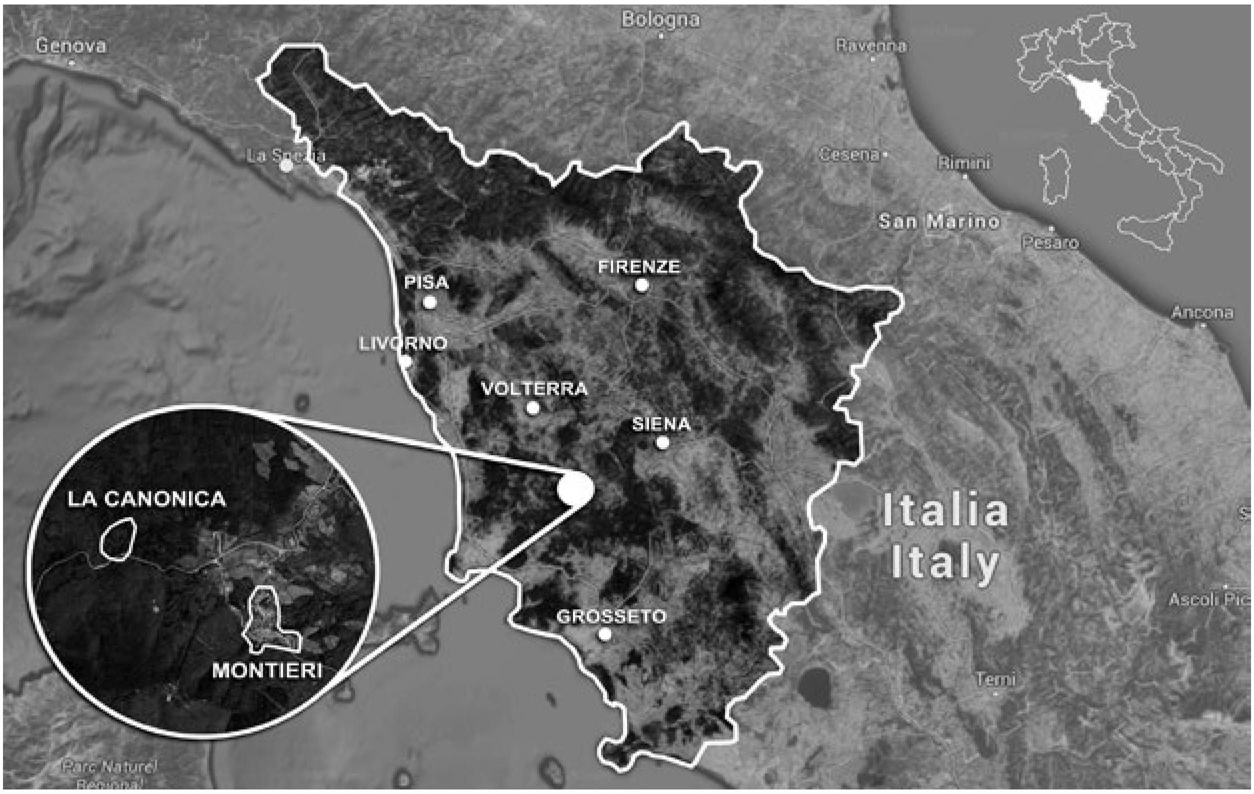

FIG. 1. GEOGRAPHICAL POSITION OF MONTIERI (GR). PICTURE FROM /WWW.GOOGLE.IT/MAPS/

FIG. 2. AERIAL VIEW OF THE ARCHAEOLOGICAL SITE. COURTESY OF DOTT. PAOLO NANNINI, SOPRINTENDENZA ARCHEOLOGICA DELLA TOSCANA.

Fig. 3. The archaeological site of "La Canonica" during the excavations.

survey was indeed to get a data-set suitable to be used both for archaeological documentation and for supporting restoration and digital reconstruction activities.

In view of this, an innovative workflow system for 3D documentation and analyses was tested. The results, presented in the following paragraphs, show how this approach can be adopted and fully integrated in routine archaeological practice, thanks to its multiple advantages: fast acquisition and post-processing of the data, 3D textured models, low cost and post-excavation analyses. The system integrates different 3D modelling approaches, in order to produce digital sets of data for different research purposes:

- 3D documentation. Using Dense Image Matching techniques, it was possible to draw up a detailed and textured digital model of the entire archaeological site. The model was used as basis for post-excavation discussion and investigation, and finally to easily derive technical archaeological documentation such as blueprints, sections, and perspective and orthographic views.

- improved analyses. Using computer graphics software, complex outputs were derived from the 3D models obtained. For instance the curved surface of the apses were rectified and developed. This allowed the facing stonework to be seen and measured without any distortion by archaeologists, improving their perception in analysing the construction phases, and evaluating the skills and capability of the builders.

- monitoring and preservation. The site was under excavation and subjected to rapid decay, due to atmospheric agents, and the excavation activity itself, for a long period. This altered the state of preservation of the monument. However, since the 3D models were recorded once the architecture came to light, 'freezing' the remains at the moment of their discovery, it was possible to easily restore the monument using the digital model as reference.

- interpretation and 3D reconstruction. Finally the 3D scanned models were used as reference for drawing up a virtual reconstruction of the medieval architecture, using computer graphic approaches. The digital reconstruction process went hand-in-hand with interpretation activities, improving researchers' perceptions, thanks to an immediate visual feedback, and allowing hypotheses to be tested, and refined when proved wrong.

The following paragraph outlines the workflow system adopted in this research, from acquisition in the field to the creation of a three-dimensional model of the site as it stands today, and hypotheses for the site's reconstruction.

2 3D survey methodological approach

The choice of methodology and instrumentation to be used during the 3D survey campaign of the building was made taking into account different operational aspects. The Church of S. Niccolò, due to the unusual plan, has a very complex geometry; it is impossible to survey with precision using traditional approaches (Fig. 3). For this reason, a 3D acquisition turned out to be the most appropriate technique, in the circumstances. The choice of the right 3D methodological approach was made taking into consideration different problematical issues such as the budget and the available instrumentation.

Furthermore, we wanted to experiment emerging 3D reconstruction tools, and test whether they can be integrated into classical archaeological surveying, and improve documentation with easy-to-obtain three-dimensional information.

In accordance with the situation, image-based modelling (IBM) was chosen as the acquisition method. This recent technology allows 3D models to be obtained in a very short time, and on a very low budget, with a complete and detailed 3D rendering from a set of uncalibrated photos by following certain steps during the acquisition, such as an adequate number of shots, a sufficient percentage of overlap between the images, adequate lighting conditions, etc. (Dellepiane *et al*. 2013). The entire modelling process is carried out almost automatically, by software that combines algorithms of computer vision in order to build a 3D model and can be briefly summarized in the following points (Fig. 4):

- image-matching: recognition of corresponding points in the collection of photos;

- structure from motion (SFM): reconstruction of the camera positions, and creation of a three dimensional low-density point cloud (sparse point cloud): the software calculates, for each corresponding point, its position in relative coordinates xyz (depth value).

- multi-view or dense stereo reconstruction: creation of a three dimensional point cloud of high density (dense point cloud).

- triangulation: construction of the polygon mesh

- texture-building: the creation and application of high-resolution images to three-dimensional model, to get a photo-realistic effect.

The automatic approach of this method involves lower accuracy in comparison with conventional scanning techniques. Nevertheless recent tests have demonstrated that this approach can be sufficiently reliable, and it has already been used with success in some sectors of archaeology, as in Dellepiane *et al*. (2013), Callieri *et al*. (2011), Forte *et al*. (2012) and Remondino, Campana (2014). The greatest advantages of IBM do not only ie in the extraction of measurements from 3D models. These techniques can also be used to enhance interpretation and analysis experiences during excavation processes. The quick procedure of 3D acquisition and processing allows a 3D model of an archaeological site to be obtained for documenting and monitoring the evolution of the excavations themselves, to improve the perception of the site during the ongoing excavation (Dellepiane *et al*., 2013), or to document monuments in emergency situations, such as during rescue excavations. In the case of our site, for example, the acquisition of all of the architecture after excavation was no longer possible, due to the fact that the monument was partially buried again to preserve it from collapse (during the excavation the archaeologists investigated the foundations of the church in order to get a better understanding of the building's construction techniques, and the wall was temporarily supported using scaffolding)

3 Acquisition Campaign of the buildings

The church and the long buildings were acquired in two different survey campaigns (2012 and 2013), but the workflow system was the same. The first step, before the photographic campaign, was the establishment of a local topographical network as a reference coordinate system for the future 3D model. A set of control points (photogrammetric targets, and architectural points) were placed or identified on the monument. These control points were then measured with a total station to record their local coordinates. The topographical network constituted the basis for the subsequent post-processing operations, such as scaling and alignment operations, and to check the geometrical accuracy of the 3D model. Then, in order to obtain a good dataset of photos, a campaign of photographic acquisition was carried out. Images were collected using a Canon reflex camera (400D for the church, and 650D for the long buildings), with a 35 mm focal length. These were taken from a range of differing heights (using a stepladder), and other positions, to cover all the parts of the monument. In this way, 'twilight zones', or areas impossible to detect because they were obstructed by other elements, were kept to a minimum, thereby reducing a typical fault associated with this approach.

Some close-ups were taken, in order to record some parts characterized by greater geometric detail such as the burial found in the sacristy, and the stairway in the main access. The campaign was accomplished without difficulty: the area around the building was free of obstacles, and so the photos were taken at regular intervals (more or less every 15 degrees), following a regular path all around the buildings, and ensuring a good sampling (each photo was taken with a large overlap with the previous one: about 70-80 %). The quality of photographic sampling is crucial for the reconstruction: the success of the subsequent reconstruction process, carried out by the software, depends on the presence of enough features to compute the camera calibration, and to find correspondences among the photos during the matching operation. Therefore the acquisition was carried out during diffuse light conditions, and in the total absence of cast shadows, in order to obtain a uniform texture. To survey the entire site, more than 1,000 photos (273 for the church, and 800 for the long buildings) were necessary.

4 Post-Processing and documentation

Once captured, the photos were imported into Photoscan (Agisoft Software) to build the 3D models. In our case, the processing was computed with a high-performance workstation (configured as follows: 64 bit operative system; Intel Xeon 2.40 GHz processor; 36 GB DDR2 Ram; Nvidia GeForce GTX 680 graphic card).

As a first step, the software computed the camera position for each photo, to build the point cloud model. Although this took a long time to compute, higher accuracy settings were established in order to obtain the best accuracy in the alignment. In order to ensure the best result in the camera alignment and, above all, to provide a reference grid to scale and orient the models, the markers acquired in the topographical campaign were used as control points. In each photo where the control points were visible, markers was placed, and their xyz coordinates were imported from an external file (created during the survey with the total station).

In the second step, the 3D model reconstruction was computed. This operation requires large hardware resources, and depends on the quantity and resolution of the loaded photos and selected target quality. After the reconstruction process, a huge model, with 135 million polygons, was created. An initial cleaning operation, and polygon decimation process, was performed in Photoscan, reducing the total amount to 1 million. Then the model was exported in .obj format, and exported to perform for further optimizations in Meshlab, an open source tool for processing and editing 3D triangular mesh (Meshlab Software). Several mesh cleaning filters were used to remove duplicated or unreferenced vertices and small isolated components, erase non-manifold faces, and finally to automatically fill small holes due to under-sampling areas. Finally the optimized model was imported again in Photoscan to build the textures.

The texture-building algorithm exploits the images already oriented on the model to generate one or more texture 'atlases', that is the result of the combination of multiple photos, which are then applied to the model by means of automatic processes. At the end of the process, 22 high quality texture maps, with 4096x4096 pixel resolution, were generated by the software. Different algorithms of texture generation were tested, but in this case the best result was performed by the one that uses an

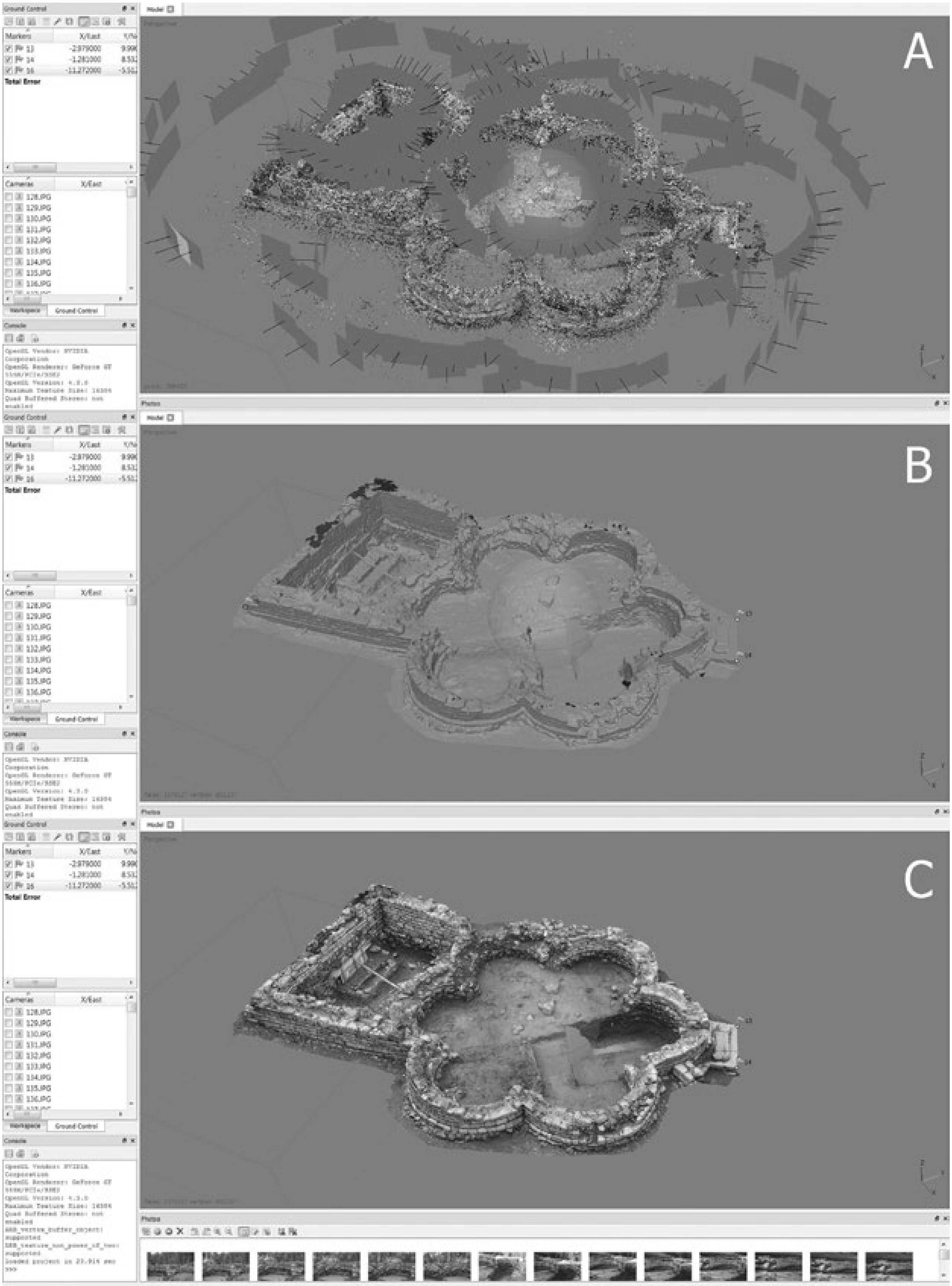

Fig. 4. Different steps performed by the software of Dense Image matching to get the 3D models of an object from photos: estimation of camera position and sparse cloud creation; dense cloud computation and mesh triangulation; texture parameterization.

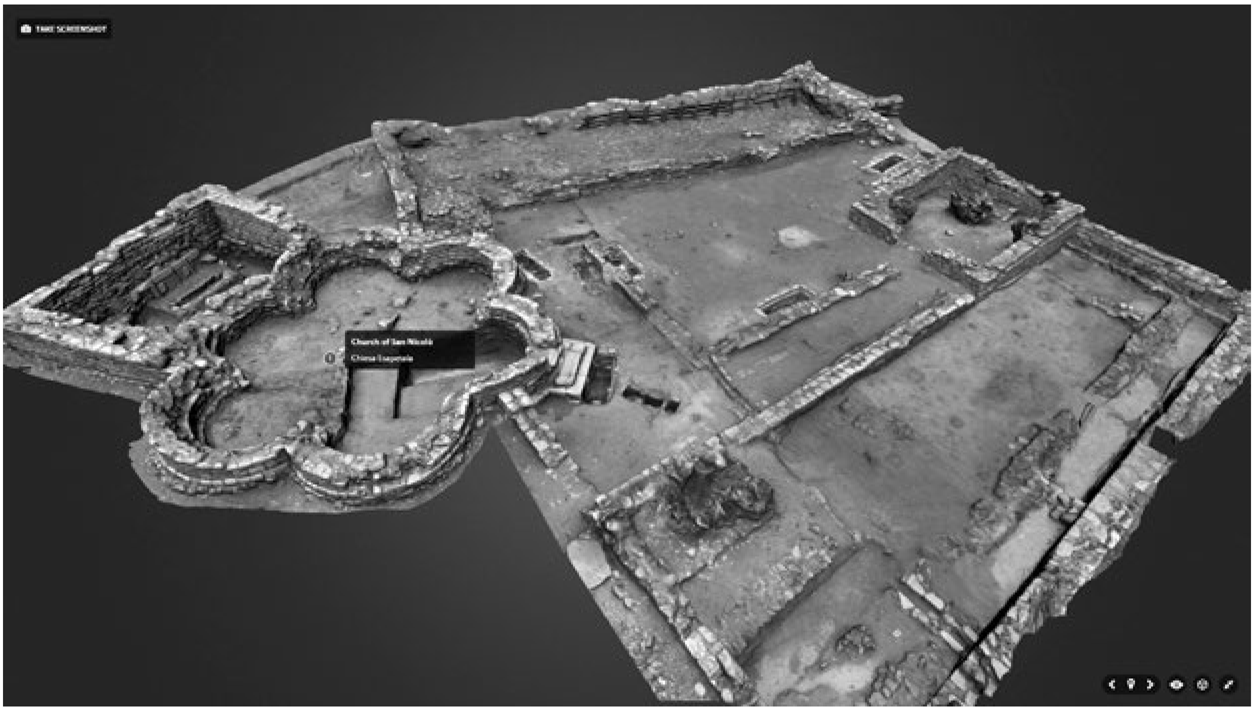

Fig. 5. Textured model of the archaeological site after the optimization processes

'average blending mode' to generate a map from the photos. Further optimizations were carried out on Blender, a computer graphic software. Here a 'texture clone paint' tool was used to fill the small gaps in the texture, or to correct minor flaws (Fig. 5).

The resulting textured model was the starting point for ensuring proper documentation of the monument, allowing detailed characterization of the stone surfaces.

The models were rendered to obtain ortho-images and rectified images of the walls (interiors and exteriors). The rectified images were used for mapping surface operations, such as characterization maps of the different materials, construction phases, lithotypes, stratigraphy and for evaluating the skills and capability of the builders (master-builder, bricklayers, stone-cutters). Moreover the geometry was used to extract accurate profiles for the layout, elevation and sections of the church and the buildings at different heights, and to integrate the topographic survey data performed with the total station (Fig. 6).

The projected design of the apses, derived from the model of the church, was particularly useful. The cylindrical surfaces inside and outside the apses, lying on surfaces of revolution generated by a straight line, had to be projected onto a plane to be analysed without any distortions. This mathematical operation was conducted in computer graphics software by 'unrolling' the curved surfaces along arcs, whose dimensions correspond to the half-circumference of the apses. The images obtained by the developments of the apses were produced at very high resolution to facilitate the archaeological reading of each stone element and masonry technique. They were also used for restoration activities such as degradation mapping of the surfaces (Fig. 7).

The most efficient way to deliver 3D content is to make it available on the internet, and in recent years several platforms for sharing models directly within internet browsers have been developed (Barrettara 2013). Uploading the model through Sketchfab, an online 3D visualization platform, allowed us to share the model of the buildings between the various professionals involved in the project, enabling interactive exploration and visual perception from non-conventional viewpoints that were impossible *in situ* (Fig. 8).

This proved to be very useful in obtaining a visual perception of the entire building from a non-traditional point of view. Indeed, the model was used as a common basis for discussion and analysis to detect and to better understand the evolution of the architecture, and to propose the reconstruction hypotheses outlined below (Callieri *et al*., 2011).

5 Interpretation and reconstruction hypotheses

The architectural and archaeological survey of the buildings was followed by the analysis of the entire documentation available in order to arrive at an interpretative hypothesis, and to propose a three-dimensional reconstruction of the buildings using Virtual Archaeology (Reilly, 1991): *the scientific discipline that seeks to research and develop ways of using computer-based visualisation for the comprehensive management of archaeological heritage*. (Lopez-Menchero and Grande 2011)

The term 'virtual' is derived from the Latin '*virtus'*, and in the scientific field it is used with the meaning of 'potential' or 'simulated'. In the field of archaeology, the term relates to the probability that an artefact, site or landscape has been restored to the same state as in the past (Boato 2008: 185).

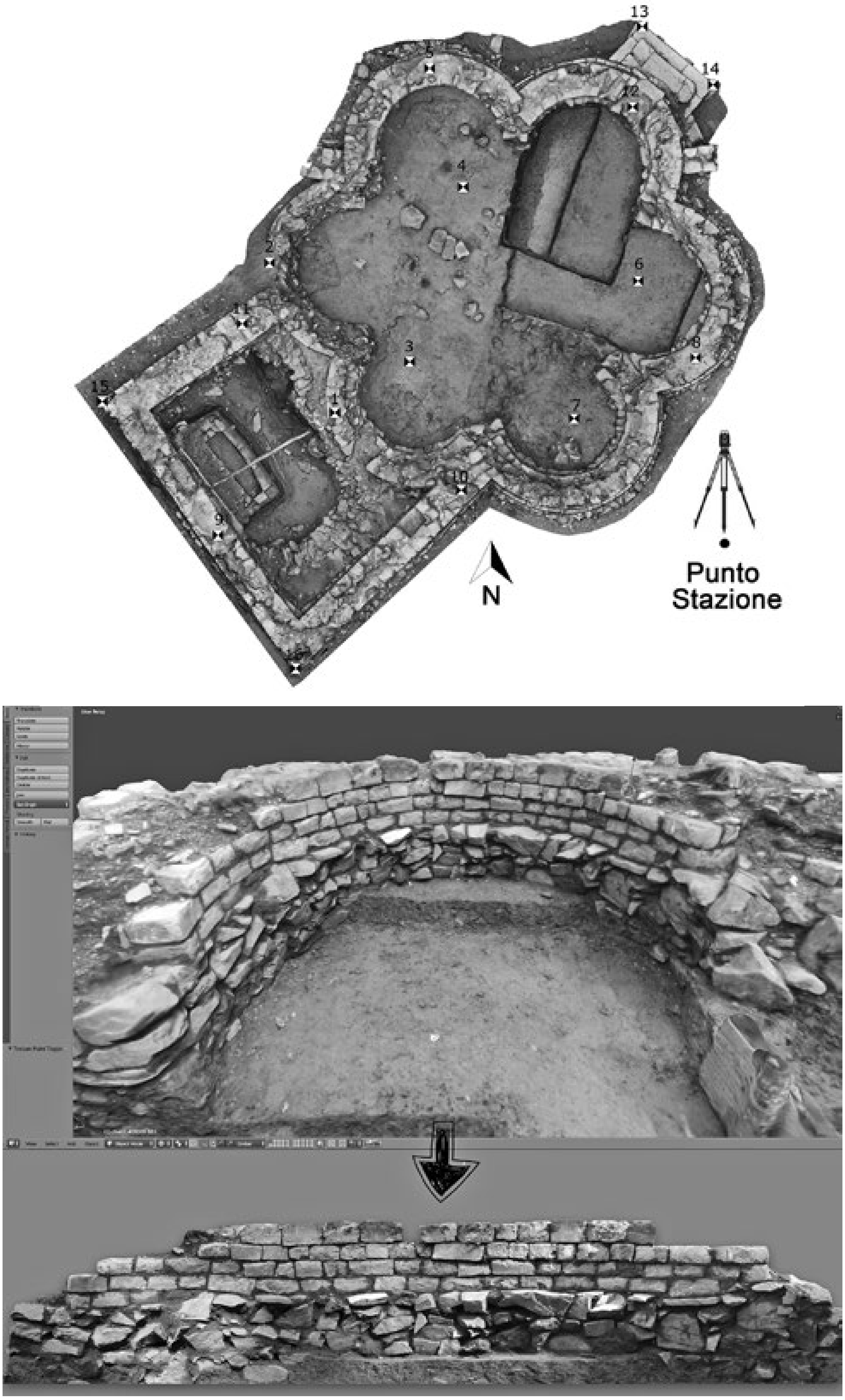

Fig. 6-7. Ortho-image of the church and a rectified images obtained by the developments of an apse.

Fig. 8. Detail of the mesh model of the archaeological site.

This research was focused on the first construction phase of the church, in order to get a better understanding of its architecture, and propose and compare different possible interpretations trying to imagine the missing parts and supplying meaning to the remains.

During the interpretation phase, virtual reconstruction played a key role in the study of the church, requiring researchers to deepen their analysis of archaeological data, by cross-checking all sources and increasing the network of available comparisons and parallels, in order to fill the gaps as much as possible (Pescarin *et al*. 2012). The virtual reconstruction process involved several steps that can be summarized as follow:

5.1 Data Acquisition.

This is the collection of all the objective documentation from the analysis conducted on the site: geometrical data (derived from the photogrammetric and topographical survey) and archaeological historical fact (historical sources, and the results of archaeological investigations).

5.2 Discussion and interpretation.

The objective data were analysed and discussed, in accordance with a proven approach, together with experts in various archaeological, historical and architectural fields, in order to analyse and resolve the question of interpretation, and draw up a reliable reconstruction hypothesis based on the scientific sources (Ferdani and Bianchi 2013).

The use of structured and traceable documentation is one of the most important topics in the reconstruction and scientific visualization of archaeological data, and was planned in accordance with the guidelines set down by the London Charter (LC), and specifically with principles 3 and 4, regarding the use and traceability of the documentation used (Denard,2012):

'In order to ensure the intellectual integrity of computer-based visualisation methods and outcomes, relevant research sources should be identified and evaluated in a structured and documented way' [LC Principle 3].

'Sufficient information should be documented and disseminated to allow computer-based visualisation methods and outcomes to be understood and evaluated in relation to the contexts and purposes for which they are deployed' [LC Principle 4] (Beacham *et al*. 2009)

Virtual archaeology aims at reconstructing archaeological artefacts as far as possible. At this stage issues regarding the lack of information and integration of gaps were addressed by identifying parallels, searching for information in the archaeological record, and in historical or iconographic sources, and making use of logical processes supported by archaeological evidence. The scientific criteria and the logical processes of reconstruction used for supporting reconstructive hypotheses are as follows:

1. Reconstruction by archaeological evidence. The reconstructed elements are based on objective and incontrovertible archaeological evidence (e.g. the stone facing apparatus of the church, special finds such as stone slabs, lintels, column bases etc.).

2. Reconstruction by structural rules. According to a given assumption, the reconstruction takes into account different structural aspects which depend not only on the building's layout and floor-plan, but also on other selective features: the quality of the walls, the geometry of the roofs, and the way in which weights and pressures would affect the load-bearing walls. In our case, these aspects were analysed to reconstruct roofing systems and doors and windows, which impact negatively on the masonry, and produce structural weakening. The position of these is therefore very important, and crucially influences the proposed reconstruction.

3. Reconstruction based on sources. Historical sources can sometimes provide direct or indirect information about the building, or the date of its foundation.

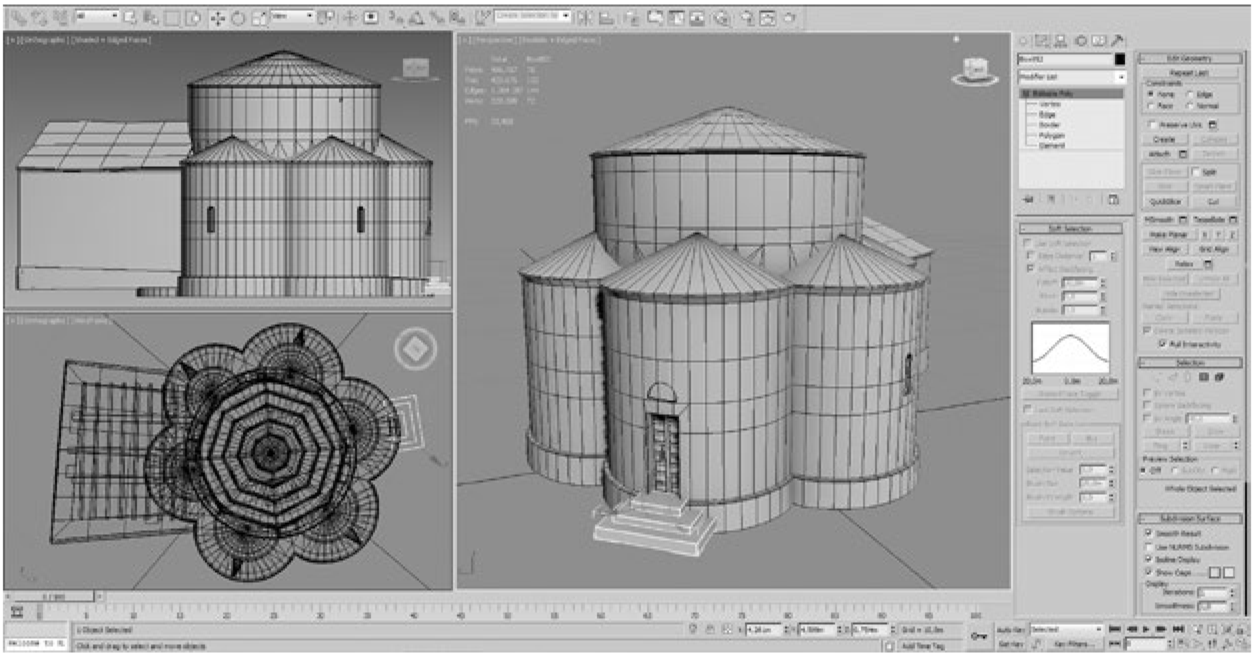

Fig. 9. 3D modelling of the reconstructive hypothesis of the church.

4. Reconstruction based on laboratory diagnoses (archaeometric, biochemical, etc.): laboratory tests involve the use of physical, chemical and biological methods, and allow useful information to be extracted from archaeological finds. In the case in hand, the analysis carried out on the bones identified in burial 1087 provided important information for dating the burial, and, indirectly, for the foundation of the site as a whole. Although the dating obtained does not provide direct information on the physical appearance of the church, it did however allow us to define a chronological range that was useful for building a range of possible typological parallels.

5. Reconstruction by deduction. Although architectural elements are often only partially preserved, they can be completed by referring to their formal characteristics, to repeated patterns, or to archaeological marks (putlog holes, hinges, etc.). During the excavation, the discovery of a monumental threshold revealed the presence in the past of a gateway; similarly, the discovery of several stone slabs allowed us to infer what the roof may have looked like.

6. Reconstruction by comparison, analogy, or style. In this case, the hypothetical reconstruction is based on a direct comparison with the remains of other contemporary structures still existing in the local area, and in the surrounding areas, or based on theoretical models that are well known and recognizable (for example, the artistic typology of doors and windows).

5.3 Three-dimensional modelling and validation.

Once the interpretative hypotheses were determined, the modeller, according to the information of experts, drew up an initial prototype of the reconstruction model, supplementing missing parts and sculpting architectural details. The first reconstruction created was used as a discussion tool. The process described above is applied recursively (on a repeated basis), and is reiterated until the proposed reconstruction model is approved as the most reliable. At this stage, the three-dimensional visualization facilitates cognitive and interpretative processes (Fig. 9).

3D models have a major impact in visualizing and interrogating archaeological data (Forte *et al*. 2015: 54). In our case, 3D allowed us to test the hypothesis proposed, and consider aspects that had been overlooked or undervalued. Some hypotheses proposed during the study proved to be wrong, when tested, due to inconsistencies that arose in virtual simulation (Dell'Unto *et al*. 2013); for example the first reconstruction hypothesis of the roofing of the central space, initially taken for granted on the basis of a well-known parallel in the local area, proved to be ineffective from a structural point of view. Given the unusual shape of the church, the placement of roof beams simply supported on the load-bearing walls would have damaged the walls of the tambour, causing its collapse. A verification in three dimensions allowed us to discard misleading hypotheses, and test new technical solutions by applying rules and solutions adopted in the medieval building site, and expanding the network of comparisons.

As mentioned above, in order to enhance discussion over the interpretation of the site, and enable interactive exploration, we imported the model into a virtual reality system for immersive simulation using Oculus Rift, a virtual reality head-mounted display (Oculus VR). Thanks to accelerometer and gyroscope sensors, this allows a high degree of embodiment inside the virtual world to be perceived, ensuring a very accurate perception of the scale and sense of presence.

The idea of using simulation systems in archaeology arose at the end of the '80s. In 1989, Sebastian Rahtz wrote a paper entitled *A Resource-Based Simulation: the Southampton-York archaeological system*. He proposed an idea to develop a system to give students insights into the strategic decisions involved in planning and carrying out an archaeological excavation (Rahtz 1988).

The concept of simulation connected to virtual archaeology was also discussed by Reilly in the famous article Towards Virtual Archaeology. The authors discussed about the new possibility offered by 3D models, and new promising technologies (Reilly 1991).

Recent reference to visualization in Archaeology can be found in Frisher and Dakouri-Hild (2008) where authors discuss about the importance of visualization science. Even though visualization has been used with success in many science fields (such as medicine, physics etc.), archaeological visualization has not developed much. It is reduced to be used for communication or documentation purposes (where 3D models are often used for the production of graphical tokens such as prospective views, blueprints, orthoimages, sections, etc., or reconstructive hypotheses) rather than improving archaeological investigation and interpretation (Llobera 2011: 194-5).

Recently, thanks to new survey technologies, and the ease with which 3D models of archaeological sites and objects can be obtained, 3D archaeology is becoming an ever more important research segment, pursuing new methods of interpretation (Dell'Unto 2014). The trials conducted in the Çatalhöyük Project (Forte *et al*. 2015), and in the Swedish Pompeii Project (Dell'Unto *et al*. 2013), where the authors use immersive systems for archaeological interpretation, show how 'the migration of 3D worlds in immersive systems, such as caves, haptic systems, and holographic projections, generates a different kind of embodiment and spatial relationship between the body and the environment' (Forte *et al*. 2015: 13).

Following this line of research, the use of such an immersive visualization tool allowed archaeologists involved in the project to discuss the different interpretations by standing inside the scanned models of the archaeological site, and perceiving it in the real scale ratio from non-conventional viewpoints (Fig. 10).

This approach demonstrates that 3D Archaeology was not a one-way activity, a mere translation in graphic form of archaeological studies. Instead, it is part of the process of scientific analysis. The three-dimensional reconstruction of archaeological artefacts has both a communicative and an analytic value: from a communications point of view, it improves the perception of the monument, converting 'raw data into information'; from a cognitive point of view, it allows archaeologists to achieve a higher level of understanding, and a greater ability to process information. It allows, as in this case, the analysis of volumetric ratios between closed and open spaces, and their arrangement and the integration of lost elements to be tested directly on the digital model.

6 Three-dimensional reconstruction of the church

The reconstruction of the church was carried out with graphics software by using the scanned model of the building as a geometrical reference.

This approach allowed great accuracy and control during the technical development of the structures, comparing the

Fig. 10. Visualisation of the high detailed model into a VR headset.

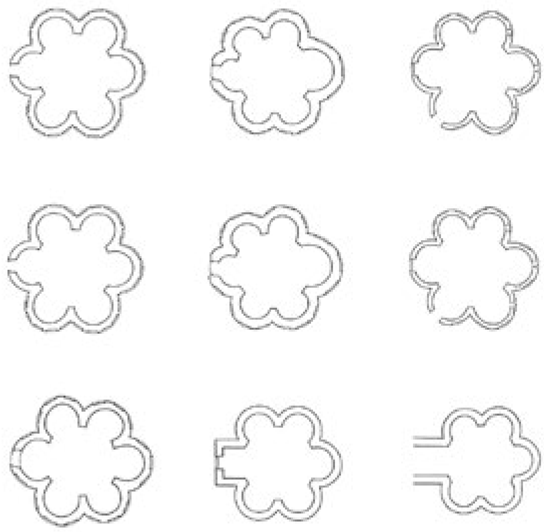

Fig. 11. Blueprints of some Dalmatian churches used as comparisons.

two models, verifying dimensions, orientations and height. Moreover, by displaying the two models overlapping in the same virtual space, it was possible to draw instant comparisons between vertical stratigraphic unity (objective data) and virtual restoration (3D reconstruction).

Furthermore, the use of such a method allowed a better interpretation of the church to be drawn up, taking into account the original architectural irregularities, and minor asymmetrical features that are found in the building.

As often stressed by archaeologists, a simple study of building techniques is insufficient for an understanding of the cultural context, which they derive from. The site must be connected to historical phenomena and parallels. Given the uniqueness of this architectural complex in Italy, no parallels have been found in Italy, except for buildings dating to Late Antiquity. The only

Fig. 12. Reconstructive section of church and its interior spaces.

very close parallels consist in a group of Dalmatian churches in and around Zadar and Split, variably dated between the 8th and 11th centuries (the buildings analysed, and the church of St. Niccolò, are characterized by a constant inner diameter that is around 10 meters) (Fig. 11).

The small chapel of Santa Trinidad (Sveta Trojica) in Split, almost completely preserved, was a very useful comparison to support our hypothetical reconstructions (see Jurkovich 1996). In particular, the Istrian model was crucial for reconstructing the upper part of the church of St. Niccolò, the roofing of the apses, the system of wooden beams, and the cylindrical tambour,which stands over the central body.

The only difference concerns the roofing system. In the Dalmatian churches, the roof over the central tambour is supported by a hemispherical dome. In the case of S. Niccolò of Montieri, a wooden system of trusses was chosen to support the roofing. Indeed, during excavation, no material from a collapsed vault was found.

For the roof, we opted for the same solution used in Dalmatian churches: a central cone covered with stone slabs (found in excavation). We only adapted the slope of the roof to our latitudes that typically range between 15 and 30 degrees (Fig. 12).

The main doorway of the church, and the apse windows, were reconstructed using parallels. In this case the reconstruction was drawn up based on stylistic analogies with well-known theoretical models. Despite having only a part of the architectural element (the threshold), the reconstruction was possible by referring to widespread standard portals in the area, dating to the 11th century (Fig. 13-14).

For the interior of the church, we chose a minimal spelling since we did not find any fixtures or architectural elements such as columns, capitals and cornices that could be attributed to this construction phase. The only exceptions are the base of an altar located between the two eastern apses, and the remains of flooring. The floor consisted in grey limestone slabs, with a single element in pink limestone called ‘Ammonitico di Gerfalco’ discovered during investigations below a small hole where a golden brooch was laid. The jewel was probably connected to a rite relating to the foundation of the church.

Simulation of the building materials was carried out using different types of texture specially created from photographs taken in situ, to give a more realistic appearance. We used Diffuse, Normal and Specular textures, in line with standard computer graphics. The diffuse texture affects the colour and the main appearance of the object with which it is associated. Normal texture simulates the small reliefs of the wall surfaces. Finally, the specular texture is an image in black and white that controls the way in which light interacts with the material: the different tones of grey correspond to a different level of reflection. Finally, to correctly reproduce the lighting conditions of the site, a lighting system was used that was integrated into the global rendering software, simulating, with a good degree of approximation, the position of the sun in relation to the geographical coordinates of the site (Fig. 13).

7 Conclusion

The reconstruction presented in this paper is therefore the result of a complex and thorough research that involved numerous professionals. This is the first step to understanding and reconstructing the evolution of the archaeological site between the 11th and 14th centuries. So far, we have only reconstructed the 11th century period, but, according to the archaeological excavation, during the 12th century a stone enclosure was constructed, bordering a central, open space, which two long buildings gave onto. In the first decades of the 13th century other variations were made to the existing system of structures.

Fig. 13. 3D reconstruction of the church.

Once all the documents on the site are complete, we will proceed with the reconstruction of the other periods, and the whole process will be formalized explaining step by step how we used the sources to arrive at the virtual reconstruction, and what the relationship is between the stratigraphic archaeological units (observed data) and their reconstructions (virtual reality).

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Bibliography

Aranguren, B. M., Bianchi, G., Bruttini, J., 2008. Montieri (GR). Archeologia urbana a Grosseto: l'intervento in via delle Fonderie. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana*. 3/2007: 435-41.

Barrettara, M. 2013. New methods for sharing and exhibiting 3D archaeology. *The Posthole* 31: 8-13.

Beacham, R., Nicolucci, F., Denard, H., Hermon, S. Bentkwoska-Kafel, A. 2009. London Charter. The Principle. http://www.londoncharter.org/principles.html [Accessed: 30th june 2015].

Boato, A. 2008. *L'archeologia in architettura*. Venezia, Marsilio Editori.

Brogiolo, G. P. 1998. *Archeologia dell'edilizia storica*, Como, New Press.

Callieri, M., Dell'unto, N., Dellepiane, M., Scopigno, R., Söderberg, B., Larsson, L. 2011. Documentation and Interpretation of an Archeological Excavation: an experience with Dense Stereo Reconstruction tools. In Dellepiane, M., Niccolucci, F., Pena Serna, S., Rushmeier, H., Van Gool, L. (eds.), *Proceedings of The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*: 33-40. Eurographics Association.

Dellepiane, M., Dell'unto, N., Callieri, M., Lindgren, S., Scopigno R. 2013. Archaeological excavation monitoring using dense stereo matching techniques. *Journal of Cultural Heritage* 14: 201-10.

Dell'Unto, N. 2014. The Use of 3D Models for Intra-Site Investigation in Archaeology. In S. Campana, and F. Remondino (ed.s), *3D Surveying and Modelling in Archaeology and Cultural Heritage. Theory and Best Practices*: 151-8. Oxford, BAR international series 2598.

Dell'Unto, N., Ferdani, D., Leander, A.M., Dellepiane, M., Callieri, M., Lindgren, S. 2013. Digital reconstruction and visualization in archaeology. Case-study drawn from the work of the Swedish Pompeii Project. In A. C. Edison, G. Guidi, S. Pescarin, L. De Luca, (eds.), *Proceeding of the 2013 Digital Heritage International Congress*, *Marseille 28th October --2 November 2013*, I: 621-8. France, IEEE.

Denard, H. 2012. A New Introduction to the London Charter. In A. Bentkowska-Kafel, D. Baker, H. Denard (eds.), *Paradata and Transparency in Virtual Heritage*: 57-71. Ashgate.

Ferdani, D., Bianchi, G. 2013. 3D Reconstruction in Archaeological Analysis of Medieval Settlements. In E. Graeme, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 1-9. Amsterdam, Amsterdam University Press.

Forte, M., Dell'Unto, N., Jonsson, K., Lercari, N. 2015. Interpretation Process at Çatalhöyük using 3D. In I. Hodder, A. Marciniak, (eds.), *Assembling Çatalhöyük*: 43-57. Maney Publishing.

Forte, M., Dell'Unto, N., Issavi, J., Onsurez, L., Lercari, N. 2012. 3D Archaeology at Çatalhöyük. *International Journal of Heritage in the Digital Era* 3: 351-77.

Frischer, B. and Dakouri-Hild, A. 2008. *Beyond illustration: 2D and 3D digital technologies as tool for discovery in archaeology*. Oxford, Archeopress.

Jurkovich, M. 1996. La rotonde de Saint-Donat a Zadar et les églises hexaconques préromanes en Croatie. In C. Sapin, M. Jannet (eds.), *Guillaume de Volpiano et l'architecture des rotondes*: 237-256. Dijon.

Llobera, M. 2011. Archaeological Visualization: Towards an Archaeological Information Science (AISc). *Journal of Archaeologicl Method and Theory* 18, 2: 192-223.

Lopez-Menchero, V., Grande, L. 2011. The principle of the Sevilla Charter. In K. Pavelka (ed.), *Proceedings of the 13th CIPA Symposium, Prague, Czech Republic, 12-16 September 2011*. http://cipa.icomos.org/fileadmin/template/doc/PRAGUE/096.pdf [Accessed: 30th June 2015].

Oculus VR 2015. Rift Next-generation virtual reality [Online] www.oculus.com/en-us/rift/ [Accessed: 30th June 2015].

Pescarin, S., Fanini, B., Ferdani. D, Lucci Baldassarri, G. 2012. Archeologia Virtuale a Montegrotto. In: M. Bassani, M., Bressan, F. Ghedini (eds.), *Aquae Patavine. Montegrotto Terme ed il termalismo in Italia. Aggiornamenti e nuove prospettive di valorizzazione*. *Atti del II convegno nazionale, Padova 14-15 giugno 2011*: 309-326. Padova, University Press.

Rahtz, S. P. Q. 1998. A Resource Based Archaeological Simulation. In S. P. Q. Rahtz (ed.), *Computer and Quantitative Methods in Archaeology*: 470-490. Oxford, British Archaeological Reports.

Reilly, P. 1991. Towards a Virtual Archaeology. In K. Lockyear, S. Rahtz (eds.), *CAA90: Computer Applications and Quantitative Methods in Archaeology 1990*: 133-9. Oxford: British Archaeological Reports International Series 565.

Remondino, F. and Campana, S. (eds.) 2014. *3D Recording and Modelling in Archaeology and Cultural Heritage. Theory and best practices*. British Archaeological Reports International Series, Oxford, Archaeopress.

A 3D Digital Approach to Study, Analyse and (Re)Interpret Cultural Heritage: the Case Study of Ayia Irini (Cyprus and Sweden)

Valentina Vassallo
valentina.vassallo@klass.lu.se; v.vassallo@cyi.ac.cy
Lund University - Department of Archaeology and Ancient History;
The Cyprus Institute - Science and Technology in Archaeology Research Centre

Abstract: This paper focuses on the on-going doctoral research of the writer. Specifically, the topic of this article is on the methodology, the theoretical approach and the first steps of the research. The general aim is the contribution of 3D documentation and the 3D digital approach to the stylistic and typological study of archaeological collections. The study is applied to the collection of the Ayia Irini archaeological excavation (Cyprus). The site was excavated and studied at the beginning of the 20th century by a Swedish archaeological mission and the collection was divided between Cyprus and Sweden. The scope, through the integration of digital technologies, is the three-dimensional documentation of the archaeological material for its (re)interpretation and its metric analysis and comparison. Particularly, the paper will focus on the pipeline and methodology developed for the choice of the sample, its digital acquisition and the analysis of the statues.

Keywords: 3D documentation, 3D digital approach, Digital analysis, Archaeological collections.

Introduction

The paper here presented is about the first steps of the on-going doctoral research of the writer, the methodology and the theoretical approach developed for the study and analysis of archaeological collections through the use of digital technologies.

1 Research aims

The idea at the base of this research comes from the necessity to answer fundamental questions in the field of Archaeology and Digital Cultural Heritage studies, in particular to solve issues about the analysis, interpretation, and re-interpretation of archaeological materials.

- How to geometrically and metrically analyse and compare archaeological artefacts of an archaeological collection in order to interpret and extract stylistic and typological information for their interpretation?
- How digital technologies can help the documentation in order not to lose any information of archaeological materials?
- How technologies can help archaeologists to give new interpretations about past studies and support current ones?

Three-dimensionality has been more and more used in the field of computer science applied to archaeology: at today it is possible to see different applications about diachronic reconstruction of different occupations of a site, virtual reality systems or modelling and animation of artefacts. Within this general frame, the on-going doctoral research aims at the contribution and use of 3D documentation for the analysis of archaeological artefacts.

The major scope, through the integration of digital technologies, is the documentation of a sample of the Ayia Irini archaeological collection, its (re)interpretation and digital analysis. The specific aim is in fact to understand how these statues were made, from a technical perspective, to identify modalities of creation, workshop/artisan(s) and so forth. Such an analysis is performed through a detailed 3D documentation of a selected sample of figurines.[1]

The topic of this paper focuses on the methodology, the theoretical approach and the first results of the research, applied to the collection documentation. Specifically, this paper focuses on the pipeline and methodology developed for the choice of the sample, its digital acquisition and the analysis of the statues on the base of a standardized study of their three-dimensional elements.

2 The case study of Ayia Irini

2.1 The archaeological context

The ancient sanctuary of Ayia Irini is located near the current village of Ayia Irini, in the Morphou district in northwest Cyprus. The sanctuary was discovered and excavated by a Swedish archaeological mission in 1929. Fig. 1

The importance of this rural open-air sanctuary lies in the fact that the worship was inaugurated in Late Cypriot III and survived until the last quarter of the Cypro-Archaic II period, furnishing the only example of a complete archaeological sequence of *strata*, proving continuity of worship from the 11th to 6th century BC Following a terrible flood around 500 BC, the *temenos* was abandoned and reused again in the 1st century BC (Gjerstad 1948).

[1] The geometrical 3D representation will allow us to perform the extraction of the statues' elements as well as their characterization.

Fig. 1. The sanctuary of Ayia Irini at the time of the discovery.

2.2 The Collection(s)

The sanctuary at Ayia Irini is famous for its large number of terracotta figurines (some of them larger than life size) that were found *in situ* positioned around the altar of the sanctuary. These figurines, *ex votos* offered most probably to a male god, number to approximately 2000. They are animals, bulls, minotaurs, chariots and male figures representing warriors and priests with helmets or conical caps and different attributes (votive offerings, arms, musical instruments) (Gjerstad 1933; Gjerstad 1948).

With the British Government's permission, the findings were divided between Sweden and Cyprus. More than half of the figurines were transferred to the Medelhavsmuseet in Stockholm (Sweden) (Karageorghis 2003), representing the largest and most important collections of Cypriot antiquities in the world outside Cyprus, while the rest is in the Cyprus museum of Nicosia (Cyprus) (Fisher and Keneberg 2003). A small number of items is conserved at the Historical Museum of Lund University (Sweden), brought there by E. Gjerstad, the archaeologist responsible for the Swedish Excavation mission in Cyprus, during his professorship at Lund University during the 1940s.[2]

3 The methodology

The methodology developed for the research is based on the following main phases:

- Gathering of historical and archaeological information about the collection
- Data sampling of the collection(s)
- 3D data capture and post-processing of the samples
- 3D analyses and comparisons of the digital artefacts

3.1 Data gathering

A gathering of high-quality data is really important to set up a verifiable and reliable plan of work and the successive study and analysis of the material, the subject of our research. The gathering consists of three different steps.

The first one is the collection of all the texts, literature, ancient sources and studies about our archaeological context and collection, as well as information about case studies with temporal, geographical or morphological similarities. In case of lack of data, the comparisons with similar cases help us to fill up the possible gaps in our documentation and give the possibility to draw some conclusions (Vassallo *et al*. 2006).

The second step is instead constituted of the direct observation of the artefacts and the capacity of the archaeologists to see the elements and the details of what they are studying. Also this activity helps to extract ideas, hypotheses and preliminary interpretations.

This kind of data gathering allows us to proceed in a further direction in the development of the methodology, helping us in the successive analysis and comparison phases. The step consists of the development of a framework (an archive) for the description of the object (both real and digital) and their characteristics, and according to a structured schema useful to preserve all the information.

The other step of the methodology is constituted of the use of digital technologies for acquiring another kind of data that

2 Since the artefacts are currently placed in different countries and museums, the use of the methodology developed for the research should help in better understanding the original spatial-metric relations between the different components of this collection.

Fig. 2. The Ayia Irini collection(s).

is not possible for an archaeologist to get simply with the direct observation. This in fact permits to geometrically and metrically obtain the shape, dimensions and texture details otherwise not visible with a naked eye or difficultly acquirable with a simple manual measurement.

3.2 Data sampling, digital technologies integration, data acquisition and post-process

3D documentation is a well-known approach to research on documenting, analysing and preserving archaeological data. The 3D model obtained by the use of a single or by the integration of different technologies and methodologies is a real database that allows us to extrapolate morphological and geometric information with a particularly high resolution (Georgiadis *et al*. 2009).[3]

A reliable and comprehensive metric description is a key element in every knowledge process: the simulation of the space through measures reduces the complexity of reality to a unique model. In particular, photogrammetry (e.g. capture from motion, image based modelling, etc.) and 3D scanning systems allow to realistically replicate the 3D geometry and texture of archaeological assets.

An important part of the methodology development consists of the data sampling of the artefacts to be three-dimensionally acquired. The choice of the dataset is representative of the material found in the archaeological site of Ayia Irini and from the museums where it is stored (Stockholm, Lund and Nicosia museums). The data sampling methodology is based mainly on typological and stylistic characteristics.

The first 3D acquisition test was carried out on the collection conserved at the Historical Museum of Lund University. It consists of 15 items belonging to the Ayia Irini collection, but it was decided to digitize 13. The choice is based only on terracottas that represent standing figurines, in order to standardize the kind of shapes chosen for future analyses and comparisons. Therefore statues representing groups (chariot groups) and animals have been deliberately excluded by the three-dimensional data acquisition campaign.

In the sample has been included and three-dimensionally acquired also 3 items that are a bit bigger in size respect to the rest of the dataset. The choice of the sampled items is focussed

Fig. 3. Data acquisition of a terracotta with NextEngine 3D Desktop laser scanner.

on figurines around 20cm high in order to verify and analyse afterwards the presence of ratio, production process, etc. during the comparison of the 3D geometries; to extract possible production elements and to see if any standardizations in the production itself exist. The data acquisition of these 3 more items would be useful for the confrontation and comparison in the extraction of standardization elements in the figurine's creation.

Due to the size of the sample, the material, the shape, and surface characteristics of the artefacts, the geometry of the statues have been digitally acquired with a NextEngine 3D Desktop laser scanner. Fig. 3

Moreover, in order to guarantee also a high definition quality texture, for the preservation of the visual characteristics (colours, material characteristics, micro elements, etc.), the statues have been digitized through an image-based modelling technique (post-processed with Agisoft PhotoScan)[4] (Verhoeven 2011).

After this, the outcomes are integrated, in order to have more detailed models both for their geometry and for their texture (not only for the scope of the 3D analysis, but also for the

[3] The study focuses also on the establishment of the pipeline for the 3D acquisition and integration of different digital techniques for the scope of the current research (Bernardini and Rushmeier 2002).

[4] In some cases where the details are not easily visible and therefore acquirable by the laser scanner, this technique provides also greater details of the geometry.

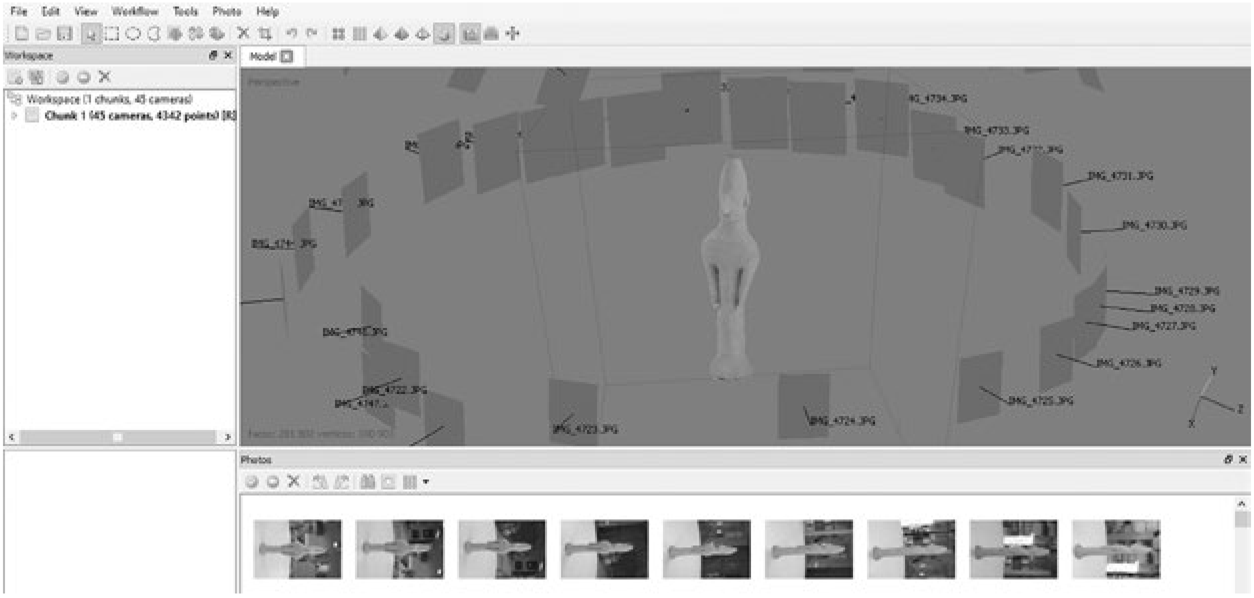

Fig. 4. Image based modelling post-process with Agisoft PhotoScan.

visualization purposes in the possible development of the doctoral project in the future) (Beraldin 2004; Remondino and El-Hakim 2006; Gonizzi Barsanti *et al*. 2013).

3.3 3D analysis and comparisons

A significant problem in archaeology is the difficulty in comparing many artefacts stylistically and geometrically, requiring this activity substantial physical information. Relating one artefact to another is an integral part of discovering its role, age, artisan, community, etc.

3D gives exactly the possibility of an interactive or automatic quantitative and qualitative comparison (Hermon *et al*. 2010). The use of 3D models allows studying in a detailed and measurable way the elements of the artefacts and it permits a visualization and measurable comparison that can be easily at disposal of the scholars for analysis.

As previously explained, this contribution is a preliminary dissemination of the on-going doctoral research. This means that the 3D analysis is under processing, and still the work of 3D acquisition has to be concluded for the different parts of the collection divided between the different museums already mentioned.

In general, the geometrical representation of measurable 3D models (with millimetric precision), will allow to perform the extraction of the statues' elements as well as their characterization. Through that it will be possible to identify technical features such as the manufacture, use of standards, guidelines or rules (e.g. ratio between the parts, standards or fixed dimensions) in the production of these artefacts or to identify the individual workshop's methodologies and techniques (or different workshops and/or artisan/s). The metrical comparison of the geometries will further help to identify the similarities and dissimilarities and therefore to draw conclusions about the production of the material (see Fig. 6.).[5]

Currently the analysis is at its early initial stage and different tests are ongoing. 3D geometries and 3D features of the statuettes are firstly being compared in Meshlab: distances between the parts, lengths and widths are measured and stored in order to create a database of these measurements and consequently to run ratios and statistical analyses. A further analysis is planned by employing Geometric Morphometrics (GM) techniques in order to compare and analyse statistically the 3D forms of the sampled items.

4 Conclusions and future works

The 3D documentation provides an effective database of information that, beyond assuring the digital preservation of the material, is first of all a useful source for further studies and a reference for new knowledge extraction. In fact, digital data give the opportunity to perform multiple tests and analyses that, differently from the test on the real object, can be repeated many times and in a more detailed way (Moro *et al*. 2007), thanks to the possibility of replicating an object with the same exact dimensions, shape, size and texture of the real one (Athanasiou *et al*. 2013).

The research aims at the study and analysis of archaeological collections through the use of digital technologies and the application of a 3D digital approach, specifically to the case study of Ayia Irini's terracotta statues. For doing so, an important step is the development of a methodology that supports all the research pipeline: the choice of the sample, the assessment of the appropriate technologies to be used, the 3D data documentation, the post-process, the digital analysis and the extraction of the results.

[5] 3D technology is used as an exploratory tool for data analysis and for catching relations between objects that are no longer in situ.

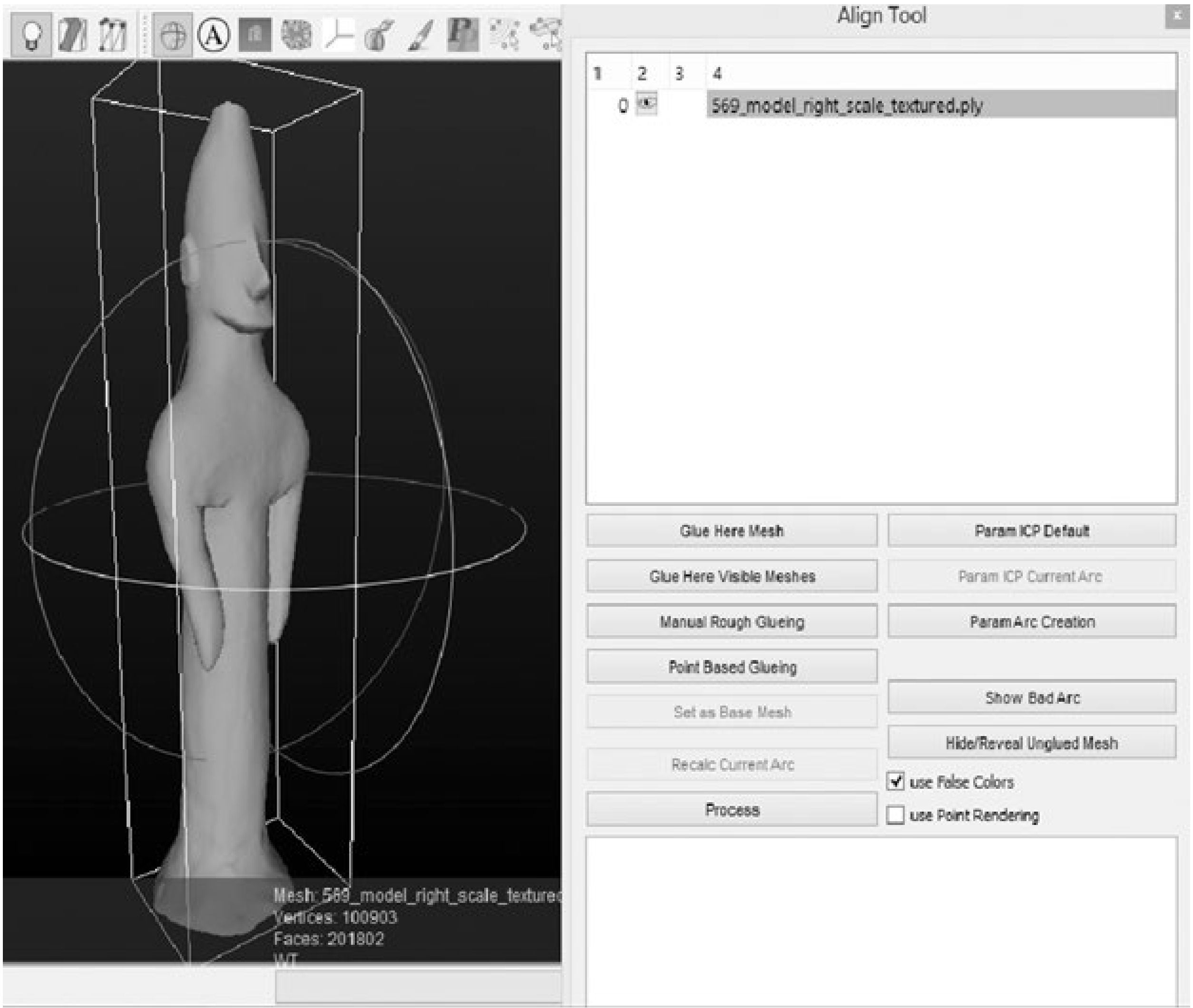

Fig. 5. Post-processing of the digital artefacts with Meshlab (Cignoni *et al.* 2008).

Fig. 6. Extraction and digital comparison of the elements from Ayia Irini's 3D models.

The methodology has been developed and successfully tested on the first sample of terracottas, conserved at the Lund University Museum. The current work is focussed on the sampling of the other part of the collection for the 3D digital data acquisition and analysis. The methodology and the pipeline could be further implemented and adjusted according to the development of the research.

The next step of the research is therefore the digital documentation of the remaining terracotta statues and after this phase will start the analysis and the comparisons between all the 3D models, in order to detect similarities and dissimilarities for the identification of rules, ratio or specific elements that can give us clues and/or confirmation about their production (e.g. use of moulds for some parts of the artefacts, serial production, one/many recognizable hands, etc.).

At the moment the research is planned only on the analysis and comparison among the 3D replicas of the Ayia Irini collection. A possible further useful development could involve the 3D digitization and analysis of some statues from Cyprus and chronologically similar. This could be useful to understand their affinity with similar statues from other archaeological sites and to have a brighter and larger view, since based on measurable elements, about the coroplastic production in Cyprus (Karageorghis 1993).

The research will possibly further include the positioning of the statues' 3D models in a 3D GIS environment of the sanctuary (Dell'Unto 2014), reconstructed on the base of the documentation, plans and drawings published by the Swedish archaeological expedition, in order to have a unified access of the collection and a holistic vision of the archaeological discovery.

Bibliography

Athanasiou, E., Faka, M., Hermon, S., Vassallo, V., Yiakoupi, K. 2013. 3D Documentation pipeline of Cultural Heritage artefacts: a multi-disciplinary implementation, In A. C. Addison, L. De Luca, G. Guidi, S. Pescarin (eds.), *Digital Heritage International Congress (DigitalHeritage), 28 Oct-1 Nov 2013 Marseille, France*: 145-152.

Beraldin, J.A. 2004. Integration of Laser Scanning and Close-Range Photogrammetry - The Last Decade and Beyond. In *XX ISPRS Congress: Proceedings of Commission VII, Instanbul, Turkey*: 972-83.

Bernardini, F., Rushmeier ,H. E. 2002. The 3D Model Acquisition Pipeline. *Computer Graphics Forum* 21, 2: 149-72.

Cignoni, P., Callieri, M., Corsini, M., Dellepiane, M., Ganovelli, F., Ranzuglia, G. 2008. MeshLab: an Open-Source Mesh Processing Tool. In *Sixth Eurographics Italian Chapter Conference*: 129-36. Eurographics.

Dell'Unto, N. 2014. The Use of 3D Models for Intra-Site Investigation in Archaeology. In S. Campana, and F. Remondino (ed.s), *3D Surveying and Modelling in Archaeology and Cultural Heritage. Theory and Best Practices*: 151-8. Oxford, BAR International Series 2598.

Georgiadis, C., Patias, P., Stylianou, G., Capturing the Past and Present: Tools and Methodologies for 3D Modeling of Small Objects. International CIPA Symposium, Kyoto, Japan, October 11-15, 2009.

Gjerstad, E., Lindros, J., Sjöqvist, E., Westholm, W. 1933. *The Swedish Cyprus Expedition. Finds and results of the excavations in Cyprus 1927-1931* 2. Stockholm.

Gjerstad, E. 1948. The Cypro-Geometric, *Cypro-Archaic and Cypro-Classical Periods. The Swedish Cyprus Expedition* 4, 2. Stockholm.

Gonizzi Barsanti, S., Remondino, F., Visintini, D. 2013. 3D Surveying and Modelling of Archaeological Sites – Some Critical Issues, In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* II-5/W1, 2013, XXIV International CIPA Symposium, 2-6 September 2013, Strasbourg, France: 145-50.

Hermon, S., Hadjicosti, M., Pilides, D., Ronzino, P., Pitzalis, D. 2012. Evaluation of Acquisition and Post-Processing Pipeline for 3D Models of Ancient Statues. Fusion of Cultures. In J. Melero, P. Cano, J. Revelles (eds.), *Abstracts of the XXXVIII Conference on Computer Application and Quantitative Methods in Archaeology*, Granada, Spain, 6-9 April 2010: 39-42.

Karageorghis, V. 1993. *The Coroplastic Art of Ancient Cyprus III. The Cypro-Archaic Period. Large and Medium Size Sculpture*, Nicosia.

Karageorghis ,V., Houby-Nielsen, S., Slej, K., Winbladh, M. L., Nordin Fisher, S., Keneberg, O. 2003. *The Cyprus Collections in the Medelhavsmuseet*, Nicosia, Stockholm, The A.G. Leventis Foundation and the Medelhavsmusset.

Moro, A., Vassallo, V., Vico, L. From the relief to the 3D reconstruction_The Methodology. In *Proceedings of Conference XXI International CIPA Symposium, 1-6 october 2007, Athens, Greece*. Available at http://www.isprs.org/proceedings/XXXVI/5-C53/papers/FP100.pdf. Accessed: 1 July 2015.

Remondino, F., El-Hakim, S. 2006. Image-based 3D Modelling: A Review. *The Photogrammetric Record* 21: 269–91.

Vassallo, V., Moro, A., Vico, L., 2006. The importance of the relief and the sources to interpret and communicate the Cultural Heritage. In S. Campana and M. Forte (eds.), *From Space to Place: 2nd International Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International Workshop, CNR, Rome, Italy, 4-7 December 2006*, Archaeopress, British Archaeological Reports International series.

Verhoeven, G. 2011. Taking computer vision aloft: archaeological three-dimensional reconstruction from aerial photographs with Photoscan. *Archaeological Prospection* 18: 67–73.

CHAPTER 4
Linking Data

Beyond the Space:
The LoCloud Historical Place Names Micro-Service

Rimvydas Laužikas
rimvydas.lauzikas@kf.vu.lt
Vilnius University Faculty of Communication, Vilnius, Lithuania

Ingrida Vosyliūtė
ingrida.vosyliute@gmail.com
Vilnius University Faculty of Communication, Vilnius, Lithuania

Justinas Jaronis
justinas.jaronis@aksprendimai.lt
Atviras kodas verslui Ltd., Vilnius, Lithuania

Abstract: Historical geo-information is usually considered as the sets of historical place names which are fixed in historical sources. In heritage digitization activities it serves as a link between reality and virtuality and ensures more qualitative data inter-operability. The perception of the historical space is important not only for preservation of historical place names as a kind of intangible heritage, but also for the participative interpretation of cultural heritage, as well as for the creation of the European narrative.

*This paper presents the Historical Place Names (HPN) microservice. HPN microservice is a web service which has been developed during the LoCloud project (*Local content in a Europeana cloud*) in collaboration between Project partners. The HPN microservice has been developed on the basis of a thesaurus of historical geo-information. The HPN microservice performs the following functions: crowdsourcing and enrichment of provider's and aggregator's historical geo-information, HPN geo-information visualization, and HPN interoperability provision.*

Keywords: Historical geo-information, historical place names, information management, digital heritage.

Introduction

Space and time are considered to be the most important dimensions of reality. Much attention is paid to their scientific analysis in physics and astronomy. Moreover, these dimensions are very important in the research of cultural heritage, the understanding of its role in contemporary society, and its use in cultural industries. Historical space and time are important aspects of the life cycle of a cultural heritage object since they help to identify, interpret, and communicate that object and/ or attached ideas. Moreover, the dating of sources and their association with certain geographical spaces allow for further historical interpretations.

Historical place names (HPN) are place names that exist in history (not contemporary place names) and are fixed in historical sources. An HPN is considered to be a place appellation, which is used to refer to several places, because its application may change over time (similar to E48 in CIDOC-CRM; The CIDOC…, 2015). On the other hand, the place as an object (similar to E53 in CIDOC-CRM, excluding movable objects) is determined as a GIS defined immovable geographic object: point, polygon, or line (such as landscape, inhabited places, buildings, natural objects, mountains, rivers, administrative areas, etc.). A place name can be understood as a historical identifier for several places (with the same meaning as E4 in CIDOC-CRM) and/or as a kind of immovable heritage ('non-material products of our minds', e.g. E28 Conceptual Object in CIDOC-CRM).

Historical geo-information is closely connected with temporal (existence of HPN is usually limited in time: from...to) and linguistic (HPN were written in various languages and in various writing systems) dimensions and 'stored' in analogue format on written sources (textual information), paper historical maps (cartographical information), and visual items (iconographical information from landscape paintings, town panoramas, etc.).

The perception of space was modified by the development of information and communication technologies, especially the wide application of GIS technology, as well as computer application to the humanitarian sciences and digitization of heritage and its presentation on the Internet. The transcoding of reality from an analogue to a digital system performed during the heritage digitization affects the HPN application used in the real world on an artificial system. In this way HPN becomes a link between reality and virtuality in digitized heritage presentation and ensures internal data inter-operability within the information system, as well as external inter-operability of several systems, thus contributing to more efficient communication of digital data.

Two methodological models can be employed for the digitization of historical, geographical, and chronological data: the 'text oriented' model and the 'object oriented' model. The 'text oriented' model was created at the early stage of the computerization of cultural heritage. It is based on a 'hierarchical' paradigm and usually describes the world via hierarchically organized and controlled vocabularies of

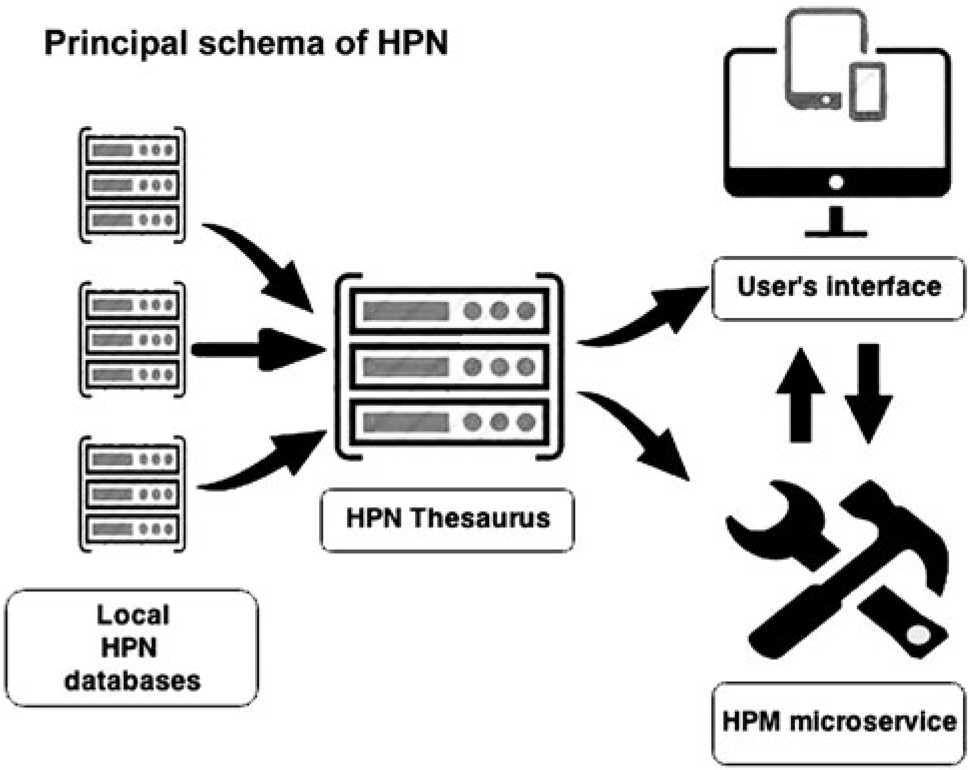

Fig. 1. Principal schema of HPN services.

proper names. Despite the evident significance of the 'text oriented' model for the development of digitization of cultural heritage, it is also necessary to note the essential limitations of this model. The actual world (reality) is continuous and is composed of interconnected objects (not concepts) that are organized according to a non-hierarchical structure. The 'object oriented' model proposes a different point of view. This model was created during the modern stage of computerization of the cultural heritage. It is based on a 'network' paradigm and usually describes the world via a network-organized object's ontology. The ontological 'object oriented' model is more connected with reality: existing place-time and place-time appellations are described as two separate classes of reality.

Computing, such as mathematical technology based on algorithms and binomial calculation, provides possibilities to define a precise geography of a place. But many digital heritage systems still tend to rely on the historical space of the 19th century marked by the myths of nationalism rather than modern geographical space realities. In the biggest digital heritage portal of the European Union 'Europeana' in summer 2015 there were 8231 objects linked to the place named Gdansk, while Danzig referred to 34,352 objects. According to the data of periodical press, Japan has asked local authorities and state-run universities not to post Google maps on their websites because some of them use non-Japanese names for disputed territories (Shen Peng 2013).

Through historical meta-theories, historical narratives, and fiction, even the physical geography of modern times as a typical science of nature acquires features of Social Sciences and Humanities (SSH). Historical geography research is an interdisciplinary field where the relationship between the natural sciences and SSH research methods and data is taken into consideration. In order to understand the exact geographical space during a specific period researchers take into account not only geo-information and various geo-calculations, but also a number of written and iconographical sources. Written and iconographical sources which were created by the people of the past reflect their attitudes to the surrounding world and provide an opportunity for modern scientists to choose suitable methods for the 'reading of the past' and comprehend the historic space in a similar way that it was understood by the people of the past.

When interpreting and using the space of a certain period, however, it is important to take into account the invisible 'human factor' — the people who lived in particular historical periods — which we can call 'historical or cultural multilingualism'. This can be defined as terminological differences of the common language determined by cultural differences of various nations. According to the communicative model of the pioneer of the American trend of semiotics, C.S. Peirce, a term (in our case HPN) is a conventional sign, which is developed by the interpreter who in his mind perceives the object of reality (Marty 1999). So, in terms of the communication of meanings, HPN is a piece of work by different human groups intended to name the object of reality (the place), and miscommunication (non-interoperability) occurs at the level of signs (words) rather than geographical objects (places).

This paper will present the historical place names (HPN) microservice, which is one solution for the above-mentioned problems. HPN microservice is a web service that was developed during the LoCloud (Local Content in a Europeana Cloud) project by Faculty of Communication of Vilnius

University and other project partners: Open Code solutions Ltd. (Lithuania), the Digital Curation Unit of the Institute for the Management of Information Systems of Athena Research and Innovation Centre (Greece), the Austrian Software and Research Company, University of the Basque Country, and Javni Zavod Republike Slovenije za Varstvo Kulturne Dediscine. The HPN microservice was developed after an investigation of more than 20 existing national and international HPN projects, databases, and information systems (e.g. GeoNames, Getty Thesaurus of Geographic names, Google Ancient Places project, Pleiades project, PastPlace Gazetteer, The Europeana Connect Geoparser Prototype, The Europeana Gazetteer Prototype, The Old Maps Online Portal, etc.). The HPN service is available at: <http://tautosaka.llti.lt/en/unitedgeo/> and his also integrated into MoRe (The Metadata & Object) repository: <http://support.locloud.eu/MORE>.

1 Historical place names microservice

1.1 The HPN Thesaurus

The HPN microservice was developed on a HPN Thesaurus based on the relevant aspects of the CARARE metadata schema (Fernie *et al.* 2013) developed by the CARARE (Connecting Archaeology and Architecture in Europeana) project. The schema enables aggregation, storage, and long-term preservation of historical geo-information. The principal HPN service schema is shown in Figure 1.

The HPN Thesaurus is a controlled vocabulary that can be used to aggregate, preserve, and improve the inter-operability and semantics between historical geo-information and contemporary geo-data, as well as a source of historical geo-information, which can be accessed in the descriptive information of cultural heritage objects. The HPN Thesaurus can be used as a data standard for documenting and/or cataloguing information. It functions as a controlled vocabulary and provides an authority control suggested by the cataloguer or indexer, including preferred names/terms and synonyms for places, structure and classification schemes, etc. It can also serve as a browsing assistant within Europeana, LoCloud, and CARARE databases (the search is based on the knowledge base that shows semantic links and paths between historical and contemporary places). HPN microservice can be used as a research tool that provides information and contextual knowledge about historical place names and other locations.

The HPN Thesaurus is considered to be a qualification of the CARARE metadata schema at the conceptual level ('Heritage Asset Identification Set' >>> global type 'Spatial' >>> 'Historical name'). The strength of HPN Thesaurus lies in its ability to collect a full range of historical geo-information about digitized and born-digital cultural heritage objects, as well as related events and their representations, thus supporting different kinds of HPN microservice and user cases.

1.2 HPN functions

HPN microservice is oriented towards providers and aggregators rather than end-users. HPN microservice performs the following functions:

- Crowd sourcing and enrichment of the provider and aggregator's historical geo-information. The microservice automatically transfers historical geo-information from local/international databases and information systems to the HPN Thesaurus. It is also able to provide historical geo-data manually via a user interface. The system has been connected with the semantic mapping and transfer of historic geo-information from local systems to the LoCloud HPN Thesaurus. The HPN geo-information is imported in GeoJSON, JSON, CSV, SQL, TXT formats and matched with other historical geo-data in the HPN Thesaurus using an automatic HPN Data Import Tool. After the matching, a manual quality check is carried out and the new HPN are added to the HPN Thesaurus. Similar procedures are used for other HPN enrichment scenarios (see Figure 2). The process ensures inter-operability between different historical geo-information sets and also allows the creation tools that enable crowd sourcing and wiki usage in the LoCloud HPN field.

- HPN geo-information visualization. The microservice is able to show historic place names on a contemporary map as an interactive clustered map with zoom function (presented in <http://tautosaka.llti.lt/en/unitedgeo/>).

- HPN inter-operability provision. The inter-operability service automatically checks transferred data and links local place names with contemporary place names during the metadata harvesting process, as well as connecting geo-names with coordinates. It connects various forms of historic (including multilingual) place names in local systems with contemporary place names and GIS data (as X and Y coordinates) stored in the HPN Thesaurus (connecting a historic name with a current name or/and administrative dependences, or connecting different variations of the same place name, etc.). The microservice is based on the integrated algorithm that rationalizes and reconciles similar place names, estimating similarities between names and geographic coordinates. The algorithm also performs an accuracy check (i.e. if a name and relevant coordinates are correct, it is ranked at 100%; if the name is correct, but the coordinates deviate by 50%, it is 75%; if the name is not correct and the coordinates do not match the allowed deviation, it is 0%). The interface allows users to perform quality checks, based on the result of the reconciliation algorithm for each LoCloud partner. Users are able to log in and visualize a list with the percentage of accuracy. The whole process of analysis and enrichment is shown in Figure 3.

2 HPN technical implementation

Implementation of this project is achieved by custom Django application, called 'united_geonames'. After adding this app to Your Django project, it provides:

- *collectunitedgeo* management command;

- Admin interface to view and confirm place matches;

- united_geo.urls to include to Your urls.py to access both user interface and web service URLs in Your project.

This application is intended to be used with the PosgreSQL 9.2 database with the following extensions:

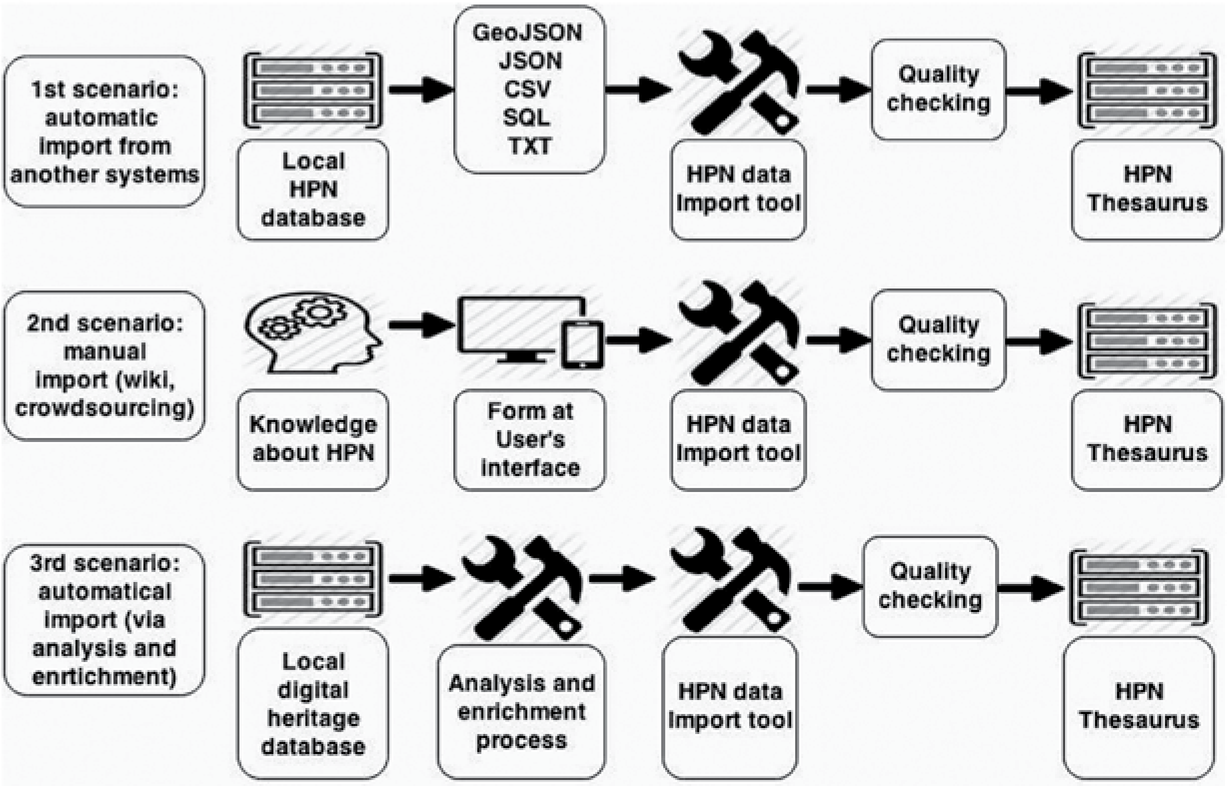

FIG. 2. HPN THESAURUS ENRICHMENT SCENARIOS.

- PostGIS (http://postgis.net/)
- Kmeans (http://pgxn.org/dist/kmeans/)
- PG Similarity (http://pgsimilarity.projects.pgfoundry.org/)

This application uses these main Django applications:

- Django-Cities for simplified integration with GeoNames;
- Django-Rest-Framework for web service interface;
- AnyCluster for server side-clustered map interface;
- CrispyForms, Bootstrap for customizable and responsive web interface

The idea of this app is to have an aggregator model *united_geonames* that has a single record for each distinct historical place name. Each imported database is then linked with the existing geoname as a synonym, or creates a new united geoname, if the synonym in the database does not exist. In this way this system links all imported databases to each other.

3 Matching algorithm

The most important part of this service is matching algorithm. Geographic synonym matching is implemented in the following way:

- United geoname has one or more synonyms with point coordinates;

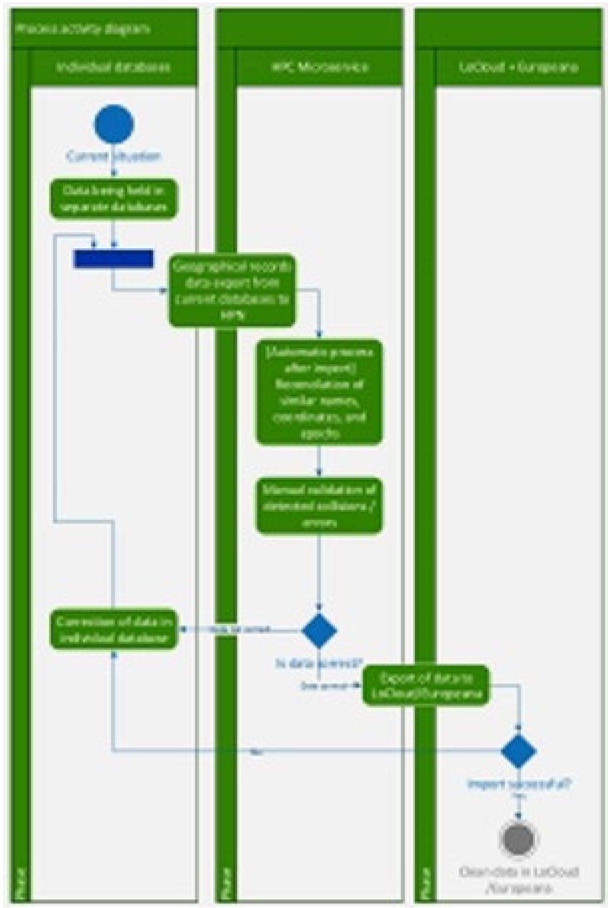

FIG. 3. ANALYSIS AND ENRICHMENT PROCESS.

- If synonym coordinates differ, they make a line (if two different synonyms) or polygon (if three or more). This shape is evaluated each time any synonym of the place changes (using *post_save* signal on *UnitedGeoNameSynonim* model), and its centroid is updated in the united_geoname model.

- If *run_matching* method receives *coordinates* as the keyword argument, it searches for the nearest places using centroid in the *united_geonames* model. We are using Postgresql 9.2 GIST indexes to speed up the search. When creating a log, the distance ranking between the place and the existing geoname is calculated using this formula:

$$GD = \frac{DISTANCE}{TRESHOLD}$$

Where GD is the geographical_distance field saved in the database, and TRESHOLD] is UNITED_GEONAMES_MAXIMUM_TRESHOLD the settings are variable. In this case, *ngram_distance* field is also calculated, using the *ngram.Ngram.searchitem()*method to compare between the place being matched and the nearest place'.

- If the run_matching method does not receive coordinates, it relies on the following keyword arguments: the first three arguments represent official spatial names (currently present in official GeoNames of country, region, and subregion) — country, region, subregion, name. If any of these arguments are 'none' type, or 'none' matches to them are not found in the UnitedGeoNames table, they are rejected. The matching query is prepared using the remainder of the arguments.

- If required, additional name matching by Ngram algorithm can be enabled using UNITED_GEONAMES_MATCH_MY_NGRAM setting. But apart from current results, with databases such as Aruodai or Stedsnav Norge, all matchable places have exact matches in GeoNames, and this setting just creates many more false matches; with Pleiades the Ngram algorithm is not applicable.

4 HPN user cases

The HPN microservice is orientated towards local memory institutions where local history researchers and digital heritage administrators are considered to be the main users of the microservice. The user cases reflect different user needs and provide different functionalities to approach them.

Local history researchers investigate history in a geographically local context. One of the most important empirical materials in local history research is historical place names, but they usually raise different sets of research questions concerning historical changes, linguistic variations, lexical formats, and the extinction of many historical place names that makes their precise location hard to define. The HPN service enables the local history researcher to verify the availability of a historical place name at LoCloud HPN Thesaurus and interconnect it with various linguistic variations, as well as localize the place by providing geographical coordinates. For the rare historical place names that are not yet recorded in the HPN database the microservice offers the possibility of supplementing the HPN Thesaurus by adding a new record of required place names.

Another usage of the HPN microservice approaches the needs of digital heritage database administrators working at local memory institutions. These institutions are usually budget-limited and do not have the high-quality computer infrastructure and means to develop highly specialized information systems, such as the Historical geo-information system. Nevertheless, a local database administrator who has basic technical skills can use HPN microservice to export selected HPN data sets and integrate them into the local information system. The HPN microservice also automatically analyses and enriches historical geo-information in a local system with information about interconnected contemporary place names, different historical and linguistic place name forms, and geographical coordinates. HPN microservice can also be supplemented with local history data packages if administrators are willing to share their data with the general public.

5 Conclusion and the next steps

The HPN microservice prototype enables small and local cultural institutions to manage their historical geo-information, collaborate in HPN knowledge crowd sourcing, enrich and connect local collections with European and global HPN data sets, and ensure better quality digitized heritage information in general. The main outlooks (the next steps) for the development of the HPN infrastructure is the enrichment of content of HPN Thesauri; the development of GIS data management models from a contemporary point-based model to a polygon-based model; the development of an HPN 'toolbox' (e.g. with historical maps creating a tool, a historical geo-information analysis tool, etc.); the enabling of inter-operability between LoCloud HPN services and other similar tools (e.g. Pleiades Plus, TGN, PastPlace); the implementation of HPN services in Europeana (internet access: <www.europeana.eu>) and (perhaps) in DARIAH-EU (Digital Research Infrastructure for the Arts and Humanities, internet access: <www.dariah.eu>) infrastructures.

Bibliography

Fernie, K., D'andrea, A., Zakrajsek, F., Ronzino, P., Koutsoudis, A., Chamzas, C., Papatheodorou, C., Carlisle, P., Ertmann-Christiansen, C., Masci, M. E., Mamo, O., Justrell, B., Clemens, S. O., Tzouvaras, V., Gavrilis, D., Angelis, S., Kakali, C., Tsakonas, G., Constantopoulos, P., Dallas, C., Pálsdóttir, S. U., Patsatzi, S., Larsen, L. I., Pletinckx, D., Drosopoulos, N., Vaitkevičius, V., Laužikas, R., Grayson, G., Stead, S. 2013. *The CARARE Metadata Schema*. Available at: http://www.carare.eu/eng/Resources/CARARE-Documentation/CARARE-metadata-schema. [Accessed: 8th july 2015].

Marty, R. 1999. *Analisis of the 76 definitions of the sign*. Available from: http://perso.numericable.fr/robert.marty/semiotique/76defeng.htm. [Accessed: 8th july 2015].

Shen Peng 2013. Google Gets Caught in Asian Island Disputes. *The International Affairs Review.* Available from: http://www.iar-gwu.org/node/512. [Accessed: 8th july 2015].

The CIDOC Conceptual Reference Model. (2015). Available from: http://www.cidoc-crm.org/docs/cidoc_crm_version_6.1.pdf. [Accessed: 8th july 2015].

Sources of experience (investigatd existing HPN projects, databases and information systems)

Bunachar Logainmneacha na hÉireann. Internet access: <http://www.logainm.ie/>.

Canadian Geographical Names Data Base. Internet access: <http://www.geobase.ca/geobase/en/index.html>.

Code Officiel Géographique. Internet access: <http://www.insee.fr/fr/methodes/nomenclatures/cog/>.

Databáze sídelních lokalit Čech, Moravy a Slezska. Internet access: <http://gis.up.npu.cz/>.

Digital Exposure of English Place-names' (DEEP) project. Internet access: <http://englishplacenames.cerch.kcl.ac.uk/>.

GeoNames. Internet access: <http://www.geonames.org/>.

Getty Thesaurus of Geographic names. Internet access: <http://www.getty.edu/research/tools/vocabularies/tgn/>.

Google Ancient Places project. Internet access: <http://googleancientplaces.wordpress.com/>.

Great Britain Historical Geographical Information System. Internet access: <http://www.port.ac.uk/research/gbhgis/>.

Historische Ortsnamen Web-Anwendunge. Internet access: <http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=3&gdz_anz_zeile=5&gdz_user_id=0>.

IS 'Aruodai' geografijos duomenų bankas. Internet access: <http://www.aruodai.lt/>.

Istoriniu vietovardžių duomenų bazė. Internet access: <http://www.lki.lt/tevi/>.

Lietuvos vietovardžių geoinformacinė duomenų bazė. Internet access: <http://lvvgdb.lki.lt/vietovardziai/Default.aspx?pid=1>.

PastPlace Gazetteer. Internet access: < http://www.pastplace.org/#/?_k=qb5n3k>.

Pelagios / Pleiades project. Internet access: <http://pelagios-project.blogspot.com/>.

Rijksdienst voor het Cultureel Erfgoed (RCE) . Internet access: <http://www.metatopos.eu/>.

The Europeana Connect Geoparser Prototype. Internet access: <http://europeana-geo.isti.cnr.it/geoparser>.

The Europeana Gazetteer Prototype. Internet access: <http://europeana-geo.isti.cnr.it/gazetteer>.

The Finnish Spatio-temporal Ontology. Internet access: <https://onki.fi/en/browser/overview/sapo>.

The Historical Gazetteer of England's Place-Names. Internet access: <http://placenames.org.uk/>.

The Old Maps Online Portal. Internet access: <http://www.oldmapsonline.org/#bbox=-110.00061,-51.981497,119.921265,72.001067&q=&datefrom=1000&dateto=2010>.

The Place Name Archives at Norway. Internet access: <http://www.dokpro.uio.no/engelsk/place_names.html>.

Vientisas istorinių vietovardžių, asmenvardžių ir istorinės chronologijos Tezauras. Internet access: <http://www.epaveldas.lt/tezauro-paieska>.

Using CIDOC CRM for Dynamically Querying ArSol, a Relational Database, from the Semantic Web

Olivier Marlet(1)
olivier.marlet@univ-tours.fr

Stéphane Curet(1)
stephane.curet@univ-tours.fr

Xavier Rodier(1)
xavier.rodier@univ-tours.fr

Béatrice Bouchou-Markhoff(2)
beatrice.bouchou@univ-tours.fr

[1] UMR 7324 - CITERES – Laboratoire Archéologie et Territoires, MSH Val-de-Loire
[2] Laboratoire d'Informatique, Université François Rabelais de Tours

Abstract: In the MASA Consortium (Memory of Archaeologists and Archaeological Sites) context, we propose opening the ArSol database, a system for processing archaeological data, to the semantic web, using the CIDOC-CRM ontology and tools that implement Ontology-Based Data Access (OBDA) principles. After designing a set of mappings from a selection of ArSol fields to the CIDOC CRM ontology, we implemented the software architecture to query ArSol from a SPARQL endpoint. We used –Ontop– a Protégé plugin, to design the OBDA mappings that are necessary for the SPARQL-to-SQL rewritings. Our final goal is to devise an application that will offer a single interface to query several distributed and independent archaeological databases, with heterogeneous structures, using CIDOC-CRM to relate them to each other. Querying ArSol in SPARQL via the CIDOC CRM is an important step towards this goal.

Keywords: Database, ontology, Ontology-Based Data Access, Semantic Web, CIDOC-CRM

1 Context

1.1 MASA consortium

In all human sciences, the exponential increase in digital documentation requires us to question its management, use, availability to the scientific community, and sustainability. In archaeology, these issues are particularly crucial because they relate to non-reproducible primary data. We gave up the fruitless debate about the possibility of adoption by the community of archaeologists of a single system that can respond to all situations and all needs a long time ago. But faced with the multiplicity of systems and data structures the question arises, 'Are most of systems inter-operable?' Fortunately, there are many points of convergence from one database to another. In other areas, particularly in medicine, several experiments show that the inter-operability of information systems can resolve these questions without leading to a reductionist homogenization.

The MASA Consortium (Memory of Archaeologists and Archaeological Sites), approved by the TGIR Huma-Num (large research cluster for digital humanities), gathers together several practitioners in French archaeological research. One of its missions is to propose solutions to sustain and harmonize archaeological information. Within this consortium, the Laboratoire Archéologie et Territoires (Archaeology and Territories) in Tours took on the task of working on the issue of archaeological data inter-operability.

The objective is to develop a unified access to digital corpuses using procedures and common tools for documenting and archiving. Sharing, and particularly querying, all archaeological data involves being relieved of the constraints of specific software, structure, vocabulary, accessibility, and language. The use of the CIDOC-CRM ontology thus seems to be the most comprehensive model that can be used as a point of convergence for various archaeological databases.

1.2 ArSol system

The goal is to enable researchers to make their system inter-operable without changing the database structure that they are used to working with (Le Goff *et al*. 2015). To this end, we decided to work on the information system that we have been using for a long time: Arsol (Archives du Sol). This system was developed with the 4D software (www.4D.com) in 1990 for all excavations based on stratigraphic principles, with the dual aims of data management and research. It currently consists of two modules: an 'Archive de fouilles' module for recording and processing the stratigraphic data; and a specific module 'Ceramics Database' (BADOC) for analysing ceramics with a view to quantifying and dating. ArSol is designed as a research tool both for recording and managing data during excavation and for manipulation and exploratory analysis of data during the post-excavation study, allowing us to shift the scale of analysis from intra- to inter-site. Therefore, ArSol offers a complete processing chain allowing queries at different levels

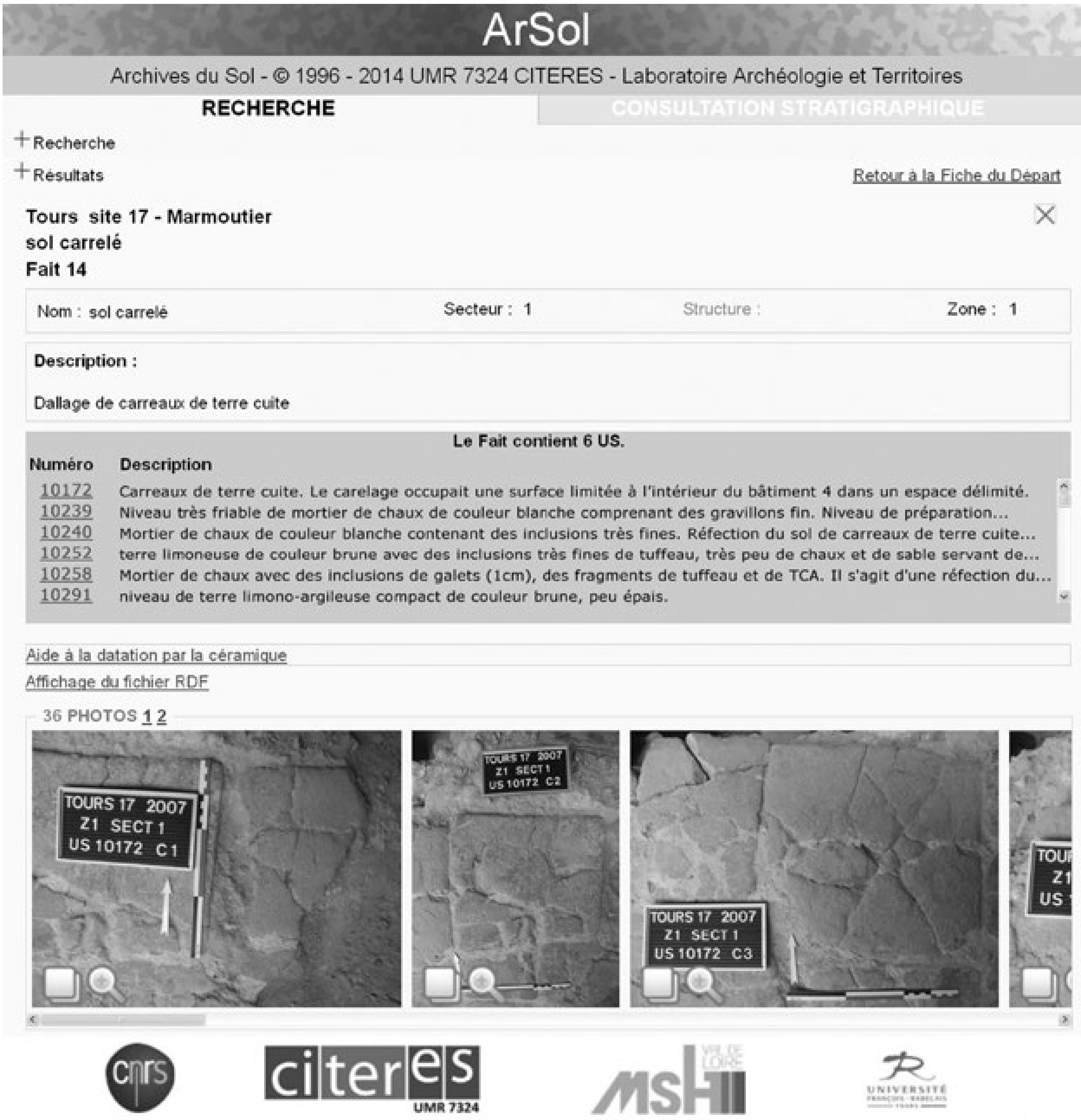

FIG. 1. ARSOL WEB VERSION (HTTP://ARSOL.UNIV-TOURS.FR).

of analysis, those being essential assets for publishing, with the ultimate aim of making evidence more robust.

In addition, to be inter-operable, it is preferable that the database is available on the web. The ArSol system has an online version allowing access to data from the web (Fig. 1). The ArSol system is therefore a valuable instrument to make various databases inter-operable by using the CIDOC-CRM ontology as a common foundation.

2 Theoretical principles

2.1 CIDOC-CRM ontology

Within the MASA consortium, we chose to use CIDOC-CRM as this is an international standard (ISO 21127:2014) that structures digital data for cultural heritage. Initiated in 1994, this ontology was originally designed for museums, but its scope is so broad that we can find most of the elements and properties specific to archaeological data. In particular, we find entity 'E22.Man-Made Object' corresponding to artefacts and entity 'E25.Man-Made Feature' corresponding to features (Fig. 2). Furthermore, one of its extensions, FRBRoo, is dedicated to library and archival items, which is an important objective for the MASA Consortium.

We see this ontology as a normalized description overlayer through which the query can pass, allowing communication with each database thanks to a system of equivalence or 'mapping'. The principle of these mappings is to match the entities of the ontology with the fields of the database. By using an ontology, data becomes free from the database management

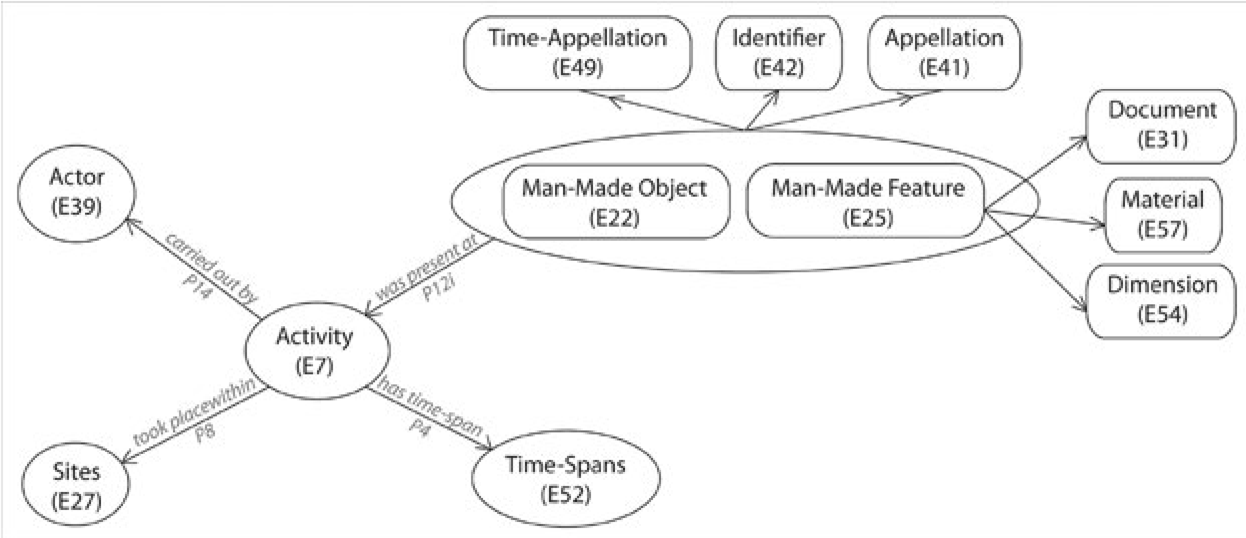

Fig. 2. A synthetic view of the ArSol data model with CIDOC CRM equivalents (after Jordal *et al.* 2011).

system software and less constrained by its own database structure.

2.2 PACTOLS Thesauri

Our project within the MASA Consortium concerns French archaeology but the CIDOC-CRM ontology is in English, but a database is truly inter-operable if it becomes free from its terminology and language. Before mapping to CIDOC-CRM, the solution is to use a standardized multilingual thesaurus, which focuses on the concept and its strict definition, rather than a vocabulary.

PACTOLS Thesauri (Peoples, Anthroponyms, Timeline, Place Names, Works, Places and Topics; http://pactols.frantiq.fr/opentheso/), widely used in social sciences especially for bibliography, is complies with the international standards for multilingual thesauri (ISO 5964:1985) and inter-operability (ISO 25964-1 and 2:2011). ArSol did not use the PACTOLS Thesauri to describe artefacts or features, for example, but only unstructured index lists, but most correspondences can be performed between PACTOLS vocabularies and ArSol vocabularies. For a few elements, present in ArSol but absent from PACTOLS, work is under way with the Frantiq network team (www.frantiq.fr/) which manages the PACTOLS Thesauri to extend the thesauri with elements from ArSol. To ensure complete concordance, it is necessary to make a mapping between the terms of PACTOLS and those used in ArSol.

3 Implementation

3.1 Mapping

To make the vocabulary match semantically is an easy task. For ontologies, this operation is called a mapping and consists in matching each field in the database with an entity of ontology respecting the whole hierarchical tree and the properties that organize the entities in relation to each other.

For ArSol, the first step of the mapping is to select tables and fields that we want to query. To query ArSol and to make it inter-operable with other databases, we decided to select only tables containing basic information common to all excavations: features and artefacts (Tab. 1). The mapping of the table FAIT (feature) and the table MOBILIER (artefacts) to the CIDOC-CRM will provide access to the data from excavations stored in ArSol, including documentation and dating (Tab. 2).

We then had to appropriate the global model of the CIDOC-CRM ontology to determine which entity matches most closely with a selected field in the database. This involves building the entire tree for positioning an entity within the model by specifying all intermediate properties and entities to locate the specific entity precisely (Fig. 3).

The next step was to write this entire tree by using RDF triples (Resource Description Framework). The triple ‘subject-predicate-object’ becomes ‘source Entity-Property-Target Entity’. The target entity at the end of one branch is the element that must be associated with the field in the database (Fig. 4). That field is collected in the mapping using a SQL query in the database. Finally, the whole file with these triples is the mapping file. For each database with a specific structure, a different mapping is required, of course.

3.2 Software architecture

How can the ontology communicate with the database using mapping as a key match? With our strong multidisciplinary approach that associates archaeologists with computer scientists, rather than by attempting to use ready-made solutions, we looked closely into the principles of OBDA systems (Ontology Based Data Access), recently introduced in the Semantic Web, which suit our needs. With this OBDA layer, the ontology is the access point to query the data, while the information remains in the databases used by researchers. The OBDA system consists of an ontology (semantic level); various data sources (in our case, ArSol); a set of mappings expressing the relationship between the data source and ontology; and an application layer to manipulate and query the system.

We chose to use –Ontop– (http://ontop.inf.unibz.it/), a solution developed by Professor Calvanese and his team at the University of Bozen-Bolzano (Italy). –Ontop– is an extension of Protégé

Tab. 1. Selection of basic archaeological information in the MOBILIER table.

Fields from Mobilier table	Selection
USNum	x
NumObjet	x
NumMobilier	x
NumSep	x
FSI	x
Année	x
EtatConservation	-
Categorie	x
Matiere	x
Description	x
Identification	x
Fonction	x
Usage	x
PhotoMobilier	x
Statut	-
Datation	x
long_mm	x
larg_mm	x
HouEp_mm	x
diam_mm	x
Type	-
Poids_gr	-
Ref_biblio	-
nCatalogueObjet	-
nCatalogueMonnaie	-
RefMonnaie	-
nCaisse	-

Tab. 2. Mapping the ArSol fields of the MOBILIER table on the CIDOC CRM categories.

Mobilier table	ArSol fields	CIDOC CRM entities	CRM categories
Contextualization	Mobilier	E22 Man-Made Object	Concept
	Type intervention	E7 Activity	Eventw
	Année	E50 Date	Time
	Contact	E51 Contact Point	Actor
Localization	Commune	E53 Place	Place
	Site	E27 Site	
Inventory	IDSite	E42 Identifier	Thing
	NumSep	E41 Appellation	
	FSI	E41 Appellation	
	USNum	E41 Appellation	
	NumObjet	E41 Appellation	
	NumMobilier	E41 Appellation	
	IDFiche	E42 Identifier	
Identification	Catégorie	E55 Type	Thing
	Identification	E55 Type	
	Description	E41 Appellation	
	Fonction	E55 Type	
	Usage	E55 Type	
	Datation	E49 Time Appellation	Time
Physical description	Matière	E57 Material	Thing
	diam_mm	E54 Dimension	
	HouEp_mm	E54 Dimension	
	larg_mm	E54 Dimension	
	long_mm	E54 Dimension	
	PhotosMobilier	E31 Document	

(free software dedicated to ontologies), developed in Java. It first allows us to specify the matches between the ontology and the database, and to evaluate SPARQL queries about the ontology, whose results are searched for in the database (Fig. 5). The integrated user interface of Protégé helps us to create the OBDA file containing statements of correspondences between ontology and data source.

To offer a SPARQL Endpoint, required for online querying, we need an HTTP server such as Jetty (Java) with the web application Sesame-Workbench that contains Quest, an –Ontop– version independent of Protégé and ensuring the interpretation of SPARQL queries. The ontology is loaded as an XML-OWL file. The data source is defined by indicating the required drivers to allow Java to communicate with the source database software (Figs. 6 and 7).

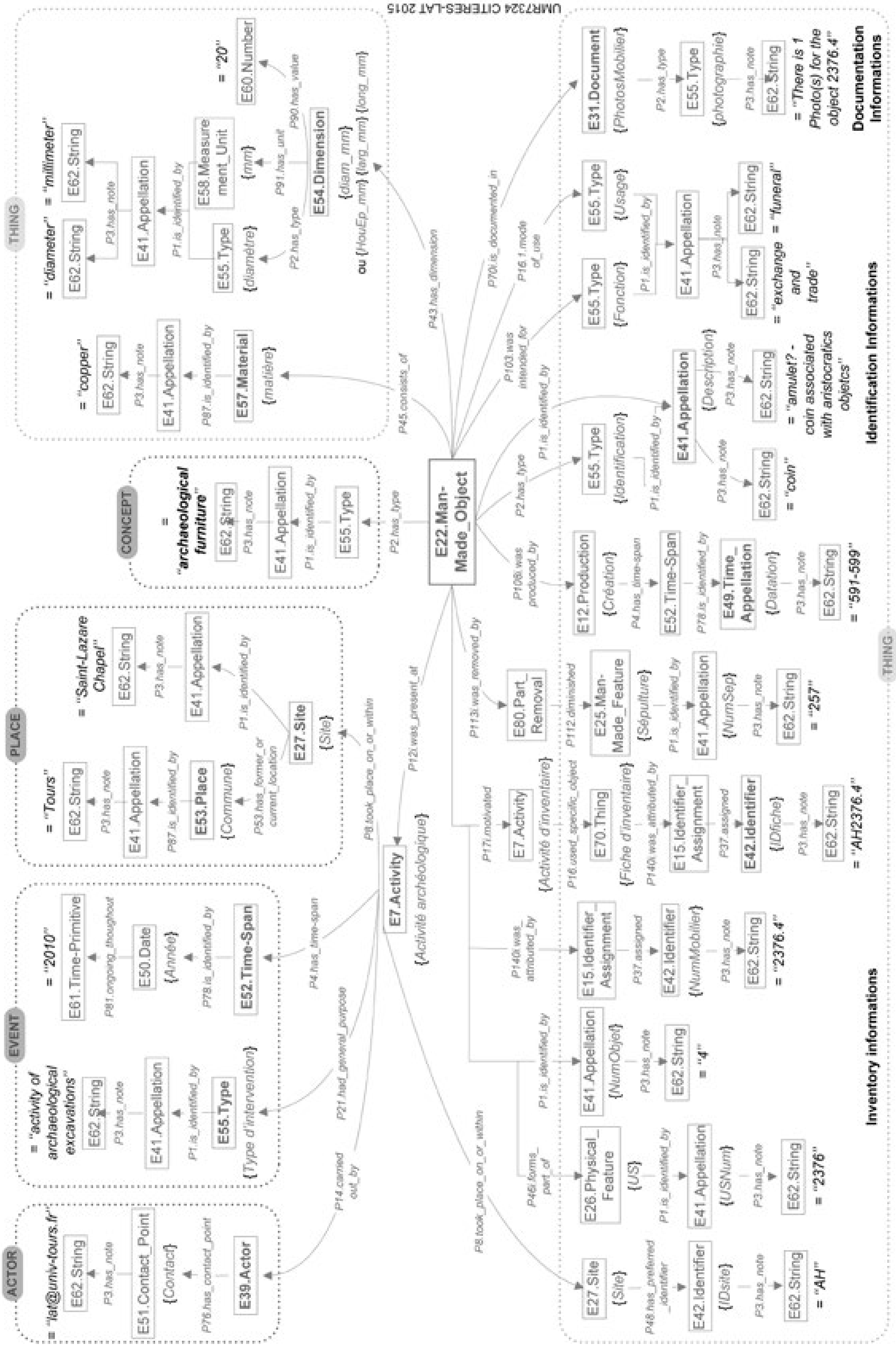

FIG. 3. CONCEPTUAL MODEL OF DATA FOR THE MOBILIER TABLE.

E22 Man-Made Object {Mobilier}. P16.1 mode of use: E55 Type {Usage}
E55 Type {Usage}. P2 has type: E55 Type
E55 Type. P1 is identified by: E41 Appellation
→ datatype = *"usage"*
et:
E55 Type {Usage}. P1 is identified by: E41 Appellation
→ value example = *"funéraire"*

Fig. 4. Example of CRMs entities and properties for the MOBILIER table with triples in RDF terminology.

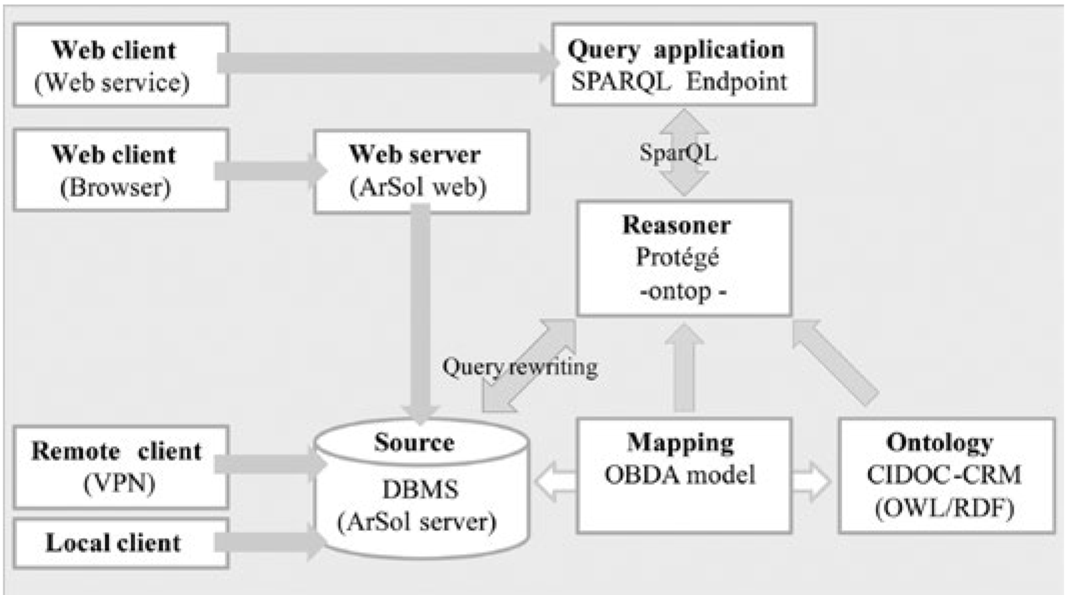

Fig. 5. Software architecture to query ArSol with OBDA system.

4 Prospects

4.1 Software constraints

The software architecture needed to implement this system is complex and, in addition to the assistance of computer scientists, requires training for the installation of the software, its settings, and its use. As –Ontop– developers are working with researchers, the OBDA solution is still in its infancy and is not yet integrated by publishers of turnkey solutions. For current users, this requires quite a significant personal investment. For ArSol, the connectors between Java and 4D will require the Italian team –Ontop– to help us modify and adapt the drivers that do not work properly with 4D.

4.2 Adding other databases

Because of the complexity of the settings and the time required to learn to use the software, the first tests with ArSol took time to give satisfying results. Now we need to expand our number of data sources to give full meaning to inter-operability. For this, we will undertake the same process with another archaeological database. The only constraint is that the database should have fields which can be mapped with the ontology, which is the case for most databases used in archaeology, and that it is web-accessible; this is the case of course with mySQL and PostgreSQL, but also with Access, FilesMaker, or 4D databases (Fig. 8).

Once this database has been chosen, we will undertake more mapping work, capitalizing on the mapping already done for ArSol, with the aim of producing a guide generic enough to enable the projects that will follow the same path to unfold more efficiently. Then, we will need to define the software driver that allows Java to communicate with the selected software; this step should be repeated only if the type of data source type has not yet been included in the –Ontop– system.

When we have demonstrated the efficiency of inter-operability through this step, we will return to ArSol to design its full mapping with an ontology. It may possibly be CIDOC CRM itself or an extension of CIDOC CRM that either exists or that will be designed for ArSol needs.

```
[PrefixDeclaration]
:               http://erlangen-crm.org/current/
owl:            http://www.w3.org/2002/07/owl#
rdf:            http://www.w3.org/1999/02/22-rdf-syntax-ns#
xsd:            http://www.w3.org/2001/XMLSchema#
xsp:            http://www.owl-ontologies.com/2005/08/07/xsp.owl#
ecrm:           http://erlangen-crm.org/current/
rdfs:           http://www.w3.org/2000/01/rdf-schema#
skos:           http://www.w3.org/2004/02/skos/core#
swrl:           http://www.w3.org/2003/11/swrl#
swrlb:          http://www.w3.org/2003/11/swrlb#
protege:        http://protege.stanford.edu/plugins/owl/protege#

[SourceDeclaration]
sourceUri       jdbc4D
connectionUrl   jdbc:odbc:BaseArsol
username        LAT
password        ********
driverClass     sun.jdbc.odbc.JdbcOdbcDriver

[MappingDeclaration] @collection [[
mappingId       MAPID-1
target          <http://arsol.univ-tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}> a ecrm:E22_Man-
                Made_Object ; ecrm:P101_had_as_general_use <http://arsol.univ-
                tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}/usage> .
                <http://arsol.univ-tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}/usage> a
                ecrm:E55_Type ;
                ecrm:P1_is_identified_by <http://arsol.univ-
                tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}/usageid> .
                <http://arsol.univ-tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}/usageid> a
                ecrm:E41_Appellation ;
                <http://arsol.univ-tours.fr/4DACTION/WFICHEWEB/imobi{CoSiUSObj}/usageid>
                ecrm:P3_has_note {G_usage} .
source          SELECT CoSiUSObj, G_usage FROM af4mobilie
]]
```

FIG. 6. EXAMPLE OF –ONTOP– OBDA FILE.

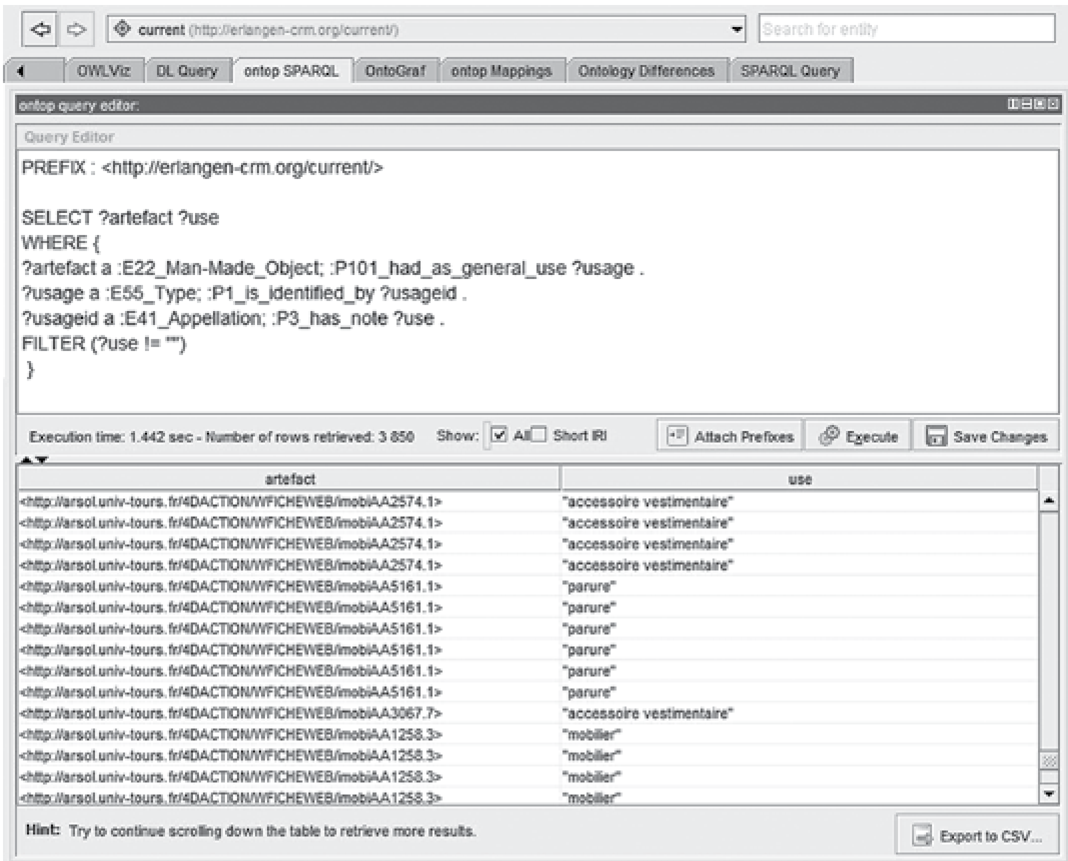

FIG. 7. SPARQL ENDPOINT.

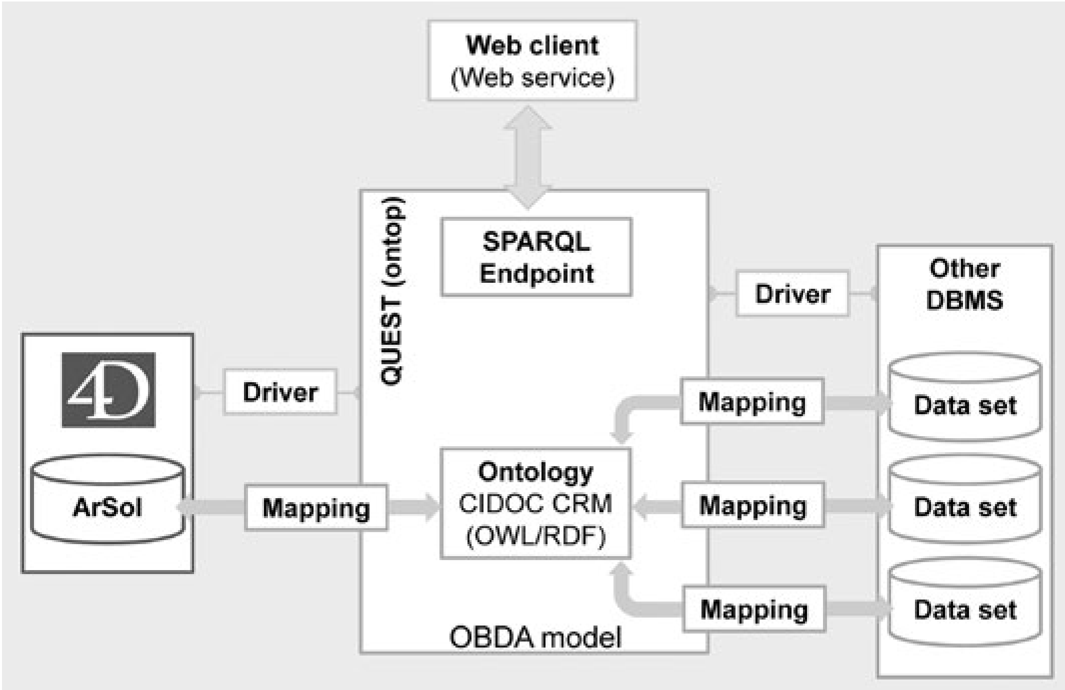

Fig. 8. Project to bring other databases to the Semantic Web with an OBDA system.

5 Conclusion

Making ArSol inter-operable was a complex operation but we have developed a methodology directly reusable for other databases. The mapping file for ArSol is obviously not reproducible for another database, but all the methodological work to implement this mapping is directly reusable for all the databases that we would like to integrate in the query system. This methodological work will help us extend the experience with other archaeological databases within the MASA Consortium.

Efforts will now focus on the presentation level. The SPARQL endpoint is essential for the web services that will query ArSol but it cannot be accepted for mainstream use. We have to allow people to access ArSol via this semantic level, so we plan to develop an application from SPARQL Endpoint to manage web interfaces for users.

This work on the inter-operability of archaeological databases falls under the responsibility of institutions. With our work within the MASA Consortium, we are attempting to demonstrate the value of this approach for the archaeologists' community.

Bibliography

Andreussi, M. and Felicetti, A. 2008. The CIDOC CRM Encoding of the 'Fontes ad Topographiam Veteris Urbis Romae Pertinentes' by Giuseppe Lugli. In Posluschny, A., Lambers, K. and Herzog, I. (eds.), *Layers of Perception, Proceedings of the 35th CAA Conference*, *Berlin, Germany, 2-6 April 2007*: 1-6. Berlin.

Bachimont, B. 2000. Engagement sémantique et engagement ontologique : conception et réalisation d'ontologies en Ingénierie des connaissances. In Charlet, J., Zacklad, M., Kassel, G. and Bourigault, D. (eds.), *Ingénierie des connaissances,* évolutions *récentes et nouveaux defies*. Paris: Eyrolles.

Calvanese, D., De Giacomo, G., Lembo, D., Lenzerini, M. and Rosati R. 2007. Tractable reasoning and efficient query answering in description logics: The DL-Lite family. *Journal of Automated Reasoning*, 39, 3: 385-429. Available from: https://cs.uwaterloo.ca/~david/tud/dllite.pdf [Accessed: 29th june 2015].

Cruz, I.F. and XIAO, H. 2005. The Role of ontologies in data integration. *Engineering intelligent systems* 13 (4): 245-52.

Cuenca Grau, B. and Giese, M. 2013. *Towards Query Formulation and Query-Driven Ontology Extensions in OBDA Systems*, 12 p. Available at: http://www.cs.ox.ac.uk/files/5511/owled2013_wp3.pdf [Accessed: 22th june 2015].

Doerr, M. 2003. The CIDOC Conceptual Reference Model: An Ontological Approach to Semantic Interoperability of Metadata. *AI Magazine* 24, 3: 75-92.

Eckkrammer , F., Feldbacher, R. and Eckkrammer, T. 2011. CIDOC-CRM in Data Management and Data Sharing. Data Sharing between Different Databases. In Erzsébet, J., Redő, F. and Szeverényi, V. (eds.), *On the Road to Reconstructing the Past, Proceedings of the 36th CAA Conference*, *Budapest, 2-6 April 2008*: 80-5.

Galinie, H., Husi, P., Rodier, X., Theureau, C. and Zadora-Rio, E. 2005. ARSOL. La chaîne de gestion des données de fouilles du laboratoire Archéologie et Territoires, *Les petits cahiers d'Anatole* 17, 27/05/2005, 25 p. Available at: http://citeres.univ-tours.fr/doc/lat/pecada/F2_17.pdf [Accessed: 22th june 2015].

Husi, P. and Rodier, X. (2011). ArSol: An Archaeological Data Processing System. In Erzsébet, J., Redő, F. and Szeverényi, V. (eds.), *On the Road to Reconstructing the Past, Proceedings of the 36th CAA Conference*, *Budapest, 2-6 April 2008*: 86-92.

Jordal, E., Uleberg, E. and Hauge, B. 2012. Was It Worth It? Experiences with a CIDOC CRM-based Database. In Mingquan, Z., Romanowska, I., Wu, Z. and Verhagen, P. (eds.), *Revive the Past, Proceedings of the 39th CAA Conference*, *Beijing, China, 12-16 April 2011*: 255-60.

Le Bœuf, P. 2009. Modélisation conceptuelle de l'information bibliographique et muséologique : CIDOC CRM et FRBROO. *Documentation et bibliothèques* 55 (4) : 209-214. Available at: http://hal-bnf.archives-ouvertes.fr/hal-00807980 [Accessed: 22th june 2015].

Le Bœuf, P. (2013). *De la sémantique des inventaires aux musées en dialogue : la modélisation CIDOC CRM*. Avril 2013. Available at: http://halshs.archives-ouvertes.fr/hal-00807664/ [Accessed: 22th june 2015].

Le Boeuf, P., Doerr, M., Ore, C.E. and Stead, S. 2013. *Definition of the CIDOC Conceptual Reference Model*. Version 5.1.2. October 2013. Available at: http://www.cidoc-crm.org/docs/cidoc_crm_version_5.1.2.pdf [Accessed: 20th july 2014].

Le goff, E., Marlet, O., Rodier, X., Curet, S. and Husi, P. 2015. Interoperability of the ArSol (Archives du Sol) database based on the CIDOC-CRM ontology. In Giligny, F., Djindjian, F., Costa, L., Moscati, P. and Robert, S. (eds.), *Concepts, methods and tools, Proceedings of the 42nd CAA Conference*, *Paris, 22-25 April 2014*: 179-86. Oxford, Archaeopress.

Lourdi, I., Papatheodorou, C. and Doerr, M. 2009. Semantic integration of collection description: combining CIDOC-CRM and Dublin Core Collections Application Profile. *D-Lib Magazine* 15 (7/8). [Online] Available at: http://www.dlib.org/dlib/july09/papatheodorou/07papatheodorou.html [Accessed: 22th june 2015].

Mcguinness, D.L. and Van Harmelen, F. 2004. *OWL Web Ontology Language Overview*. [Online] Available at: http://www.w3.org/TR/owl-features/ [Accessed: 22th june 2015].

Rodriguez-Muro, M. and Calvanese, D. 2008. *Towards an open framework for Ontology Based Data Access with Protégé and DIG 1.1.* , 4p. Available at: http://ceur-ws.org/Vol-432/owled2008eu_submission_37.pdf [Accessed: 22th june 2015].

Rodriguez-Muro, M., Kontchakov, R. and Zakharyaschev, M. 2013. *OBDA with Ontop*, 6 p. Available from: http://www.dcs.bbk.ac.uk/~roman/papers/ORE1.pdf [Accessed: 22th june 2015].

Rodriguez-Muro, M., Kontchakov, R. and Zakharyaschev, M. 2013. *Ontop at work*, 12 p. Available from: http://webont.org/owled/2013/papers/owled2013_18.pdf [Accessed: 22th june 2015].

Szabados, A.-V. 2012. Du système documentaire du LIMC au portail CLAROS. Interopérabilité et optimisation de l'information archéologique grâce à l'usage des normes. In Giligny, F., Costa, L., Djindjian, R., Ciezar, P. and Desachy, B. (eds.), *2e Journées d'Informatique et Archéologie de Paris - JIAP 2010, Paris, France, 11-12 juin 2010*, *Archaeologia e Calcolatori* 3: 11-25.

Szabados, A.-V. and Letricot, R. (2012). L'ontologie CIDOC CRM appliquée aux objets du patrimoine antique. In Giligny, F., Costa, L., Djindjian, R., Ciezar, P. and Desachy, B. (eds.), *3e Journées d'Informatique et Archéologie de Paris - JIAP 2012, Paris, France, 1-2 Juin 2012*. Available at: http://halshs.archives-ouvertes.fr/halshs-00752996 [Accessed: 22th june 2015].

Connecting Cultural Heritage Data: The Syrian Heritage Project in the IT Infrastructure of the German Archaeological Institute

Sebastian Cuy[(1)]
sebastian.cuy@uni-koeln.de

Philipp Gerth[(2)]
philipp.gerth@dainst.de

Reinhard Förtsch[(2)]
reinhard.foertsch@dainst.de

[1] CoDArchLab, University of Cologne, Germany
[2] German Archaeological Institute (DAI), Germany

Abstract: The Syrian Heritage Archive Project is creating a national heritage inventory for Syria within the IT infrastructure of the DAI, which is enriched by digitized archives on archaeology and building history, in order to support preservation and reconstruction and also help to prevent illegal trade.

This paper describes the IT strategy and especially the key role of spatial data infrastructures within the project. The paper then discusses issues encountered in integrating various data sources via the principles of 'linked open data' and provides several use cases for data aggregation.

Keywords: Aggregation, Linked open data, Spatial data, Cultural heritage

Introduction

The fall of Syria into a civil war in 2011 has led not only to a humanitarian disaster, but has also threatened the rich cultural heritage of Syria. This cultural heritage can be divided into movable and immovable parts and each faces different threats. The immovable cultural heritage is threatened by destruction due to air strikes, artillery, and ongoing fighting which have erased large parts of the historical centres of Aleppo, Homs, and other cities, while the movable heritage is falling victim to illicit trafficking by museum plundering and the looting of archaeological sites.

As active on-site involvement is impossible at the moment, in November 2013 the German Archaeological Institute (DAI) in cooperation with the Museum for Islamic Art Berlin (MIK) started the Syrian Heritage Archive Project (SyrHer), funded by the German Foreign Office and supported by various Syrian research scholars working on the project in Germany.

Meanwhile a lot of initiatives have begun, which monitor the current destructions via satellite imagery and gather information of damage reports from social media. This is important information in its own right, often collected under life-threatening circumstances by those who channel the information to the outside world. It is therefore a pity that most of this information does not refer to a scientifically defined, unique object-ID of a building or statue, but is simply connected to unstandardized quotations of locations and objects, buildings, etc. To add value to these reports, they should be collected and connected to known locations, and the best way to do this is to create a grid of URI-defined objects in Syria, to which the damage reports can then be linked in the future. Without such a layer the often-quoted GIS systems are no more than a pretty visualization, lacking a proper data architecture. This can be changed by digitizing existing archives located outside Syria, far from the risks of civil war, and where time can be taken to create this unique object-ID grid.

The SyrHer project decided to concentrate more on the digitization of research data in their own archives and to make this data publically available. Following the guideline 'You can only protect what you know' (Fless 2014: 21) the main task is defined as follows: to create a comprehensive national registry of archaeological sites from the available sources, which can be used to support education, preservation, and reconstruction, as well as help to prevent illicit trafficking of antiquities.

One major challenge posed in this project was the integration of various types of research data generated by archaeological, art historical, and architectural history projects in order to create a data layer with additional data for the comprehensive national registry of archaeological sites. As Syria by no means lacks an infrastructure for cultural heritage, the DAI is in close contact with the responsible Syrian IT departments and our aim is also to establish inter-operability with their existing systems.

2 iDAI.world - The IT infrastructure of the DAI

The SyrHer project has to handle very heterogeneous research data such as excavation data, texts, archives, cadastral plans, historical maps, etc. This implies a big challenge for organizing

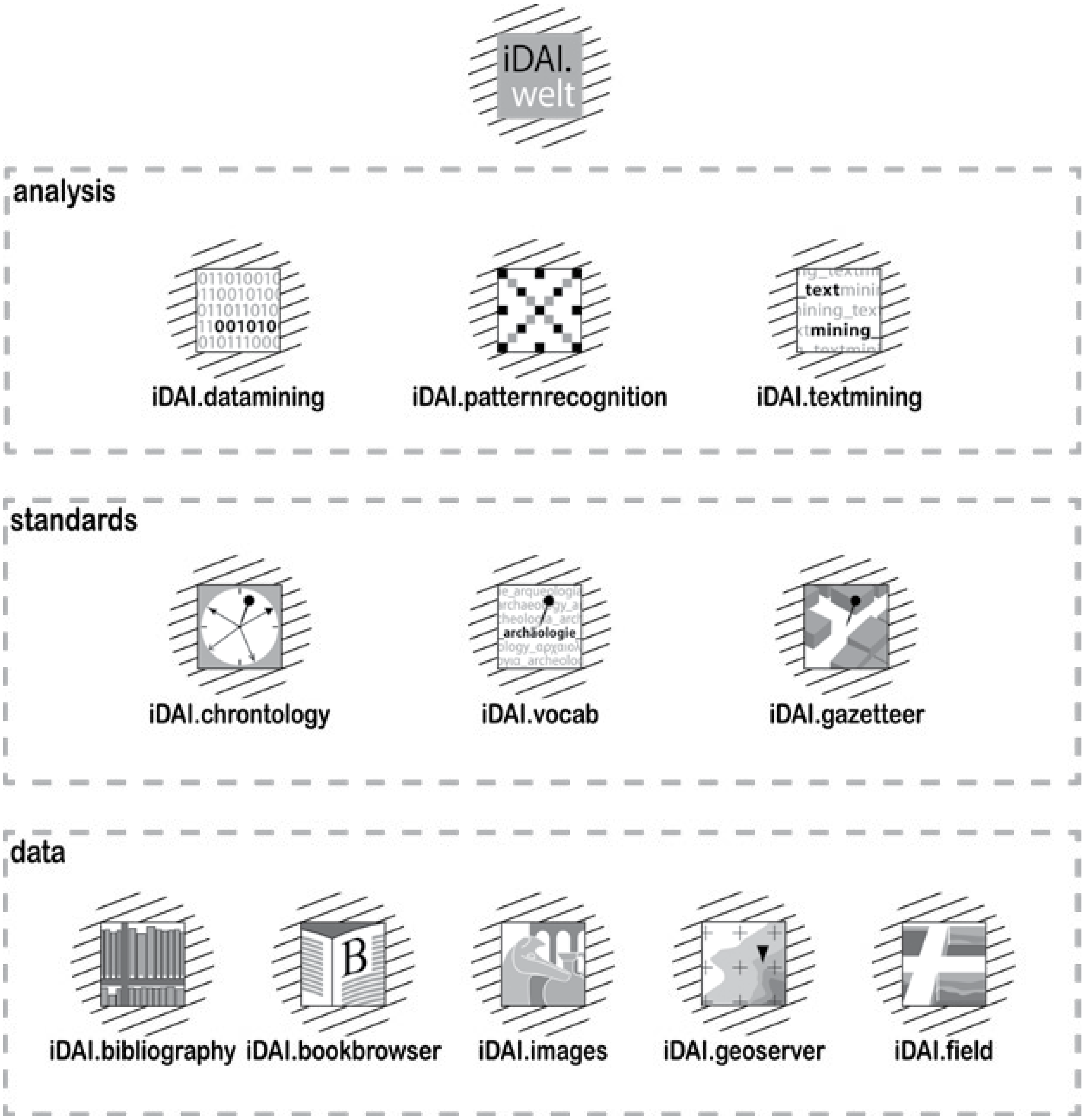

Fig. 1. iDAI.world — The IT infrastructure of the DAI.

the data for an IT infrastructure. Due to data sustainability issues over the project's life span, we are using the already available and tested IT infrastructure of the DAI, instead of designing and creating a new project specific infrastructure. The open application interfaces of the existing infrastructure allow us to aggregate the heterogeneous research data (excavation data, texts, archives, cadastral plans, historical maps, etc.) and to present them within a unified user interface.

In the past years the DAI was able to implement applications and web services for various domains and types of data relevant for archaeological studies. In relationship to the SyrHer project, the IT infrastructure of the DAI, the so-called iDAI.world (DAI 2015), consists of a three-layer architecture:

- Data: domain-specific information systems
- Standards: standardization of data
- Analysis: tools for analysis the data

The most important infrastructures used within the project will be briefly introduced below.

2.1 Data Layer

2.1.1 iDAI.objects/Arachne

http://arachne.dainst.org/

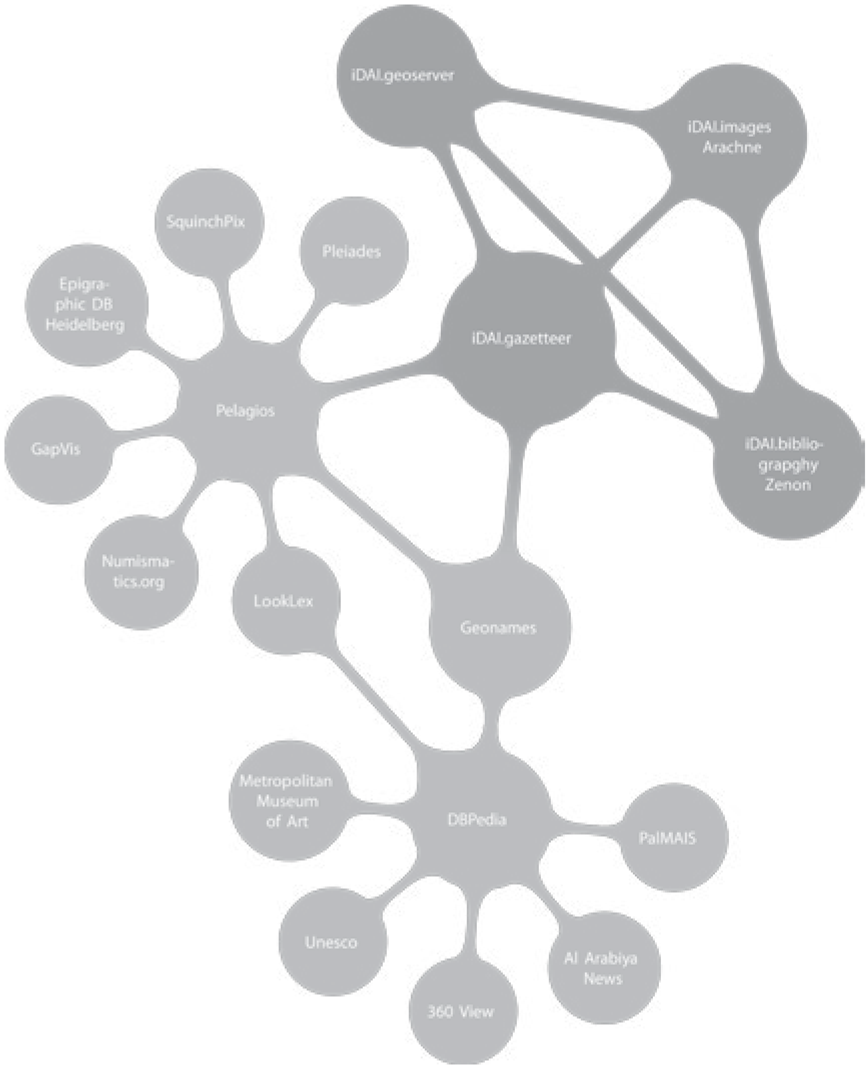

FIG. 2. LINKED DATA CLOUD OF DAI SYSTEMS (DARK) AND EXTERNAL SYSTEMS.

iDAI.objects, also knows as Arachne, is the central object database of the DAI developed at the Cologne Digital Archaeology Laboratory (CoDArchLab). Currently it allows research into over 300,000 highly structured descriptions of artefacts of archaeological interest and over 2,000,000 images and corresponding metadata of varying degrees of structure. Arachne also incorporates interfaces for browsing digitized books that are connected to the referenced objects.

As such Arachne provided a natural cornerstone for the publication of all metadata and pictorial material concerning physical objects and textual sources gathered in the course of the Syrian Heritage Project. Until now (mid-2015) around 70,000 images relevant for the study of Syrian archaeology have already been made available in Arachne.

2.1.2 iDAI.bibliography/Zenon

http://zenon.dainst.org/

iDAI.bibliography/Zenon is one of the largest bibliographic databases for classical studies (approximately 1 million catalogue records). This database includes not only the library collections of the different DAI-departments, the DEI Amman (GPIA Amman), and the Winckelmann Society, but also retro-digitized source material, e-resources, analytical records/articles, maps, and archival materials. In addition to book and journal titles, essays and reviews are indexed by subject and topographic criteria and are updated on a daily basis. These bibliographic data are heavily interconnected with other DAI databases such as the iDAI.gazetteer. Furthermore iDAI.bibliography/Zenon is integrated into the search engine 'PropylaeumSEARCH' (2015) in Propylaeum, the Virtual Library Classical Studies. In the course of the SyrHer project bibliographic entries covering Syria are being explicitly linked to the iDAI.gazetteer.

2.1.3 iDAI.geo

http://geoserver.dainst.org/

The importance of spatial data and GIS systems in archaeological research has grown in recent decades, from the local level with excavation data to the regional level, which is often studied in the context of landscape archaeological issues. The DAI's research projects have produced vast amounts

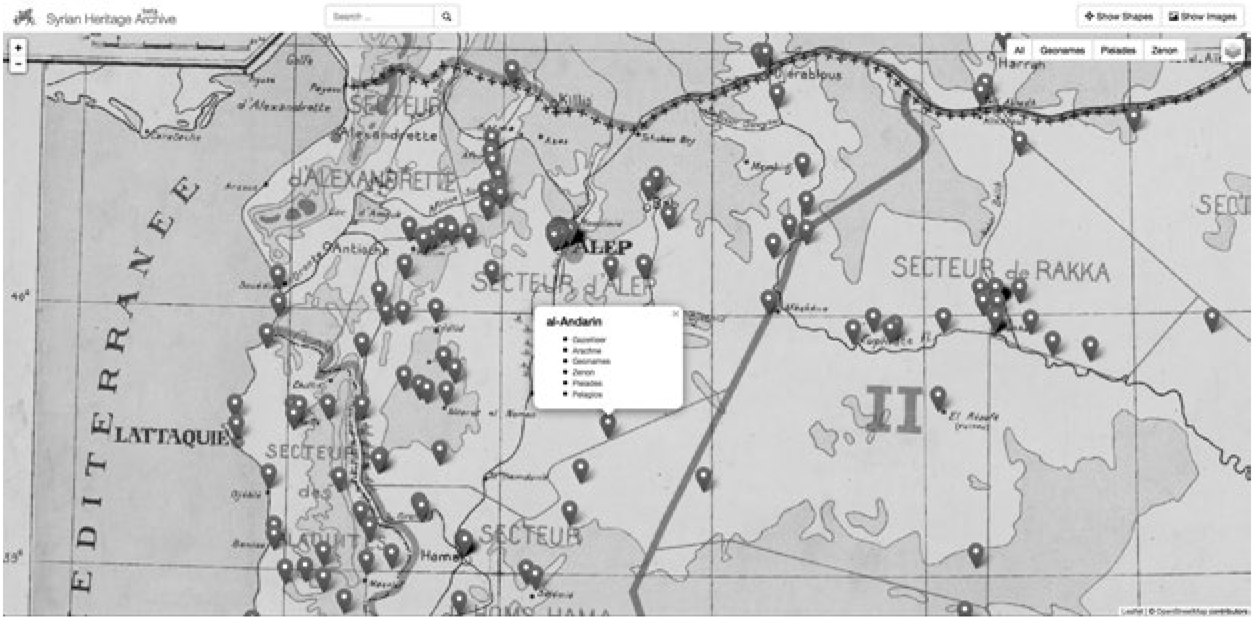

FIG. 3. SITE REGISTRY OF SYRIAN HERITAGE SITES WITH INTEGRATED DATA FROM DAI'S SYSTEMS WITH LINKS TO EXTERNAL DATA.

FIG. 4. HERITAGE-BUILDING INVENTORY OF ALEPPO WITH INTEGRATED DATA FROM DAI'S SYSTEMS AND EXTERNAL DATA.

of spatial data often stored in insufficient, non-proprietory formats. These data are usually collected with great effort and have a high potential for further and future research. In this respect, Data storage and availability of different data sets play an increasingly important role.

The main task of iDAI.geo lies in the server-based storage and provision of the spatial data in reusable formats. Furthermore, working in a virtual research environment, especially for large projects, the same database is easy accessible simultaneously by all participants. In addition, the creation of web-based maps with linked content from other DAI systems for publication purposes is considered a large added value compared to a static map.

iDAI.geo is based on the Open Source CMS 'Geonode' (2015), which has been adapted to the requirements of the German Archaeological Institute. It is a web-based infrastructure where scientists and researchers can store their data directly on the server. It is mandatory to add OGC compliant metadata, which follows the ISO Standard DIN EN ISO 19115. Once uploaded, the data can be used to create web maps, which are embeddable in other websites. As the whole infrastructure is using the OGC standards WMS and WFS (OGC 2015), the inter-operability with DesktopGIS and WebGIS systems is ensured.

For the Syrian Heritage Archive Project, there were around 80 topographical maps, cadastral plans, and other plans from architectural studies and excavations. Those raster maps and vector layers were digitized, georeferenced, and uploaded with the appropriate metadata into iDAI.geo.

2.2 Standards layer

2.2.1 iDAI.vocab

http://archwort.dainst.org/thesaurus/de/vocab/index.php

iDAI.vocab is a thesaurus of German technical archaeological terms with extensive multilingual support. Its aim is to collect and organize the terminology used in the services of the DAI. The terms in the vocabulary are classified according to a standard set of relations. In addition, iDAI.vocab provides a web interface where users can easily look up a concept, investigate its relations to other terms, and find the translation of the term in a variety of different languages. The terms are also connected to the equivalent concepts in other reference works, such as the Getty's AAT and Dbpedia.

Overall, there are around 3500 translated Arabic terms in the archaeological dictionary of the DAI.

2.2.2 iDAI.gazetteer

http://gazetteer.dainst.org/

The DAI's resources for managing geo data were of particular value for this enterprise. On the one hand, the geoserver 'iDAI.geo' makes various sets of spatial information accessible while on the other, the 'iDAI.gazetteer' is used as a hub to connect the different resources within the DAI infrastructure and also acts as a gate to the Linked Data cloud by establishing links to existing resources such as Pleiades, Pelagios, and geonames. Thus users can not only view all data collected in the project but also use the resulting application as a starting point for further research into other systems.

As a result of the Syrian Heritage Project the iDAI.gazetteer currently contains descriptions of around 900 places in Syria that are relevant for archaeological research.

3 Linked data

The design of the iDAI.world as a system of various loosely coupled, domain-specific applications has the advantage of few interdependencies, enabling a more agile development process as well as giving the benefit of being able to tailor the application and its user interfaces to the specific needs of the particular domain experts and users. This design comes at a price, however: the need to integrate the different data sources to enable the presentation of the heterogeneous sources as a thematic whole, which was one of the goals of the Syrian Heritage Project.

In the last decade the technologies and principles subsumed under the headline 'Linked data' have gained increasing attention, both outside (Bizer *et al.* 2009) and inside (Isaksen *et al.* 2014) the scientific community. Adopting the approach of publishing data in standardized RDF formats with persistent URIs seemed a good starting point for the integration of the various data sources inside the iDAI.world. This has not only provided us with well-defined interfaces for integrating our own resources, but also enabled us to open up further the applications of the iDAI ecosystem to the public in order to connect to the general linked open data cloud. This way users will not only be able seamlessly to explore the heterogeneous content provided by the DAI but they will also make use of information gathered elsewhere by other institutions.

The following use cases therefore can be seen as a case study dealing with the integration of heterogeneous sources. Furthermore, they provide the best practice for realizing applications that bring together various linked data sources and can thereby give insights into the feasibility of the linked open data approach in general.

3.1 Use case: site registry

Creating a comprehensive register of sites in Syria is one of the central goals of the SyrHer project. The systematic organization of the various places relevant to archaeological research in Syria includes translation and transliteration of place names, georeferencing the locations, the creation of new identifiers, and the connection with existing identifiers. This registry will serve as a hub for connecting otherwise incompatible data sets on the basis of shared locations. The registry itself is created inside the iDAI.gazetteer while the data recorded in the other systems of the iDAI.world explicitly references these unique gazetteer identifiers.

In order to make this registry available we decided to provide a web application that offers users a location-based browsing interface. Besides being able to drill down geographically into areas relevant to the user, we are also able to provide links to the connected resources, thereby offering a simple but effective tool for starting location-based research into different systems. Many places managed in the iDAI.gazetteer are not only referenced by the applications of the iDAI.world but are also explicitly linked to places described by the Geonames (2015) and Pleiades (2015) projects. In this way a user is able to discover a large amount of resources connected through these links, as for example the various archaeological data sets linked to Pleiades through the work done in the Pelagios project.

This use case shows that a relatively basic linking on the basis of commonly referenced entities, such as places, can already provide additional value to existing systems. Even if systems are not fully mapped according to a common standard, offering links to other resources enables users to navigate the web for linked data and find a way out of data silos.

3.2 Use case: heritage-building inventory of Aleppo

In the second use case all available data for the UNESCO world heritage site 'Aleppo' (UNESCO 2015) were collected and provided by a WebGIS for a comprehensive heritage-building inventory. As a result all historic buildings stored in the gazetteer are displayed as polygons, where the gazetteer just provides the links to further metadata of the object, such as stored information from architectural historical studies in

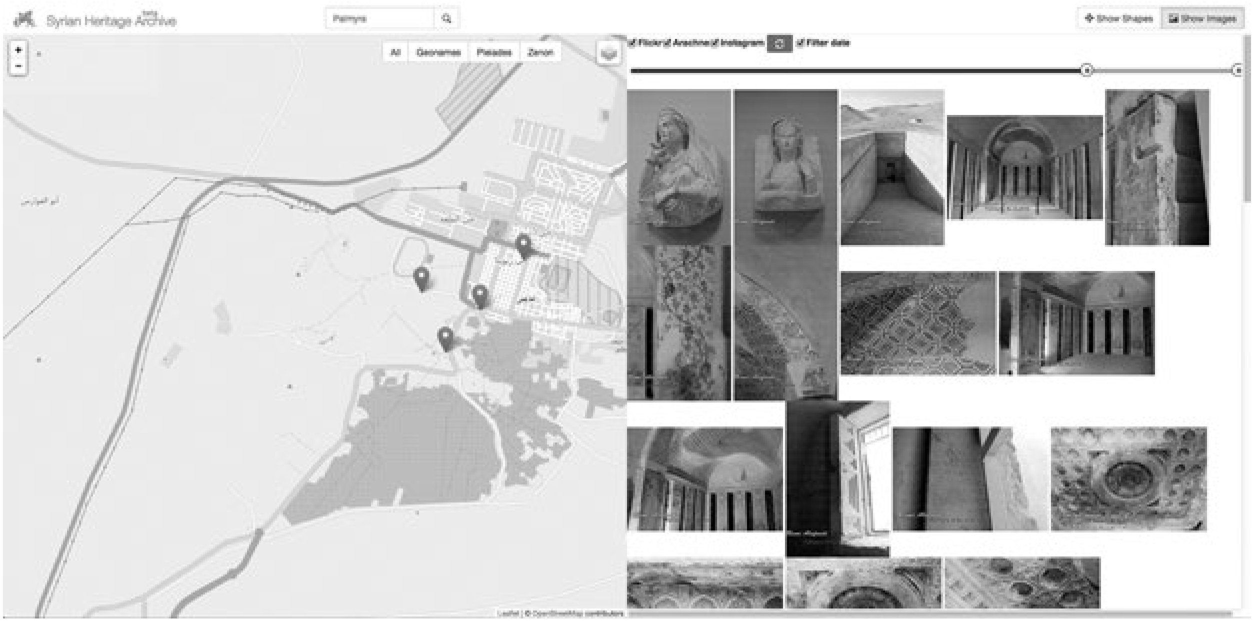

FIG. 5. INTEGRATED DATA OF AVAILABLE OPEN APIS FOR IMAGES FILTERED BY LOCATION AND TIME.

Arachne. As background maps, there are several architectural study plans (Gaube, Wirth 1984, map 1-5), served via WMS by iDAI.geo. Furthermore, external spatial data can be integrated using the WFS standard, for example damage assessment points of the UNOSAT CHS-Syria project (UNITAR 2015) are integrated with a total of 3875 affected structures in the centre of Aleppo. By using OGC standards, it is possible to integrate data from archaeological, building history, and recent damage assessments from different sources.

3.3 Use case: integration of open APIs

As another case study we searched for ways to integrate resources even further. As it turned out, however, none of the directly relevant resources (Perini and Cunliffe 2014) makes use of Semantic Web standards, which ruled out the integration on the basis of a shared ontology. Moreover, very few projects offer open APIs that allow integration on a more basic level. In the end we decided to incorporate image data retrieved from Flickr and Instagram, in addition to images retrieved from iDAI.objects, into the demo application described above.

Both APIs offer extensive search endpoints that also allow filtering according to geographical and temporal criteria. In this way we were able to develop interface components that enable users to select geographical areas and time frames, and compare different conditions of the same geographical area as photographed by different people at different times. This approach yielded results of varying relevance. Good results can be seen for popular sites that feature immovable artefacts such as buildings or ruins, for example Palmyra and the citadel of Aleppo. Data for many locations seemed to be very sparse, however, probably due to the fact that many relevant images accessible through the open APIs lacked even basic metadata such as the location and creation dates. Another striking drawback that became obvious in these case studies was the lack of any standardized description of content. Without semantic annotation there were no feasible criteria to filter out pictures with no archaeological relevance, which is a problem especially in urban areas where pictures of everyday social life tend to make up the majority of images in general purpose databases.

4 Conclusion

In the development of the application for the integration of the various data sources of the Syrian Heritage Project we purposely followed a pragmatic approach. In contrast to other important academic work on the integration of archaeological data with the help of Semantic Web technologies (cf. May *et al.* 2011), which focus on the creation and mapping of shared terminology and ontology, our main goal was to deliver an application geared towards non-technical end-users who do not have the means to map and convert existing data structures extensively.

It turns out that using a combination of open APIs and linked data principles for connecting heterogeneous sources, we were able to fulfill the goal of creating an application that offers added value to researchers by making different sources comparable in a common interface. This was mainly possible through the extensive use of standardized geospatial data, making use of OGC interface standards and linked data gazetteers, which offered a natural common ground for all data gathered in the project.

This shows that the development of linked data gazetteers, such as Geonames, Pleiades, or the iDAI.gazetteer, is beginning to bear fruit. The use cases also show the shortcomings of data currently available on the web, however, and that the community still lacks similar services for standardized temporal and descriptive concepts. As such, initiatives and supportive tools are already under way (see PeriodO 2015) and we are confident that the linked data approach will gain momentum. We hope that more applications showing the potential of open and linked data will emerge as these play an essential role in bringing forward the vision of a web of data.

Bibliography

Bizer, C., Heath, T., Berners-Lee, T. 2009. Linked Data - The Story So Far. *International Journal on Semantic Web and Information Systems* 5, 3: 1–22.

DAI. 2015.Die digitale Welt am DAI. iDAI.welt. [Online] Available at: http://www.dainst.org/forschung/forschung-digital/idai.welt. [Accessed: 08th july 2015].

Fless, F. 2014. Forschung und Ausbildung als Internationale Aufgabe. Archäologie Weltweit. Sonderausgabe 1_2014.

Gaube, H., Wirth, E. 1984. Aleppo: historische und geographische Beiträge zur baulichen Gestaltung, zur sozialen Organisation und zur wirtschaftlichen Dynamik einer vorderasiatischen Fernhandelsmetropole. Beihefte zum Tübinger Atlas des Vorderen Orients. Geisteswissenschaften. 58.

GEONODE (2015) Open Source Geospatial Content Management System [Online] Available at: http://geonode.org/ [Accessed: 08th July 2015].

GEONAMES (2015) Geonames [Online] Available at: http://www.geonames.org [Accessed: 08th july 2015].

Isaksen, L., Simon, R., Barker, E., De Soto Canamares, P. 2014. Pelagios and the Emerging Graph of Ancient World Data. In Fussell, L., Lutters,W. 2014 (eds.), *WebSci '14. Proceedings of the 2014 ACM Conference on Web Science*: 197-201. New York, ACM.

Perini, S. and Cunliffe, E. 2014. Towards a protection of the Syrian cultural heritage: A summary of the international responses Volume II [Online].Available at: http://www.heritageforpeace.org/wp-content/uploads/2014/10/Towards-a-protection-of-the-Syrian-cultural-heritage_Oct-2014.pdf [Accessed: 08th july 2015].

PERIODO (2015) PeriodO [Online] Available at: http://perio.do/ [Accessed: 08th july 2015]

PLEIADES (2015) Pleiades [Online] Available at: http://www.pleiades.org [Accessed: 08th july 2015]

PROPYLAEUM SEARCH (2015) Propylaeum Search [Online] Available at: https://www.propylaeum.de/metaopac/ [Accessed: 08th july 2015]

OGC. (2015) OGC Standards and supporting documents. [Online] Available at: http://www.opengeospatial.org/standards. [Accessed: 08th july 2015]

UNESCO. (2015) Ancient City of Aleppo. [Online] Available at: http://whc.unesco.org/en/list/21 [Accessed: 08th july 2015]

UNITAR. (2015) CHS-Syria. [Online] Available at: http://www.unitar.org/unosat/chs-syria [Accessed: 08th july 2015]

May, K., Binding, C., Tudhope, D., Jeffrey, S. 2011. Semantic Technologies Enhancing Links and Linked Data for Archaeological Resources. In Mingquan, Z., Romanowska, I., Zhongke, W., Pengfei, X., Verhagen, P. (eds.), *Revive the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 39th International Conference, Beijing, April 12-16*: 261-72.Amsterdam, Pallas Publication.

The Labelling System: A Bottom-up Approach for Enriched Vocabularies in the Humanities

Florian Thiery
florian.thiery@hs-mainz.de

Thomas Engel
thomas.engel@hs-mainz.de

i3mainz – Institute for Spatial Information and Surveying Technology, Mainz, Germany

Abstract: Shared thesauri of concepts are increasingly used in the process of data modelling and annotating resources in the Semantic Web. This growing family of linked data resources follows a top-down principle. In contrast, the Labelling System follows a bottom-up approach, enabling scientists working in the digital humanities to manage, create, and publish their own controlled vocabularies in SKOS (Simple Knowledge Organization System). The created concepts can then be interlinked with well-known LOD (Linked Open Data) resources, a process named the 'Labelling Approach'. The Labelling System is domain-independent, while uniting perspectives of different scientific disciplines on the same label and therefore contributing to interdisciplinary collaboration for building up cross- and inter-domain linked data communities. This paper addresses principles of the Labelling System in the light of archaeological use cases.

*Keywords: Con*trolled vocabulary, ontology, Semantic Web, Linked Open Data, SKOS

Introduction

Recently, the humanities have been aiming to interlink their areas of knowledge within the Semantic Web. This necessarily involves the implementation of a controlled and standardized vocabulary, to solve the well-known problem of ambiguity of terms like 'Roma', which may apply to the antique capital of the Roman Empire as well as to a European ethnic group. Obviously, the meaning of a term is revealed through its context. Particularly for working in cross-domain environments, a common understanding of terms is essential for collaboration, joint analysis, and data exchange.

Some institutions already provide authoritative thesauri as LOD (Berners-Lee 2009). Their hierarchically ordered terms appear very much like long-established vocabularies of natural sciences. But does this top-down approach meet the demands of the discursive character of the humanities? And if not, how can we enable humanists to build up their own vocabulary and make it accessible, transparent, quotable, and reusable?

This paper proposes solutions to overcome the vocabulary bottleneck using the Labelling Approach.

1.1 Controlled vocabularies: standards and implementations

The development of cultural and historical concepts requires the abstraction of historical realities in tags or classified items. A collection of project-specific terms are called controlled vocabularies. Such a vocabulary can be defined as a managed set of terms in one or more languages designed for a particular purpose. This is incorporated in multiple standards like ISO 25964 as well as the W3C standardized SKOS (Miles and Bechhofer 2009). SKOS is a data model for knowledge organization systems like thesauri to represent them in RDF, the Resource Description Framework (Klyne *et al.* 2014), the technical basis of the Semantic Web (Eckert 2011).

Designed as general-purpose tools, there are some applications for creating, editing, and sharing SKOS vocabularies like TemaTres (TemaTres 2015), OpenSKOS (Picturae 2013), VocBench (Food and Agriculture Organization of the United Nation, n.d.), and CultuurLINK (CultuurLINK, n.d.). From a technical point of view, they do not provide the usability required for humanist domains. Existing systems present a high barrier in terms of conceptual knowledge in Linked Data techniques. Furthermore, they do not provide simple collaboration features to strengthen the scientific discourse during the creation process. Hence, a different approach is necessary.

1.2 Reference thesauri in the Semantic Web

Today, a growing number of controlled vocabularies in machine-readable formats are available. Most of them are part of the Semantic Web and accessible in open standardized formats, particularly modelled in RDF as LOD. Pioneers in this field are the natural sciences, especially biomedical sciences (Momtchev *et al.* 2009). Research in the humanities is project-specific and terms are often a subject of scientific discourse, but some organizations, such as SKOS thesauri, are starting to model their knowledge for special disciplines. In this context we refer to LOD vocabulary examples of the Getty Research Institute (Getty Research Institute 2015) as well as Historic England (Heritage Data 2015).

1.3 From keyword lists to enriched thesauri: the term 'Roma' as an example

The development of a controlled vocabulary can be divided into three crucial steps: analysis, construction, and maintenance. While building up a set of terms and their relations, an 'evolutionary process' is set into motion: starting from a 'naive term' as a keyword, evolving to a meaningful 'intelligent term' formed by descriptions via strings or links in the web.

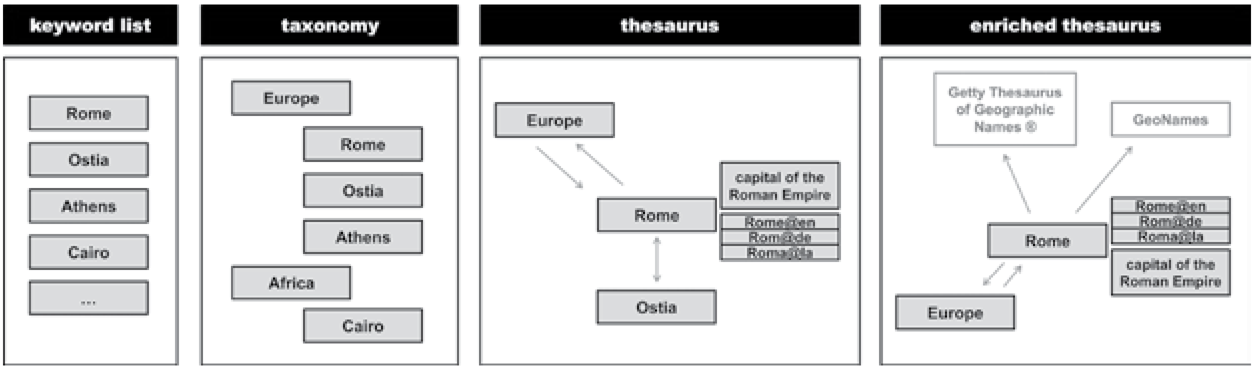

Fig. 1. Evolutionary process using the term 'Rome'.

Figure 1 shows the development of a thesaurus containing central cities in the Roman Empire. First, 'naive' terms are collected in a keyword list. Second, these terms are organized in a hierarchy (taxonomy), for example according to geographical regions. Third, multilingual concepts containing labels are created and organized relationally and can therefore be used for indexing and searching (thesaurus). Finally, these thesauri concepts are linked to reference thesauri in the worldwide (semantic) web. These 'intelligent terms' organized in enriched thesauri can be understood and classified by scientists of any discipline because of their linkage to globally defined concepts. As an example, the term 'Roma' can be linked to authoritative thesauri like GeoNames (Geonames, n.d.) or the Getty Thesaurus of Geographic Names (TGN 2013) defining an administrative unit instead of an ethnic group.

1.4 Bottom-up approach

Within humanities research it is impossible to define controlled vocabularies that cover all conceivable applications and are generally accepted. Therefore, a top-down approach developing authoritative reference thesauri as described in section 1.3 can be just part of the solution. So how can the problem of broad rather than project-specific thesauri be solved? Building up self-defined terms linked to reference thesauri can be a way out of this bottleneck. This is why we propose the bottom-up 'Labelling Approach' (Section 2).

Take as an example the term 'potter': in a particular research question, such as the distribution of trade networks of Samian Ware, a 'potter' can be defined as a human being or organization that lived in the Roman Empire and was responsible for producing Samian Ware. The Getty AAT term 'potters' describes them as makers of vessels, tableware, vases, and other ware made of ceramic (Jean Paul Getty Trust 2004). A link to that term cannot cover all definitions for a 'Samian Potter'. This can be solved using the bottom-up approach explained in the following sections.

2 Labelling Approach

The 'Labelling Approach' is based on the idea that each vocabulary term, built for a specific application, is defined by linking to one or more concepts in a reference thesaurus, available as an HTTP-URI (Berners-Lee *et al.* 2005) (Fig. 1). A label can be understood as a vocabulary term, represented by a particular set of concepts. The approach is generic and can be applied to any scientific domain. It is motivated by the fact that vocabulary construction and semantically defining terms is hard for domain experts and even harder in a research context, where the vocabulary is part of the research process (Piotrowski *et al.* 2014).

Labels created through the Labelling Approach are specified as concepts within the SKOS ontology, providing the flexibility to structure concepts relationally and multilingually. It provides a set of methods and ideas for designing a controlled vocabulary, helping researchers to communicate internally, as well as between disciplines using LOD (Section 4). The Labelling Approach contains the following steps:

1. Creation of detailed concepts for individual research questions: each specific research topic has its own list of concepts with an individual meaning. Concepts in authoritative reference thesauri are often broad and generic. Individual concepts, however, are assigned according to their position within the reference thesauri hierarchy. Defining a relation to an existing concept permits integration of personal labels within the Semantic Web (Section 4.1).

2. Enrichment of concepts by linking into a hierarchy of a domain expert's reference thesaurus — adoption of an expert's knowledge and hierarchical structures and relations for a label (Section 4.2 and Figure 2).

3. Defining a label to add specifications of different domains: the process of interlinking vocabulary terms to different concepts helps the user to clarify the reasoning and the layer of knowledge the label is representing (Section 4.3).

4. Linking generic tags to specific contexts: one term can have different meanings. They are specified using diverse reference concepts (Section 4.3).

3 Labelling System

The current web-based prototype (i3mainz, n.d.) of the Labelling System, implementing the Labelling Approach, is freely available under an MIT licence (i3mainz 2015). The Labelling System uses open source technologies (Section 3.1) and common LOD standards (Section 3.2). Its main purpose is to enable users to create thesauri without any knowledge

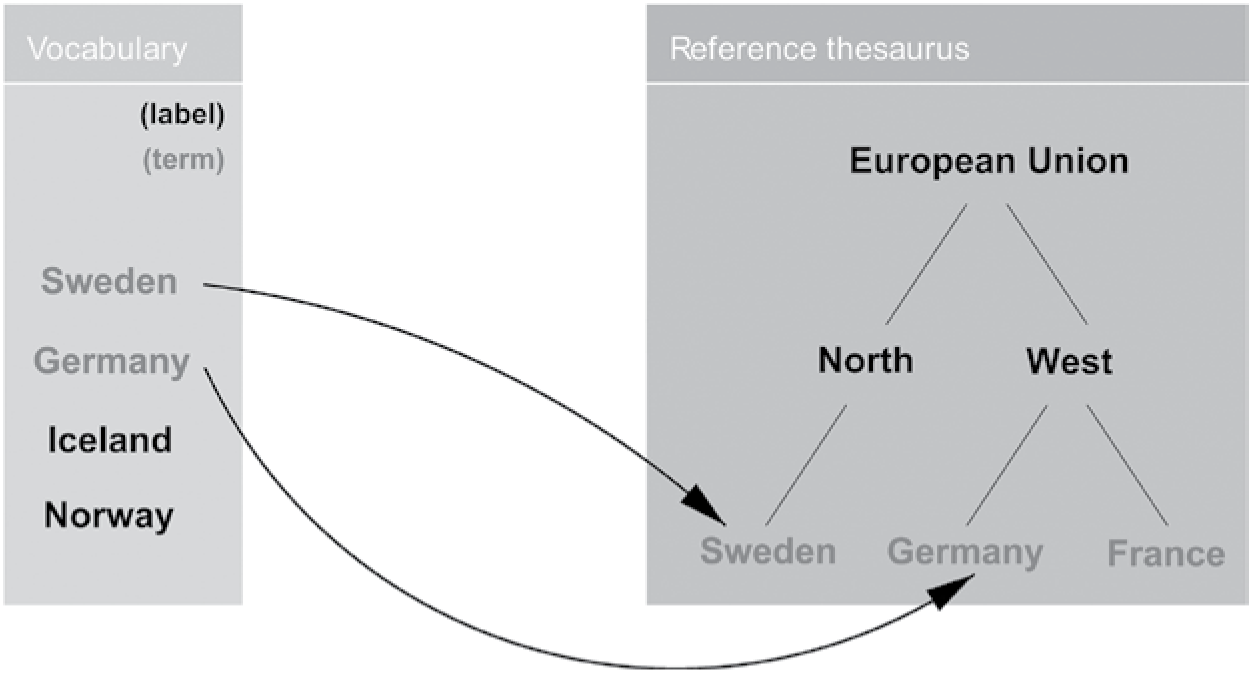

FIG. 2. LABELLING APPROACH.

of SKOS, RDF, or ontologies. Collaboration projects in vocabulary term creation are also explicitly encouraged.

To summarize, the Labelling System is a web-based tool:

- for creating controlled vocabularies;
- for building internal vocabulary term relations;
- for enriching vocabulary terms and semantically modelling their relationships to external concepts belonging to thesauri (=labelling);
- for publishing and sharing vocabularies as quotable URI.

Within the Labelling System, several user roles are defined. The permissions are structured hierarchically: higher-level roles subsume the permissions of lower-level roles. Agents are permitted to query the system for available content via the Semantic Web interfaces (Section 3.4). Users are able to create enriched controlled vocabularies. In addition, ontologists are allowed to import, for example, reference thesauri by storing the URI for a SPARQL endpoint.

All steps of the evolutionary process from a simple keyword list to enriched thesauri, described in section 1.3, can be handled within the Labelling System. Building up enriched thesauri using the Labelling Approach is as easy as the creation of a 'simple' keyword list (Figure 3).

The Labelling System is not designed to be a centralized service. In contrast, using an open-source approach, it enables creating instances in different infrastructures, producing customized URIs as a consequence.

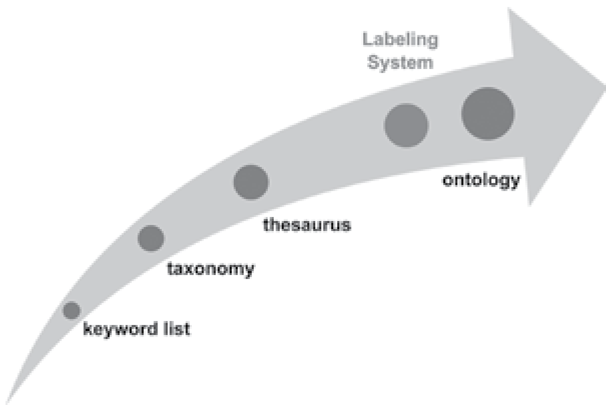

FIG. 3. LOCATION OF THE LABELLING SYSTEM WITHIN THE EVOLUTIONARY PROCESS.

3.1 Technology

The prototype is built on top of two open-source frameworks using Java, Maven, PHP, and MySQL: OpenRDF Sesame triplestore (Brockstra 2002) and Usercake management system (Usercake 2012). The current client-server application is running on Linux distributions, using Apache HTTP Server as well as Apache Tomcat. The prototypical graphical user interface (Labelling System, n.d.) is based on HTML5, CSS3, and JavaScript.

OpenRDF Sesame is an open source Java framework for processing RDF data. It offers an API that can be handled in Java servlets including libraries for managing RDF data like Apache Jena. As a consequence, all data and resources produced by the Labelling System and their inner relations are stored in an RDF ontology (Section 3.2) and are therefore queryable through the triplestore.

In contrast, UserCake uses a relational database (MySQL). It controls the administration of users and their specific roles and is extendable for LDAP based authentication.

Using technologies like HTML5, CSS3, and JavaScript enables the presentation of complex structures in a user-friendly and familiar layout. JavaScript libraries like jQuery and D3.js support displaying complex semantic data structures.

3.2 Ontologies

The Labelling System aims for scalability and strict conformity with common standards. This implies the usage of standardized Linked Data models, in particular SKOS and Dublin Core (Dublin Core 2012), as well as FOAF (Brickley and Miller 2014) and RDF-Schema (Brickley and Guha 2014).

A well-defined list of terms developed by the Dublin Core Metadata Initiative (DCMI), the 'DCMI Metadata Terms' or 'Element Set', is perfectly suited for describing metadata of Labelling System resources. In particular the properties dc:creator, dc:identifier, dc:date, dc:language, and dct:licence are used.

A SKOS vocabulary is based on concepts as units of thoughts. In the human mind concepts exist as an abstract entity. A SKOS concept is therefore used to represent items (terms, ideas, meanings, objects, or events) in a knowledge organization system. Furthermore, a SKOS concept scheme is similar to a vocabulary and a container for concepts. Labelling System vocabularies are stored as a skos:ConceptScheme. Labels as skos:Concept belong to a scheme. Each concept scheme is available as URI and is also downloadable. Conceptually, the product is comparable to big authoritative vocabularies of providers like the Getty Research Institute or Historic England.

As mentioned in section 3.1, all resources and instances of the Labelling System and their internal relations are structured in an RDF ontology (Thiery 2015a). Managing the inner structure requires a set of classes and properties defined in the 'Labelling System Vocabulary' (Thiery 2015b). The Labelling System is composed of five big classes: ls:Project, ls:Vocabulary, ls:Label, ls:SPARQLendpoint, and ls:GUI. A project is a container for a set of vocabularies. A vocabulary is a set of arbitrary terms and can be hidden or public (ls:state). A label is a vocabulary term linked to a particular set of published concepts characterized by a preference language (ls:prefLang) for visualization reasons. Each connection is created via a bidirectional ls:contains and ls:belongsTo property. Each SPARQL endpoint imported by an ontologist is stored with its properties, such as name, query, and SPARQL endpoint URL. Users are able to store personal metadata to emphasize the individual research question of their own projects, vocabularies, and labels. Properties defining individual user-GUIs exist but are not used in the current prototype. Labelling System classes are identified by HTTP addressable URIs (ls:identifier) based on the Universally Unique Identifiers (UUID) (Leach *et al.* 2005).

3.3 Labelling process

A label is independent and primarily identified with an UUID, quotable via an URI. It may belong to one or more vocabularies and projects. All these components are loosely coupled. In addition, labels provide a mandatory multilingual human-readable appellation (rdfs:label or skos:prefLabel) which represents a typical term in a controlled vocabulary. Alternative multilingual appellations (skos:altLabel) and documentation terms like notes (skos:note) and definitions (skos:definition) are optional and can be used to describe a label in free texts. Each vocabulary including labels is published under a Creative Commons Attribution (CC-BY) licence. The relations between concepts are not bidirectional and only reflect the author's personal view of his concepts. In the modelling process, legal rights of thesauri providers have to be respected. Currently, no 'code of ethics' for creating vocabularies exists. However, the Labelling System should not be used to create copies of existing thesauri to circumvent legal aspects.

The 'Labelling System Ontology' provides a well-defined canon of semantic predicates, which can be used to link a vocabulary term to an external SKOS concept or web resource as well as to generate internal relations. Applying the Labelling Approach, links to concepts of reference thesauri, or simple HTTP web resources, eight RDF properties come into play (Figure 4). SKOS supports hierarchical, associative, and mapping relationships.

For building up hierarchical relations in a vocabulary, skos:broader and skos:narrower are used. The broader and narrower terms are not transitive, but are bidirectional connected within the Labelling System Ontology. In contrast, the associative related property (skos:related) implies an unidirectional relationship. By convention, the SKOS mapping properties are expected to be asserted between concepts that belong to different concept schemes. The relationships skos:closeMatch and skos:exactMatch represent concept mappings. The skos:closeMatch term indicates that two concepts are sufficiently similar and that they may be used interchangeably in some contexts. Skos:exactMatch denotes a higher degree of similarity. Both concepts have the same meaning in all contexts. The mapping properties skos:broadMatch, skos:narrowMatch, and skos:relatedMatch are equivalent to skos:broader, skos:narrower, and skos:related but refer to concepts belonging to different concept schemes (Miles and Bechhofer 2009).

Linking to other web resources that are not modelled as SKOS concepts can be realized using the rdfs:seeAlso, rdfs:isDefinedBy, and owl:sameAs properties.

For linking resources, the following best practices for RDF properties are as follows:

- broader/broadMatch: My label A has a broader Label/Concept B;
- narrower/narrowMatch: My label A has a narrower Label/Concept B;
- related/relatedMatch/seeAlso: My label A is related in some way to Label/Concept/Resource B;
- closeMatch/isDefinedBy: My label A is similar to Concept/Resource B;
- exactMatch/sameAs: My label A is the same as Concept/Resource B.

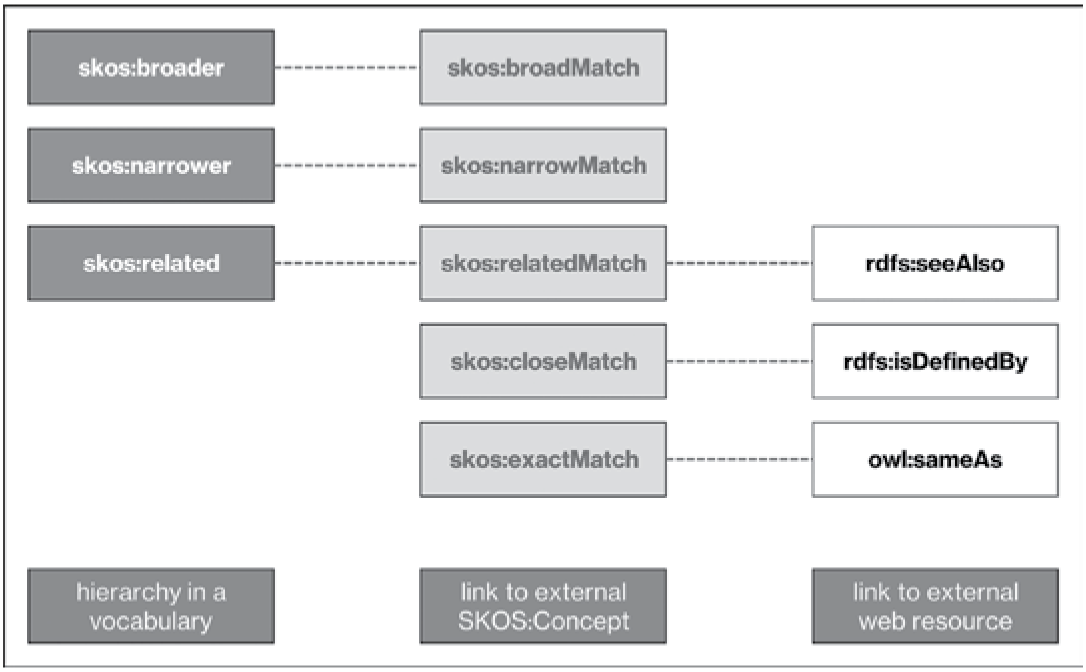

Fig. 4. Labelling System predicate canon.

The labelling process will be supported by a user-friendly GUI in the release version. Integrated SPARQL endpoints of reference thesauri providers allow searching for the existence of a particular substring in the set of concepts, and returns the resource. Uploaded SKOS concept schemes can be queried the same way. Finally, a manual entry of resource URIs provides access to the world of digital encyclopaedias (e.g. DBpedia) or gazetteers such as GeoNames or Pleiades.

The single steps of the labelling process can be combined in a semi-automatic procedure. First, appellations, descriptions, and links are placed into a CSV-file and uploaded to the server. Then the Labelling System server application validates all labels and their relations and converts them into triples aligned to the ontology. This possibility is designed for humanists who keep their data mostly in tables and do not want to change their usual methodology for the process of building enriched controlled vocabularies.

3.4 Semantic Web interfaces

The Labelling System offers two major Semantic Web interfaces for all resources and relations created in the labelling process: the REST-API (Thiery 2015c) and the SPARQL-API (Thiery 2015d).

All data and properties are stored in a well-defined RDF ontology. The SPARQL-API enables querying every resource individually with its relations and literals of triples using SPARQL (W3C 2013). Any user can access the SPARQL endpoint and include it into their own application via HTTP requests. Humanists can use a graphical.

The REST-API gives access to the Labelling System resources through an XML browsable interface. Each resource can be fetched with HTTP-GET and will be represented in well-defined and standardized linked data formats such as RDF, TTL, N3, and JSON-LD. It is also possible to download a dump of a skos:ConceptScheme. This dump could be used in other software frameworks using SKOS modelled thesauri, for example the Arches RDM (Getty Conservation Institute and World Monuments Fund 2015).

In contrast to the SPARQL endpoint, in the REST view (Richardson 2007), a label is only reachable via a particular concept scheme. Thus, a label implies a special use case.

4 Use cases in the humanities

The use of terms within the humanities can be a source of ambiguities in many ways. As stated in section 3.2, knowledge in archaeological domains is often based on the creation of theoretical concepts. Not only classic areas of ambiguities such as time concepts, space, place, or place types are the results of this process. The use of typology classifications for archaeological artefacts can also be misleading, as the meaning of concept terms may vary through time, within different regions and between authors and/or schools. Furthermore, modern archaeology as an interdisciplinary science incorporates several natural sciences as well as humanities domains. Those external domains have already defined generic vocabularies and corresponding data in many cases, creating useful authoritative resources to link to. Self-created thesauri are naturally more detailed than authoritative ones, which is reflected in very few skos:narrowMatch relations in contrast to skos:broadMatch or skos:relatedMatch. This can be different in other disciplines (Piotrowski *et al.* 2014). Creating new, more granular vocabularies located within the Semantic Web, humanists are able to publish a quotable thesaurus in the same way that text or data is published.

The following four examples have been identified as prototypical archaeological use cases.

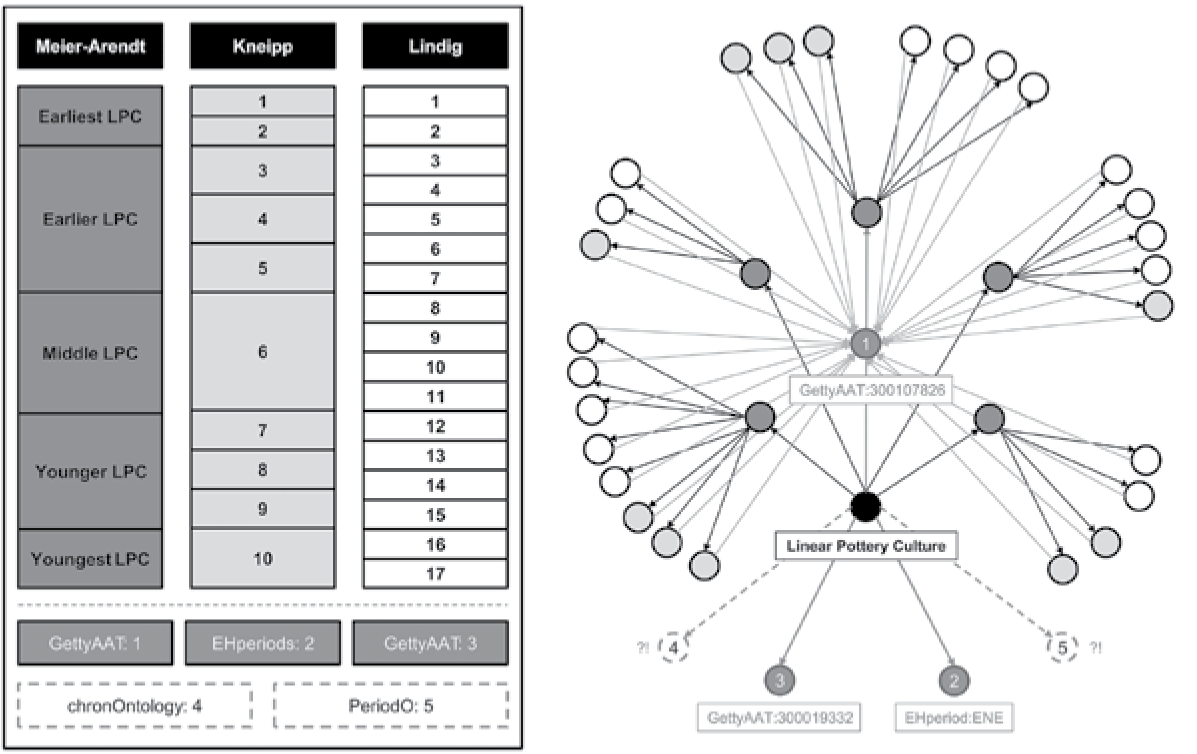

Fig. 5. Use case time concepts.

4.1 Creating concepts for individual research questions

As a key component of archaeological research, the conceptualization of time changes frequently. The same term describing a temporal phase can be used to express different ideas of it. Until now, a researcher's exact understanding of a time concept is often undefined. A researcher using temporal concepts today is able to use the Labelling System to define them by adding a relation to authoritative vocabularies and add useful metadata in order to make his/her research comprehensible. Authoritative vocabularies provide generic representations of knowledge resulting in their granularity not being sufficient for certain research questions.

Starting the conceptualization, a label is created that ideally includes all of the temporal concepts concerned and is linkable to at least one external authoritative SKOS thesaurus. In this use-case, the label is named 'Linear Pottery Culture'. Following on, for each temporal system within the linear pottery culture (Meier-Arendt 1966; Kneipp 1998; Lindig 2002) a new label is created, starting with the least granular one. This enables the researcher to build up a graph of phases that reflects the hierarchy of concepts.

Every created label gets a quotable UUID available as URI. The whole enriched thesaurus is available online and downloadable as a SKOS concept scheme. In the next step, all created concepts can be linked to external resources/thesauri using the proper relation (Figure 5; Section 3.3). In the near future, LOD gazetteers for temporal concepts will be delivered by projects like chronOntology (DFG 2015) and PeriodO (PeriodO n.d.). The latter will also offer a service to create definitions of a temporal concept. Providing a more generic approach, the Labelling System covers all domains. Consequently, scientists must decide where the creation of temporal concepts would be reasonable.

It is possible to create detailed temporal concepts sufficient for individual research questions. Furthermore, relations can be interlinked to existing temporal concepts like Getty AAT or Historic England. The relations between phases only include hierarchical and associative structures, so they are limited to skos:related, skos:narrower, and skos:broader relations. Relative chronological relationships like 'during' or 'starts with' (see Freksa 1992) cannot be implemented as they are not within the scope of the Labelling System project.

4.2 Enriching concepts by linking into hierarchies of reference thesauri

Self-created concepts concerning external scientific domains are normally not aligned to thesauri created by relevant domain experts. As an example of a natural sciences vocabulary that can be enriched by considering authoritative concepts, bones of a human skeleton were conceptualized.

After the creation of hierarchically aligned concepts for a human skeleton, these concepts are interlinked to authoritative thesauri. In this example, the concepts with the appellations 'Ulna' and 'Radius' have a skos:narrower relation to a higher-level concept 'Human Skeleton'. Furthermore, they are skos:related to each other to point out that they are both forearm bones.

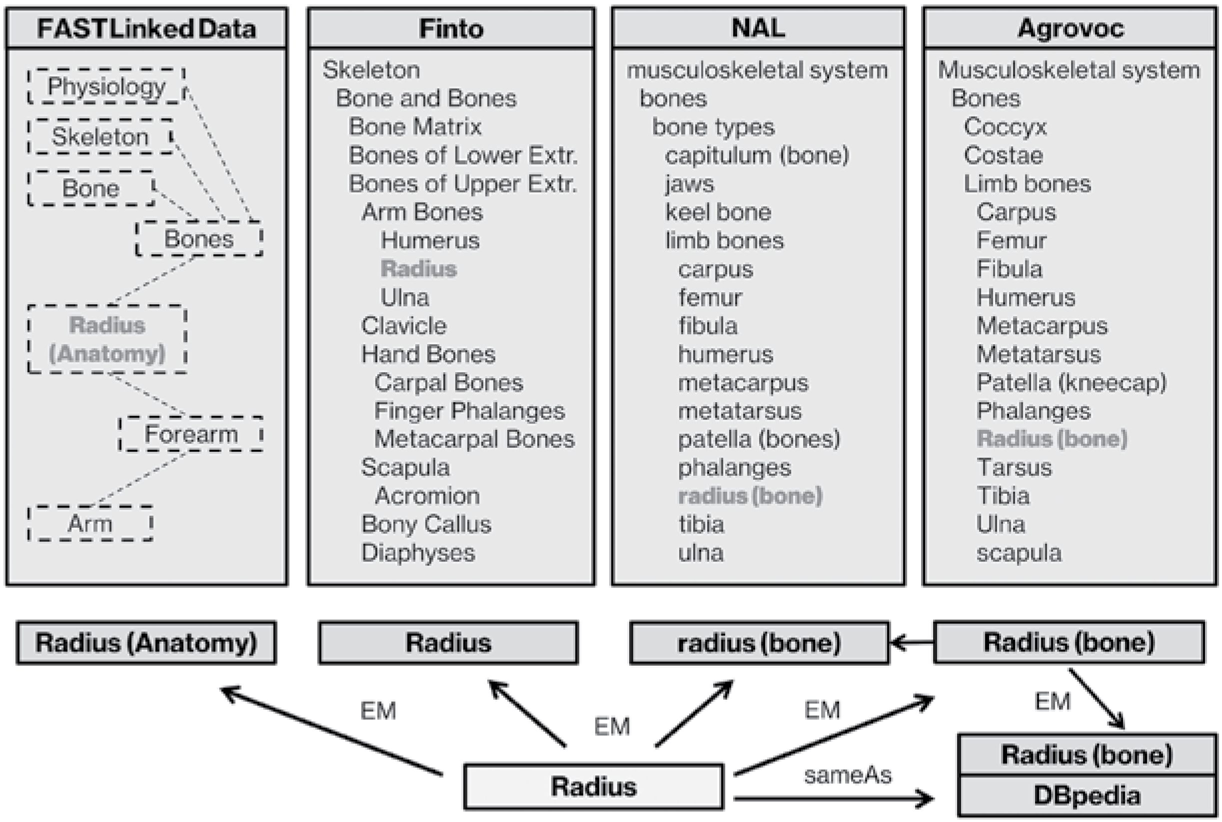

Fig. 6. Use case radius bone.

In a second step, external vocabularies are identified providing different concepts of bones in the human body. These were conceptualized for certain reasons, a fact that has to be considered before defining relations. Moreover, the concept must be inspected closely to identify its alignment to other interlinked vocabularies (Figure 6). If a concept expresses exactly the same as the example's 'Radius' concept a skos:exactMatch relation is necessary. Otherwise, choosing skos:closeMatch or skos:relatedMatch might be more reasonable.

By linking into vocabulary hierarchies of domain experts, the value of self-created concepts will be increased. Adopting expert knowledge, especially the structure relations, ensures a higher level of standardization. Furthermore, authoritative vocabularies are interlinked via self-created thesauri and are therefore loosely coupled. This can be seen as an alignment between existing vocabularies originating from different domains.

4.3 Defining concepts by adding properties from different domains

Appellations of place types or functions can describe different things in space, time, or culture. Generic tags for specific meanings lead to ambiguities that are difficult to resolve if their context is not transferred. There are different layers of knowledge, e.g. historical agents, socio-political contexts, or historians' interpretations. Depending on the used sources, an appellation can cover a variety of meanings.

To show the ambiguity a place type appellation can adopt, the place type 'earthwork' is created twice. As the concept names are usually associated with different things, it is crucial to define their meaning further (Figure 7). In this example, the first concept 'earthwork' is defined as a dwelling, has an agricultural aspect, and dates to the early Neolithic period. The second concept 'earthwork' is a dwelling with a shelter function used for defensive purposes. The functions defining the concept can also be related to authoritative vocabularies so that no ambiguities are generated on this second level.

A researcher is able to add specifications of space, time or culture, or any additional attributes to concepts defining a term. By doing so, generic tags are linked to specific concepts. In this example, a concept 'place type' is defined by terms expressing its functional context. The process of interlinking vocabulary terms of concepts to a functional concept, which is interlinked itself, helps humanists to clarify the reasoning and layers of knowledge. In this way, a structured, well-defined vocabulary for place types can be created, expressing exactly what it was intended for.

4.4 Synthesis of labelling methods in the world of Samian Ware

As described in section 1.4, it is currently impossible to find an existing concept for a 'Samian Potter'. The Labelling Approach can correct things by defining temporal concepts and the function as a person or organization that is responsible for

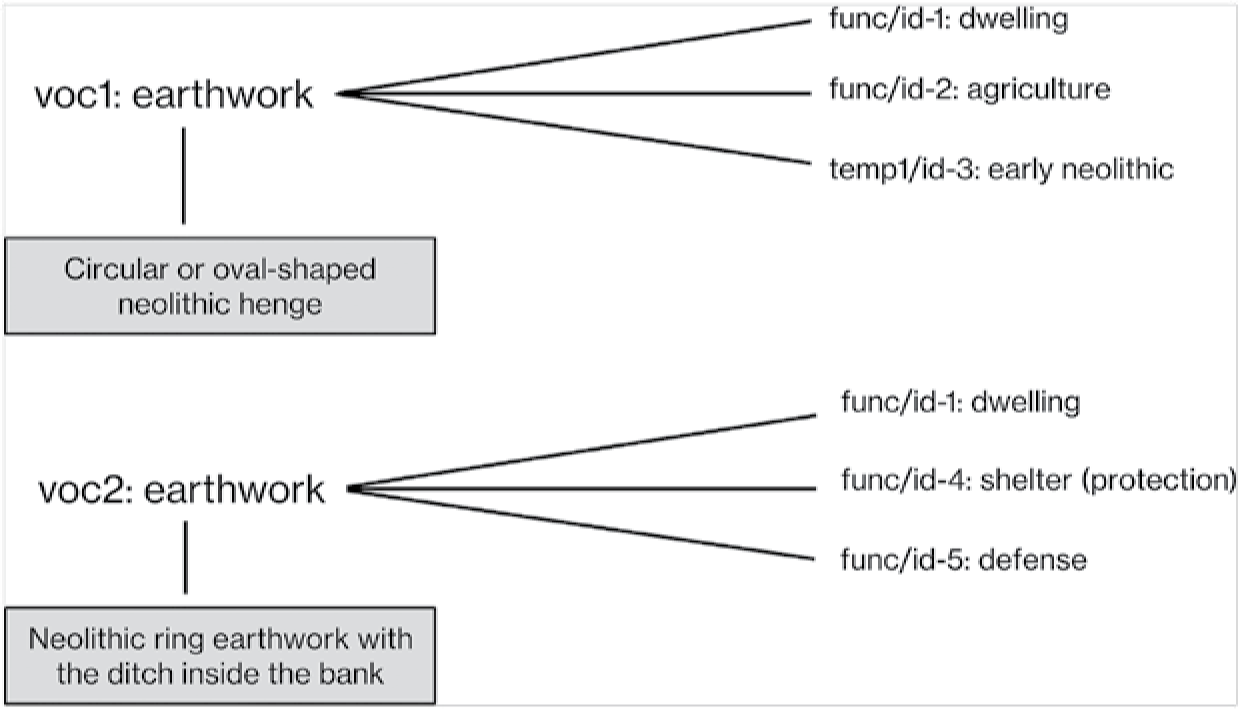

Fig. 7. Use case earthwork.

creating and trading Samian Ware. Links to Pelagios (Pelagios, n.d.) or Pleiades (Pleiades, n.d.) can locate the term ‘potter’ into the Linked Data Cloud as a synthesis of the mentioned use cases in the world of Samian Ware.

5 Remaining challenges

Using Linked Open Data and the Semantic Web to build up a network of concepts entails advantages, and also questions and challenges that are to be managed in the future to ensure the success of the Labelling Approach. The following issues have been identified so far:

1. It is hard to find reference thesauri that could be imported into the Labelling System. A definition for a catalogue service, which makes thesauri of all domains in the Semantic Web searchable, is not yet in sight. It might be a good idea to implement such a service in the cultural heritage domain as a prototype. A first concept is currently being discussed at i3mainz.

2. As a consequence of unidirectional relations between two vocabulary terms, it is not possible to find all resources in the Semantic Web linked to a single term. For example a label ‘Roma’ which is defined via unidirectional links (e.g. skos:relatedMatch) to Getty TGN and GeoNames does not inform the authoritative thesauri that the relation exists. A service analysing and displaying such relationships would identify the relevance of thesauri and their single terms through the number and provenance of links.

3. A major search engine in the LOD cloud, searching all interlinked repositories, is missing. It is usually possible to query one repository via a SPARQL endpoint and to follow the resulting links. Using gazetteers like Pleiades (AWMC, n.d.) and through multiple access points, the Pelagios Project (Pelagios, n.d.) works on basic approaches to connect repositories in the field of ancient places.

4. The open approach of the Labelling System entails the risk of building identical vocabularies (Section 3.3). This requires a proper Labelling Process as best practice: (a) to search for existing thesauri; (b) discuss them and as a consequence go through a mutual learning process; (c) adjust the individual approach.

6 Outlook

The Labelling System as the implementation of the Labelling Approach is still in a prototype phase. Use cases of various research areas will facilitate further development.

Currently, a user-friendly graphical user interface is still missing. Human-computer interaction in accordance to an intuitive GUI will help solve the major challenge of involving people outside the Semantic Web and Linked Data community in the labelling processes. Hence, the key goal for the release version is a ‘labelling framework’ for non-LOD experts.

For instance, the Labelling System may be used for the Arches Project (Arches 2012) and their Reference Data Manager, which is able to import SKOS thesauri. Being able to annotate point clouds via RDF triples in a web interface, the Generic Viewer (GenericViewer 2014) also supports SKOS. Furthermore, big databases placed in one organization, like TOMBA and NAVIS (RGZM, n.d.), could use Labelling System labels to interchange information on a meta-level.

Finally, humanists must be able to find and evaluate labels in the Semantic Web cloud independently. Exclusive ‘islands of knowledge', published, standardized, represented as Linked Open Data, and linked to reference thesauri is just the beginning. Although additional efforts are still necessary, the Labelling Approach provides a generic solution to eliminate the semantic bottleneck.

Bibliography

Arches (n.d.) *What is Arches?*. [Online] http://archesproject.org/what-is-arches. [Accessed: 11 november 2015].

AWMC (n.d.) *About Pleiades*. [Online] http://pleiades.stoa.org/home. [Accessed: 11 november 2015].

Berners-Lee, T. 2009. *Linked Data*. [Online] http://www.w3.org/DesignIssues/LinkedData.html. [Accessed: 11 november 2015].

Berners-Lee, T., Fielding, R., Masinter, L. 2005. *Uniform Resource Identifier (URI): Generic Syntax*. [Online] https://tools.ietf.org/html/rfc3986. [Accessed: 11 november 2015].

Brickley, D., Guha, R.V. 2014. *RDF Schema 1.1*. [Online] http://www.w3.org/TR/rdf-schema. [Accessed: 11 november 2015].

Brickley, D., Miller, L. 2014. *FOAF Vocabulary Specification 0.99*. [Online] http://xmlns.com/foaf/spec. [Accessed: 11 november 2015].

Broekstra J., Kampman A., van Harmelen, F. 2002. Sesame: A generic architecture for storing and querying RDF and RDF Schema. In: Horrocks, I., Hendler, J. (eds.), *The Semantic Web – ISWC 2002. First International Semantic Web Conference Sardinia, Italy, June 9–12, 2002 Proceedings*: 54-68. Berlin, Springer.

CultuurLINK (n.d.) *Connecting Cultural Heritage. Align your vocabulary with the Dutch cultural heritage hub*. [Online] http://cultuurlink.beeldengeluid.nl. [Accessed: 11 november 2015].

DFG 2015. *chronOntology: ein Zeit-Gazetteer für die historisch-kulturwissenschaftlichen Fächer*. [Online] http://gepris.dfg.de/gepris/projekt/247900032. [Accessed: 11 november 2015].

Dublin Core 2012. *Dublin Core Metadata Element Set*. [Online] http://dublincore.org/documents/dces. [Accessed: 11 november 2015].

Eckert, K. 2011. *SKOS: eine Sprache für die* Übertragung *von Thesauri ins Semantic Web*. [Online] http://www.metadaten-twr.org/2011/01/19/skos-simple-knowledge-organisation-system. [Accessed: 11 november 2015].

Freksa, C. 1992. Temporal reasoning based on semi-intervals. *Artificial Intelligence 54*. Available from: http://cindy.informatik.uni-bremen.de/cosy/staff/freksa/publications/TemReBaSeIn92.pdf. [Accessed: 11 november 2015].

Food and Agriculture Organization of the United Nation (n.d.) *VocBench 2.0*. [Online] http://vocbench.uniroma2.it. [Accessed: 11 november 2015].

GenericViewer (n.d.) *GenericViewer*. [Online] http://www.spatialhumanities.de/en/ibr/technology/genericviewer.html. [Accessed: 11 november 2015].

Geonames (n.d.) *About GeoNames*. [Online] http://www.geonames.org/about.html. [Accessed: 11 november 2015].

Getty Conservation Institute and World Monuments Fund 2015. *Reference Data Manager (RDM). Revision e418cca2de6a+*. [Online] http://arches3.readthedocs.org/en/latest/rdm. [Accessed: 11 november 2015].

Getty Research Institute 2015 *Getty Vocabularies as Linked Open Data*. [Online] http://www.getty.edu/research/tools/vocabularies/lod/index.html. [Accessed: 11 november 2015].

Heritage Data 2015. *Vocabularies*. [Online] http://www.heritagedata.org/blog/vocabularies-provided. [Accessed: 11 november 2015].

i3mainz (n.d.) *The Labelling System*. [Online] http://i3mainz.hs-mainz.de/en/projekte/Labellingsystem. [Accessed: 11th November 2015].

i3mainz 2015. *The Labelling System*. [Online] https://github.com/i3mainz/LabellingSystem. [Accessed: 11 november 2015].

Jean Paul Getty Trust 2004. *potters*. [Online] http://vocab.getty.edu/aat/300025414. [Accessed: 11 november 2015].

Klyne, G., Carroll, J.J., McBride, B. 2014. *RDF 1.1 Concepts and Abstract Syntax*. [Online] http://www.w3.org/TR/rdf11-concepts. [Accessed: 11 november 2015].

Kneipp, J. 1998. *Bandkeramik zwischen Rhein, Weser und Main.* Universitätsforschungen zur Prähistorischen Archäologie 47. Bonn, Habelt.

Labelling System (n.d.) *The Labelling System*. [Online] http://Labelling.i3mainz.hs-mainz.de/client. [Accessed: 11 november 2015].

Leach, P. J., Mealling, M., and Salz, R. 2005. *A Universally Unique Identifier (UUID) URN Namespace*. RFC 4122, 2005. [Online] http://www.ietf.org/rfc/rfc4122. [Accessed: 11 november 2015].

Lindig, S. 2002. *Das Früh- und Mittelneolithikum im Neckarmündungsgebiet.* Universitätsforschungen zur Prähistorischen Archäologie 85. Bonn, Habelt.

Meier-Arendt, W. 1966. *Die bandkeramische Kultur im Untermaingebiet*. Veröffentlichungen des Amtes für Bodendenkmalpflege im Regierungsbezirk Darmstadt, Band 3. Bonn, Habelt.

Miles, A., Bechhofer, S. 2009. *SKOS Simple Knowledge Organization System Reference*. W3C Recommendation, World Wide Web Consortium. [Online] http://www.w3.org/TR/skos-reference. [Accessed: 11 november 2015].

Momtchev V., Peychev D., Primov, T. and Georgiev G. 2009. *Expanding the Pathway and Interaction Knowledge in Linked Life Data*. Proceedings of International Semantic Web Challenge, 2009. Available from: http://challenge.semanticweb.org/documents/Linked%20Life%20Data-LLD%20semantic%20web%20challenge%202009.pdf. [Accessed: 11 november 2015].

Pelagios (n.d.) *About*. [Online] http://pelagios-project.blogspot.de/p/about-pelagios.html. [Accessed: 11 november 2015].

PeriodO (n.d.). *PeriodO*. [Online] http://perio.do/narrative. [Accessed: 11 november 2015].

Picturae 2013. *OpenSKOS: Simple Knowledge Organization System Repository*. [Online] http://openskos.org. [Accessed: 11 november 2015].

Piotrowski, M., Colavizza, G., Thiery, F. and Bruhn, K.-C. 2014. The Labelling System: A New Approach to Overcome the Vocabulary Bottleneck, in: *DH-CASE II: Collaborative Annotations on Shared Environments: Metadata, Tools and Techniques in the Digital Humanities*: 1–6. New York, ACM.

Pleiades (n.d.). *Pleiades*. [Online] http://pleiades.stoa.org. [Accessed: 29 june 2015].

RGZM (n.d.). *RGZM: Online Databases*. [Online] http://web.rgzm.de/en/research/onlinedatabases.html. [Accessed: 11 november 2015].

Richardson, L., Roby, L. 2007. *RESTful Webservices. Web services for the real world*. Sebastopol, O'Reilly Media.

TemaTres 2015. *TemaTres*. [Online] http://www.vocabularyserver.com. [Accessed: 11 november 2015].

TGN 2011. *Getty Thesaurus of Geographic Names*. [Online] http://getty.edu/research/tools/vocabularies/guidelines#tgn. [Accessed: 11 november 2015].

Thiery, F. 2015a. *Labelling System Ontology. Copeman Edition*. [Online] http://Labelling.i3mainz.hs-mainz.de/ontology. [Accessed: 11 november 2015].

Thiery, F. 2015b. *Labelling System Vocabulary. Edison Edition*. [Online] http://Labelling.i3mainz.hs-mainz.de/vocab. [Accessed: 11 november 2015].

Thiery, F. 2015c. *Labelling System REST-API. Archway Edition.* [Online] http://Labelling.i3mainz.hs-mainz.de/rest-api. [Accessed: 11 november 2015].

Thiery, F. 2015d. *Labelling System SPARQL-API. Aldgate Edition.* [Online] http://Labelling.i3mainz.hs-mainz.de/sparql-api. [Accessed: 11 november 2015].

Usercake 2012. *Home*. [Online] http://usercake.com/index.php. [Accessed: 11 november 2015].

W3C 2013. *SPARQL 1.1 Overview*. [Online] http://www.w3.org/TR/sparql11-overview. [Accessed: 11 november 2015].

Providing 3D Content to Europeana

Andrea D'Andrea

Centro Interdipartimentale di Servizi di Archeologia, Università degli Studi di Napoli L'Orientale

Abstract: As the general public is becoming increasingly familiar with 3D content, the challenge of 3DICONS was to provide high-quality 3D cultural heritage content to Europeana, in particular the project dealing with the use of existing tools and methods to integrate them in a complete supply chain of 3D digitization and contribute a significant mass of 3D content. 3DICONS digitized a series of architectural and archaeological masterpieces of worldwide and European cultural significance and provided 3D models and related digital content to Europeana, with the objective of contributing to the critical mass of highly engaging content available to users.

Keywords: Europeana, 3D models, metadata, provenance, paradata

Introduction

From 2012 to 2015 the European Project 3DICONS focused on providing 3000 metadata, concerning 5000 3D models and related content, to the digital library Europeana.[1]

The 3D models range from large and complex architecture and archaeological monuments to small findings giving a broad impression of the potentiality of the 3D data capture, processing, and visualization. Through 3D models the general public can visit sites that may be in remote locations, fragile, and in some cases difficult to understand.

3DICONS contributed to the expansion of 3D models into Europeana, offering enhanced experiences for its users by bringing exciting and engaging content for archaeological monuments and historic buildings. The availability within Europeana of 3D models of architecture or archaeological monuments shows that best practices and guidelines are useful for the new initiative and 3D data collections.[2]

The project produced many reports on the 3D data-acquisition, 3D data-processing, and 3D data visualization; a large number of case studies have been presented in the guidelines report. All these contributions are downloadable for free from the project's website. They represent an updated technical pipeline of the 3D model creation, with the addition of rich metadata describing the real object and its digital replica. Mainly in terms of metadata, the project has provided an innovative schema including information about provenance and paradata in order to keep track of the complete digitization process.

The broad context of the 3DICONS was the 2020 strategy for Europe and the Digital Agenda for a flourishing digital economy, and the standards and increased inter-operability needed to support Europeana as a multilingual common access point to millions of objects for all European citizens. Europeana provides access to more than 14 million books, maps, recordings, photographs, archival documents, paintings, and films from 1500 cultural institutions across Europe. This content is beginning to illustrate the potential for Europeana to be used in schools and other services. Yet there is great potential to continue extending and enhancing the content base.[3] Europeana has itself set out in its Strategic Plan objectives, in terms of both extending the content base and in seeking to cultivate new ways for its users to participate in their cultural heritage and to enhance their experience. 3DICONS has been implemented with the aim of supporting these policy objectives by enabling increased access to important cultural heritage sites through an effective use of digital technology.

The project, carried out by an interdisciplinary consortium, including partners from different European countries and with different competences, aimed to exploit existing tools and methods and to integrate them in a complete supply chain of 3D digitization that will contribute a significant mass of 3D content to Europeana. The 3DICONS consortium consisted of sixteen organizations based across Europe, providing technical support and content to Europeana as follows:[4]

- The project has been coordinated by Centro Interdipartimentale di Servizi di Archeologia (CISA), Università degli Studi di Napoli L'Orientale.

- Two technical partners (the National Technical University of Athens and the Digital Curation Unit of the Athena Research Center) were responsible for providing the components of the aggregation service (the MINT2 mapping tool, the MoRE2 ingestion repository, and the Metadata Editor) and for providing support and technical advice to the project partners in their use of the metadata creation, mapping, and ingestion tools.

- Fourteen partners (including CISA and Athena Research Center) provided 3D content. These organizations consisted of a cross section of the different entities involved in 3D technology for cultural heritage, namely five major national research organizations, two universities and a polytechnic, two research foundations, two commercial SMEs, and two national museums.

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1 The paper is largely based on the Final Progress Report submitted at the end of the project (January 2015). 3DICONS (3dicons-project.eu/) was a pilot project funded under the European Commission's ICT Policy Support Programme. For the general objectives of the project: D'Andrea 2012; D'Andrea and Fernie 2013.

2 The 3D models and all digital resources provided to Europeana are availableat:www.europeana.eu/portal/search.html?query=PROVIDER %3A+%223D+ICONS %22&rows=24.

3 This was highlighted in the New Renaissance, Report on Europeana in January 2011: ec.europa.eu/information_society/activities/digital_libraries/doc/refgroup/final_ report_ cds.pdf.

4 The complete list of participants is available at http://3dicons-project.eu/eng/About/Consortium.

3DICONS relied on the achievements of the CARARE and other European projects,[5] which have already provided digital assets on European archaeology and architecture. It used the CARARE aggregation service and extended CARARE's coverage by digitising monuments and buildings in 3D and creating a large number of related digital items such as images and videos.

The content includes many of the most famous monuments and buildings in Europe. At the end of the project some 60 such iconic monuments and sites have been made available on Europeana, incorporating about 5000 3D models of architectural and archaeological monuments, more than 17,000 high-resolution images and 287 videos. All the selected masterpieces belong to UNESCO World Heritage Sites. The process set up in the project involved technologies for both surveying and modelling (topographic surveying, 3D laser scanning, image-based modelling, etc.). A range of well-known technological solutions available for the processes was tested, and the equipment used was selected according to the features of individual objects.[6]

The paper reports on the main achievements reached by the project during its implementation and the contribution of CISA, the leader of Consortium, to the realization of these targets.

1 Project objectives

The 3DICONS project focused on creating and providing digital content to Europeana, including 3D models and reconstructions, enlarged models of important details and related images, texts, and videos. Also included and re-contextualized in 3D are objects belonging to a monument but presently located elsewhere, for example in museums. The project's activities predominantly consisted of new digitizations but also included some existing 3D data, all of which have been converted into formats accessible by Europeana users. The project complemented the collections made available to Europeana via CARARE, Europeana Local[7] and Athena,[8] which developed the content base for the architectural and archaeological heritage. An equally important aspect of the project was to develop an IPR Management Scheme specifically aimed at 3D content and which was also compliant with the Europeana Data Exchange Agreement[9] (and consequently, the Creative Commons licensing framework).

3DICONS relied on the results of previous EU projects, most notably on CARARE, for the aggregation services and guidelines on the publication of 3D for Europeana, and on 3DCOFORM for the 3D creation, management, and visualization tools. 3DICONS provided a complete digitization and publication pipeline that addresses digitization methodologies, post-processing, and conversion to end viewer-friendly publication formats and IPR aspects. 3DICONS has also updated the CARARE metadata schema to accommodate 3D content and mapped this to EDM schema[10] adopted by Europeana.

The project has worked closely with its stakeholders, with more experienced partners providing technical support and knowledge to the less experienced partners. Metadata creation guidelines and a metadata editing tool to facilitate content providers with little or no technical knowledge of XML, or metadata schemas that provide their 3D content to Europeana, were developed by the project.

Close collaboration with Europeana has established a best practice pathway for the ingestion and format of the metadata and display of 3D models and associated content to end-users.

Finally, the project has highlighted the many positive aspects that investment in 3D technology brings to the cultural heritage sector, from an effective means of documentation and monitoring of historical objects and monuments, the provision of exciting and engaging content for end-users of all ages, and the opening up of commercial and experimental opportunities for organizations which create and hold this type of content.

2 Project achievements

The main results achieved by the project are:

- The current inventory of monuments and buildings has been made available to Europeana, providing:
    - 3000 metadata relating to 5000 3D models
    - Over 17,000 images
    - 287 videos
- Where permitted, the original 3D datasets are also available for research purposes
- The update of the CARARE metadata schema, renamed CARARE 2.0
- An online Metadata Editor tool which uses reusable templates based on CARARE 2.0, has been developed for general use and is being adapted for other Europeana content projects
- The pipeline has been documented in the Guidelines and Case Studies for the acquisition and production of 3D models
- Dissemination activities have resulted in many articles and papers publishing presentations at conferences and well-attended workshops.

5 www.carare.eu. CARARE is a Best Practice Network designed to involve the network of heritage organizations, archaeological museums, research institutions, and specialist digital archives in making the digital content that they hold available to Europeana. Other similar initiatives are 3D-COFORM: www.3d-coform.eu; EuropeanaConnect: www.europeanaconnect.eu; Linked Heritage: www.linkedheritage.eu.

6 Different deliverables deal with the acquisition process (D.3.2), the post-processing phase (D.4.3), and the publication formats suitable for the Internet and Europeana. All the information will be summarized in the deliverable D.7.3 'Guidelines', which will be ready at the end of the project.

7 http://www.europeanalocal.eu/.

8 http://www.athenaeurope.org/.

9 http://pro.europeana.eu/page/the-data-exchange-agreement.

10 http://pro.europeana.eu/page/edm-documentation.

- A Portal showing the geo-location of all acquired and published monuments.

The target users of the 3DICONS content include:

- Members of the general public, tourists, and students who wish to be able to explore and enjoy architectural and archaeological masterpieces through Europeana, which are often inaccessible to visitors either as a result of their remote locations or because conservation management restricts access to only parts of the monuments.

- The cultural institutions who are in charge of internationally and nationally important monuments and buildings and who need tried and tested mechanisms to produce high-quality 3D documentation and publish the results for Europeana as well as on their own websites.

- UNESCO and cultural institutions wishing to find new ways of delivering their missions to promote understanding and increase the sustainability of world and European heritage.

- Content providers and creative industry SMEs wishing to identify sustainable business processes and models.

The needs of this diverse set of target users provided a range of organizational and technical challenges for the project:

- Obtaining permission to access and digitize the monuments and to publish the resulting 3D models;

- Developing processing techniques that produce 3D models of good visual quality while keeping the file sizes as small as possible to enable the models to work on standard computers;

- Creating the metadata for each digital resource without the need for expert knowledge of XML or the CARARE 2.0 metadata schema;

- Producing high-quality metadata and user-friendly landing pages for the content made available to Europeana;

- Keeping abreast of the latest technical developments in 3D viewers and utilising these to the project's advantage.

3 Project activities

The main 3DICONS activities consisted of planning the content acquisition and gaining permission for access and the rights to create and publish the content, carrying out the digitization, cleaning and manipulating the datasets, post-processing these to create the require 3D models, creating the metadata and ingesting this Europeana, and publishing the models in user-friendly formats.

The first year of the project involved substantial preparation in obtaining permission for access to and scanning of sites and monuments before proceeding to the digitization phase. As an illustration of the complexity of IPR for 3D cultural heritage, around half of the original content was eventually replaced with other items as well additional content being made available where IPR was not an issue. After 18 months the project published a report on IPR Schemes that described the various licensing scenarios and possible solutions. It appears that Europeana's adoption of the Creative Commons licensing framework along with other prominent initiatives such as WikiLovesMonuments[11] is having a positive impact, in that this is making digital content owners pay more attention to IPR while also enabling them to open up access to their collections. This change in attitude was evidenced in 3DICONS where more organizations have started to use Creative Commons for licensing since the start of the project.

During the first two years, the project partners were mainly occupied with digitizing the selected sites and monuments, some of which involved trips to remote areas and archaeological sites of great importance. Obstacles that had to be overcome were gaining access to remote sites (e.g. Skellig Michael can only be accessed by boat during the summer months), delays caused by bad weather, and restricted access times due to the monuments or museums also being open to the public — or closed for restoration. Several different scanning methods were used, from hand-held scanners for the museum objects, UAVs for large monuments, to LIDAR for complete sites.

In order to support the complete 3D model creation process, there have also been significant developments in the infrastructure and tools. At the end of the first year, the CARARE 2.0 metadata schema was published, having been updated to include 'provenance' that is specific to 3D models (e.g. dataset type, processing method, equipment and settings used, final formats). 3DICONS used the same infrastructure as CARARE, adapted to the new schema for ingestion to Europeana. It was also realized that a simple metadata editing tool would greatly speed up the creation of the required metadata and assist the less experienced partners, in addition to providing a valuable facility for newcomers wishing to use the 3DICONS pipeline. Consequently, a Metadata Editor tool was developed which has the advantages of creating reusable templates for each end-user and producing CARARE 2.0 compliant XML files for ingestion into MoRE2.

Creating the metadata and the ingestion process into Europeana proved to be a steep learning curve for all concerned. The project also implemented a strict quality-control procedure to ensure that all content provided to Europeana was of high quality; this review process led to adjustments to the metadata to improve them and also some revisions to the publishing and viewing technologies used to meet the required standards.

Once the 3D model has been created, a suitable publication format must be selected to make the model viewable by the Europeana end-user. The project carried out extensive testing and experimentation to determine which formats were suitable, based on how well supported these were across different platforms, what sort of models suited specific publication formats, and whether the technology was compliant with IPR requirements such as low resolution and security.

Due to the varied nature of the 3D assets that have been published, as well as to the continuous evolution of the 3D presentation over the Internet, several techniques have been used for visualizing the 3D models. At present, the most suitable formats are 3D PDF for objects of low complexity

[11] http://wikilovesmonuments.wikimedia.it/.

(e.g. museum objects), HTML5/WebGL for objects and highly complex point cloud models, Unity3D/UnReal for less complex buildings and sites and the more complex ones where the level of detail can be optimized. Pseudo 3D is also an option for highly complex models across the board. Some partners employed a web-streaming viewer for complex 3D models.

It should be noted that with the current rapid changes in 3D viewing technologies, other options have been made available during the implementation of the project and some partners have started to experiment making 3D models available in this latest platform which offers high-quality, responsive viewing on the most basic of PCs.

A number of 3DICONS partners have relied on 3D PDF as their publication format, as 3D PDF is still a powerful and multi-platform way to deliver 3D content on nearly all desktop computers. It has a simple and stable production workflow, which integrates easily into cultural heritage organizations. 3D PDF, however, has some issues concerning the delivery and availability on mobile platforms (smart phones, tablets). Other partners have used the recently developed HTML5/WebGL standards. The web streaming 3DHOP has been used to create online interactive preview for some 3D models. Partners have also developed some models suitable for the stereovision of the 3D models using a smart phone and a small Google CardBoard.[12]

Finally, the project has been widely disseminated through social media, conferences, journals, and other channels. Over 30 papers about the project have been published in conference proceedings, academic journals, and articles in national newspapers in Spain, Ireland, the UK, and Greece.

4 Impact and sustainability

One of the benefits of participating has been the transfer of knowledge between partners, enabling those newer to 3D technologies to improve their skills and the quality of their acquired datasets and resulting models. To this end, some of the partners have participated in training workshops to learn about the latest acquisition and modelling techniques, such as the use of UAVs and photogrammetry. Some partners have organized their own training workshops. MNIR (Muzeul Naţional de Istorie a României of Bucharest – Romania) hosted a summer school for other cultural heritage institutions in Romania, having gained extensive expertise from their participation in the project. FBK (Foundation Bruno Kessler of Trento – Italy) provides an annual 3D summer school as well. The 3DICONS project also organized two internal metadata training workshops and a very successful technical workshop describing the different models and techniques adopted by partners at the Digital Heritage Conference hosted in Marseilles at the end of October 2013.

The results of the work carried out by the project are available as a print-ready PDF entitled 'Guidelines' which comes with several case studies illustrating the different types of data capture and output. This can be downloaded from the Resources section of the 3DICONS website.

[12] https://www.google.com/get/cardboard/.

The 3DICONS Project has had a substantial impact on the cultural heritage community and is the leading provider of 3D content for iconic European monuments and related historical objects. The pipeline developed by the project provides several options for the capture, processing, and publication of 3D models, covering many different techniques and methodologies for a wide range of subjects, from the smallest object such as a coin to large archaeological sites. Equally important is the topic of IPR and guidelines are provided for the best way to approach this complex issue. One positive outcome from the project has been the adoption of the Creative Commons licence scheme by several of the partners for their 3D models. As illustrated by the external collaborations developed by the project, cultural heritage owners and curators are adopting the 3DICONS approach for the production of 3D models.

Within the project, several partners have gained substantial technical knowledge in order to apply this, not just for creating 3D models for Europeana but for their own documentation, monitoring, and curating purposes. Where partners have created 3D models in partnership with museums and their local authorities in charge of monuments, these organizations have benefitted from the use of 3D models for promoting their cultural heritage. This is encouraging many of these authorities to be less restrictive with their IPR and to move towards the Creative Commons model. Some examples include:

- The data collected for the Neolithic site of Knowth is now being utilized by the Office of Public Works (OPW) in conjunction with the Dublin Discovery Programme to produce an immersive experience at the Bruna Boinne visitor complex, including the use of oculus rift and unity technology. This will generate revenue for the Discovery Programme over the coming years.

- PRISMA, an Italian SME developing mobile guides of heritage sites, has an agreement to use 3D ICONS models in their guides.

- The Museum of Vetulonia, Tuscany will be making physical replicas from the 3DICONS models of the same area (Etruscan sites) in preparation for an exhibition at EXPO2015.

3DICONS has provided owners of existing 3D models relating to cultural heritage and those organizations who are beginning to include 3D technology in their workflow, with guidelines and case studies to help them manage IPR issues, capture and create their models, a metadata schema tailored for 3D models, a simple tool to enable metadata to be created for Europeana, and also a showcase repository which enables a straightforward method for storing and hosting 3D content. In addition, there have been several enquiries regarding commercial collaboration and these developments are ongoing.

5 CISA contribution

CISA contributed to the creation of 3D content by acquiring and processing many statues and sarcophagi from the Archaeological Museum of Naples and some archaeological monuments in Naples (Roman Theatre, Baths of Carminiello ai Mannesi), Herculaneum (Augusteum, Terrace of Nonio Balbo, Sacello of Augustali) and Pompeii (some tombs from the Necropolis of Porta Ercolano, some domus of the Regio

VI). At the end of the project 120 3D models were created for a total of 578 digital resources provided to Europeana.[13]

In the project CISA has been mainly involved in the aggregation and ingestion process. Furthermore CISA has contributed to update the metadata schema adopted by the previous CARARE, extending it to support provenance, transformation, and London Charter[14] paradata required for quality assurance of 3D models. One of the main 3DICONS was to develop a metadata schema able to capture all the semantics present in the digitation process (provenance) and in understanding and interpretation of data objects (paradata). 3DICONS updated the previous CARARE schema by investigating what additional data might be required and how this could be represented. This has resulted in the CARARE 2.0 schema, updated to include provenance information and paradata relating to 3D models, which was specified as an extension to the CIDOC-CRM, called CRMdig.[15] The CARARE 2.0 schema is a much richer dataset than the Europeana EDM and has made available a number of commonly used cultural heritage mappings already used in the cultural heritage sector.[16] Thanks to the recent developments of integration between CARARE and EDM and to the publication of object templates of EDM,[17] the updated CARARE2 schema has also enabled some simplification. The last OWL version of EDM[18] has been aligned to CIDOC-CRM Core Classes and some properties of CIDOC-CRM have been reused in EDM, allowing a more simple integration of CRMdig into EDM. This has enabled the provenance and paradata to be added to the CARARE schema without changing substantially the original schema and the mapping to EDM.

It is hoped that the new schema will increasingly encourage European Institutions to adopt a clearer approach in describing the features of a cultural object, the techniques and methodologies chosen for the digitations, and the motivations at the base of the creation of the digital object. The complete knowledge of the digital resource will allow a more efficient reuse of the archive, increasing the usability of the resources available online. Thus it will be easier to compare models and their complexity, any eventual innovation in their creation, and their reliability.

Furthermore, a 3D model repository has been developed and used by CISA to host and facilitate the publication of all 3D models and related content.[19]

[13] Data created by CISA are accessible at www.europeana.eu/portal/search.html?qt=false&rows=24&qf=DATA_PROVIDER%3A%22CISA+-Interdipartimental+Center+for+Archaeology%22. Metadata have been published under the terms of the Creative Commons CC0 1.0 Universal Public Domain Dedication and therefore can be reused by third parties without any restrictions. CISA contributed to the Deliverable D.2.1 (Digitization planning report), D.4.2 (Interim Report on Metadata Creation) and D.6.1 (Report on metadata and thesauri). All deliverables are accessible on the project website.

[14] www.londoncharter.org.

[15] http://www.ics.forth.gr/isl/index_main.php?l=e&c=656.

[16] E.g. LIDO: www.lido-schema.org/schema/v1.0/lido-v1.0-schema-listing.html; and MIDAS www.heritage-standards.org.uk/midas/docs/meta/index.html?url=/midas/docs/meta/midas_meta_xsd.html.

[17] http://europeanalabs.eu/wiki/EDMObjectTemplatesProviders.

[18] http://lists.w3.org/Archives/Public/public-data-shapes-wg/2015May/att-0053/EDM-v524-120820.owl.

[19] See Achille Felicetti's contribution at the CAA Conference 2015.

6 Conclusions

The general objective of 3DICONS was to enhance the content base available to Europeana users through targeted 3D digitization of European architectural and archaeological monuments and buildings, selected through their listing by UNESCO on its World Heritage (WH) list or by member states as being of exceptional and outstanding cultural importance.

The project aimed to complement the collections that are being made accessible to Europeana via CARARE, Europeana Local, Athena, and other projects which have developed the content base for the archaeological and architectural heritage. In the end a critical mass of content has been delivered relating to internationally important cultural assets from many different European countries managed by European Cultural Institutions offering added value for Europeana.

Knowledge gained from the 3D-COFORM project has already made a valuable contribution to the early work packages of 3DICONS and it is evident that many of the partners have built on know-how gained from previous research and digitizing activities. In addition to adapting the MINT metadata mapping and MoRe repository tools to work with the new CARARE 2.0 metadata schema developed in 3D-ICONS, NTUA has used experience gained from CARARE and their other involvement in other Europeana content supply projects, to enhance the tools and add new features to facilitate metadata creation and processing.

As nearly all the content is being digitized for the project and most partners had little experience in recording metadata with their 3D models, a tool was needed to simplify and streamline the metadata creation process. This has resulted in the development of the online Metadata Editing Tool, which enables reusable templates to be created and used and outputs fully CARARE2-compliant metadata records that can be ingested directly into MoRE2. This tool has been adapted for use by other Europeana projects.

Some issues arose during the work on publication formats for which solutions were found:

- Display technology did not function well on low-end computers. This has required some partners to use additional resources and external technical support to improve their viewer technology.

- Certain partners were allowed to make low-resolution 3D models available due to their national legislation and copyright restrictions. This has required a fine balance between the size of the 3D model and making available an object that is still pleasing to the viewer, regardless of the restriction.

- Due to certain browsers not being able to handle 3D PDF (as they have embedded PDF viewers to circumnavigate the security problem with Adobe), partners have been required to use the HTML command that forces the PDF file to be downloaded in their metadata so that it can be viewed correctly in Adobe Reader.

A portal (http://3dicons.ceti.gr/) was originally developed for the presentation of the 3DICONS items on (i) a geolocation system; and (ii) to present the rich metadata provided by the CARARE 2 schema, and it was soon used by the partners to check the validity of their data before they was published in EUROPEANA. The capability to publish data in the portal a very short time after it was published in MoRE2 was crucial for this operation. The partners were able to see their data published and decide if corrections were necessary before the final submission to Europeana. At the same time, if their data were already published in Europeana's portal, there is a direct link to them in the Portal so they can view them as they are presented in Europeana. One further facility provided by the Portal was the statistical summary of the digital resources (by type) for each partner. This was useful for the partners to check against the number of records published in MORE2 as it would identify any issues if there was a mismatch. It allowed the content providers and the project management to track the monthly ingestion targets specified in the Ingestion Schedule and to report the ingestion progress to the Commission. Although the number of metadata records created and published was intended to be tracked in the Progress Monitoring Tool, this function was superseded by the Statistics report in the Portal, as the numbers (and type of digital resource) are extracted automatically from the metadata published in MORE 2, providing a greater level of detail and saving time as no manual input of the figures is required.

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Bibliography

D'Andrea, A. 2012. Integrating Architectural and Archaeological 3D-Models into Europeana. *Newsletter, di Archeologia CISA*, Volume 3, p. 87-109. Available at: http://www.unior.it/userfiles/workarea_231/Andrea%202012.pdf [Accessed: 15 november 2015].

D'Andrea, A., Fernie, K. 2013. 3DICONS Metadata Schema for 3D Objects. *Newsletter di Archeologia CISA*, Volume 4, p. 159-181. Available at: http://www.unior.it/userfiles/workarea_231/file/NL4/Articoli/03_DAndrea-Fernie.pdf [Accessed: 15 november 2015].

How To Move from Relational to 5 Star Linked Open Data – A Numismatic Example

Karsten Tolle
tolle@dbis.cs.uni-frankfurt.de
Databases and Information Systems (DBIS), Johann Wolfgang Goethe-University of Frankfurt, Frankfurt am Main, Germany

David Wigg-Wolf
david.wigg-wolf@dainst.de
Römisch-Germanische Kommission (RGK), Frankfurt am Main, Germany

Abstract: We used and adapted our database solution Antike Fundmünzen in Europa (AFE), in which we recorded finds of ancient coins for different use cases in Germany and Poland, and we are currently working on Romania. As with many others, our backend system is based on a relational database. In order to become 5 Star Linked Open Data, we mapped our data to different ontologies from Nomisma.org, Dublin Core, SKOS, and others. In this paper we describe our experiences, ranging from the challenges we encountered, to how we addressed and implemented them, and the problems that remain. The challenges we describe entail technical and sociological issues. We describe our methodology for addressing and overcoming these challenges. The overall approach is to minimize the changes of the existing system, and to model things in a manner that follows the way of thinking of the domain experts, so making it easier for them to understand and accept.

Keywords: Sociological challenges, ontology, modelling

1 Introduction

We did not start in an empty green field. As in many other cases, we started our work from an existing database that had grown over decades, and was often modified in order to handle increasing requirements. These existing legacy data are of high value and need to be preserved. Our goal was to generate a solution that is built on top of these legacy data, but can also fit new requirements for the Linked Open Data world. This resulted in our database solution called Antike Fundmünzen in Europa (AFE-WEB), where we record finds of ancient coins. In addition, we tried to preserve as much information as possible, which also includes containments of possible coin types, or marking attributes of a coin as uncertain if the exact value cannot be confirmed. Like many others, our backend system is still based on a traditional relational database. In order to become 5 Star Linked Open Data, we mapped our data to different ontologies from Nomisma.org, Dublin Core, SKOS, and others. We have applied our approach to the three different instances of AFE, which are currently online (AFE 2015).

In this paper we will present our methodology for transforming the existing data step by step into a new system capable of handling the new requirements, up to 5 Star Linked Open Data as defined by Berners-Lee (2006) and shown in Table 1.

Before explaining the methodology in section 4, we will briefly discuss our situation, which is probably similar to many others. In section 2, therefore, we concentrate first on the technical system and data level. Besides technical issues, we also had to deal with fears, resentments, and bias on the part of different parties. These sociological issues are, in our view, still a barrier to starting the real revolution for pushing for Linked Open Data. We will discuss our view on them in section 3.

In section 5 we briefly explain some of our work so far and what we plan. This includes some background on the technology we used for implementing our cases. Before our final conclusion, we describe in section 6 the problems that remain, focusing on the usage of different modelling approaches and their implications.

Tab. 1. The 5 Star Linked Open Data scheme defined by Berners-Lee (2006).

★	Available on the web (whatever format) but with an open licence, to be Open Data
★★	Available as machine-readable structured data (e.g. excel instead of image scan of a table)
★★★	as (2 star) plus non-proprietary format (e.g. CSV instead of excel)
★★★★	All the above, plus use of open standards from W3C (RDF and SPARQL) to identify things, so that people can point at your data
★★★★★	All the above, plus: Link your data to other people's data to provide context

Diameter		MinDiameter	MaxDiameter	
4,5 x 5	→	4,5	5	If separated, data get a clearer meaning and it is easier to write expressive queries on top.

Coin	Issuer		Coin	Issuer	
5	Titus/Nero	→	5	Titus	Here the meaning might still be an issue, are they both issuers or is it an alternative?
			5	Nero	

Coin	Issuer	
8	Aedui/Lingones (Kaletedou)?	Uncertainty is often expressed in different ways, and in more complicated cases you do not even know what exactly is uncertain.

Fig. 1. Three examples of non-atomic data, with complexity increasing from the top down. For the first two a possible solution is provided.

2 Facing the real world

The database we first worked with had existed for many years, and began as a dBASE III+ database in the 1980s. This database was changed and adopted over time, set up and maintained by a domain expert. When we started, the latest version was held in an MS Access database with a form for data entry. The underlying schema was not normalized, and only very few foreign keys were used to ensure the integrity of the data.

As we are dealing in this paper with sociological challenges in particular, a few things must be stressed at this point:

A. The database was used successfully for more than 20 years (which is true for only very few databases). This means it (the data kept inside) has huge value, and it is remarkable that non-IT experts where able to set it up and keep it running over this time span.

B. For computer systems as well as for database schemas, there is a permanent need for maintenance (on the data and schema level).

C. Changes in a live system in order to fulfil new requirements tend to generate solutions that do not conform to best practice for design (for different reasons — time, resources, knowledge). This is what is sometimes called 'historically grown', meaning a quick and inadequate solution had to be applied.

Therefore, the initial situation is a global problem that also exists for many other domains, and is also independent of whoever implemented it. What follows is a list of the main problems we repeatedly encountered when adapting our database to LOD. Some of these are easy to correct, but others are difficult even to find, and in most cases (except for some typing or trimming issues) the domain experts have to check them. A more comprehensive overview of such data cleansing challenges, including a classification of data problems, can be found in Müller and Freytag (2003).

A. Not normalized, not even 1st normal form (database normalization) examples are shown in Figure 1.

B. Errors in typing due to a lack of referential integrity, e.g. we found four different spellings for 'unidentified coin': 'Uidentified coin', 'Uindentified coin', 'Unidentified coin', and 'Unidentified coins'.

C. Usage of synonyms due to a lack of referential integrity (especially when used by different users).

3 Sociological Challenges

Although the Linked Open Data (LOD) approach is finding increasingly wide acceptance and application, its adoption and use within the community is still limited. One reason is limited resources, but there are also sociological challenges that need to be addressed. Once these are overcome, it will increase the acceptability and attractiveness of LOD and facilitate its use in new, successful projects.

The following list represents the main challenges we have come across:

1. People do not want to change their habits and the way of working they have used for many years.

2. Fears:

   2.1 of loss of control and power;

   2.2 of changing existing running systems (uncertainty that the changed system will be as good and stable as the current one);

   2.3 of running into licenses issues (especially with respect to images).

3. Security of sensitive data (find spots, ownership).

4. Traditional key performance indicators (KPI), e.g. number of hits on a web page; are those negatively influenced by LOD?

5. The price for the setup and maintenance of a new system is not known.

6. Sustainability, … how will things be in 5–10 years? … will investments made now still pay off?

As can be seen, many items in our list are based on habits and fears related to not knowing the future. This makes them extremely difficult to argue with, because nobody knows the future and changing habits is a painful task.

First of all, it is important to understand the LOD approach. LOD is based on technology; the main driving force, in our view, are the domain experts, who need to agree on definitions for their concepts while setting up common thesauri or even ontologies. Such thesauri or ontologies might be changed, merged, or replaced in future, but they will have a strong influence and there is no way of turning back the clock. Experts that are not part of it now, run the risk of losing control and power in the future (i.e. the same fear as *item 2.1* but from another angle).

The positive news about the methodology used and that will be presented in the next section is that most of the fears and unknown issues are becoming more or less obsolete. This is due to the fact that the methodology described here changes the system through a minimalistic approach of upgrading running systems rather than reimplementing them. This way they can still be used as they were before (habits can remain – *item 1*), and costs are manageable thanks to step-by-step upgrades (*item 5*). The most critical step is the very first one, where it is necessary to analyse the current status of the system and clean up potential problems such as those mentioned in section 2. Depending on the situation, this step might have high costs, and if they are too high a reimplementation from scratch might be considered. This step is independent of LOD, however, and is basically a clean-up, which is useful in any case; the longer one waits the more expensive it will get.

Of course LOD will change a few things. When the public is granted access to data, it is important to ensure that the data provided really is meant to be public. This means they should not be sensitive (e.g. detailed find spot coordinates) and the relevant licenses should be owned (*items 2.3* and *3*). These items are an issue that one needs to be aware of but there are solutions for them. On the other hand, if the data are kept locked up, they would not be diffused in the way that LOD are. In fact LOD makes data more visible than before. Therefore, KPIs like the number of hits on a web page are more likely to be increased (*item 4*). As an example let us take OCRE (OCRE 2015), where for the corpus of Roman imperial coin types, existing specimens located at various museums are linked by LOD. OCRE itself only takes the basic information; the images, for example, remain on the museum system. This means that each time an image is shown on OCRE, it is loaded from the museum itself and the museum gets a log entry (a hit) on its server. We think that the days of using the number of hits as KPI are over, however, but such hits provide an excellent overview of where and how LOD is used, and this allows investment to be made in the right direction. Furthermore, each time a museum's LOD is used somewhere else, the likelihood is very high that the users end up on the original web page of the museum (which in this case is only one link away).

Item 2.2 is of course relevant. In Germany the saying is, 'never change a running system', in other words, as long as one is happy with a system, it should be kept. For different reasons, however, systems need to be maintained and patched over time, such as new requirements or security issues. If this is not done, sooner or later the system will collapse. Since our methodology does not force anyone to replace his/her system with a new one, there is no reason to be afraid.

Finally, there is sustainability (*item 6*). We have been asked many times, 'What if Nomisma.org [for example] goes offline?'. This is clearly not desirable but first, all of our solutions would still run and second, all the ontologies, concept descriptions, and thesauri are open and can be copied. It would thus be easy to simply upload it somewhere else. The really important issue is that people behind the scenes are performing the maintenance and update work. As long as there is a community of people interested in it, it will carry on.

Independent of all these arguments, we encountered two main issues that need to be addressed in order to raise the acceptance rate for LOD:

1. People need to understand what is happening;
2. (most importantly) people need to see the benefits, e.g. by demonstrating the potential with other implementations that are running, or by rapid prototyping/mock-ups.

4 Our Methodology

As mentioned above, we started with relational data, which is probably what most people do. Our methodology is therefore based on an approach of keeping the data within the relational DBMS, and only defining a mapping in order to dump LOD or to allow access via a SPARQL endpoint. This methodology comprises four steps listed below and described in more detail further down:

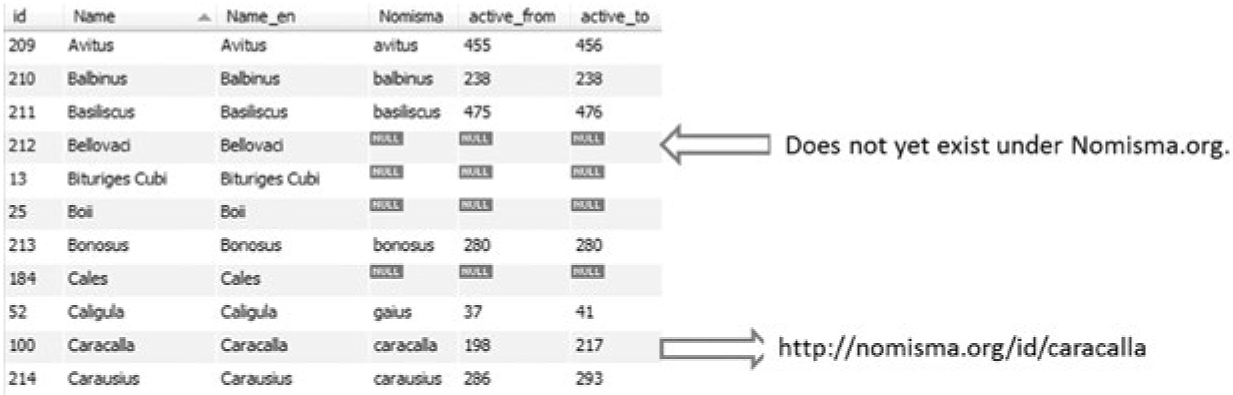
1. Cleaning the data (essential homework, in order to ensure reasonable data quality);
2. Mapping to existing thesauri (zero star);
3. Communicating with the domain community – to identity how the LOD should be modelled in order to be useful;
4. Implementing the relational DB to RDF mapping.

4.1 Cleaning the data

As stated in section 2, data should always be analysed and cleaned up from time to time. Besides the obvious problems, errors, or inconsistencies, which should be eliminated, the most important thing is to split information into their smallest parts (1st normal form), otherwise problems will arise in querying or mapping data. Such changes are normally combined with a change of the underlying database schema, which might affect systems running on top of it.

Depending on the situation, the cleaning may be extremely challenging and time-consuming. This is due to the fact that although unclean data can in many cases be detected by IT experts, the solution for these cases has to come from the domain experts, and some cases can only be detected with the relevant domain knowledge. In other words, both sides need to work closely together.

Decisions on the schema level should be compiled in a report documenting the reasons why certain things were modelled in a



id	Name	Name_en	Nomisma	active_from	active_to
209	Avitus	Avitus	avitus	455	456
210	Balbinus	Balbinus	balbinus	238	238
211	Basiliscus	Basiliscus	basiliscus	475	476
212	Bellovaci	Bellovaci	NULL	NULL	NULL
13	Bituriges Cubi	Bituriges Cubi	NULL	NULL	NULL
25	Boii	Boii	NULL	NULL	NULL
213	Bonosus	Bonosus	bonosus	280	280
184	Cales	Cales	NULL	NULL	NULL
52	Caligula	Caligula	gaius	37	41
100	Caracalla	Caracalla	caracalla	198	217
214	Carausius	Carausius	carausius	286	293

Fig. 2. The zero star mapping does not require a 100% fit. Items which do not exist in the thesauri that are to be mapped can simply stay empty. They are not needed; they simply exist within the thesauri and are not imported.

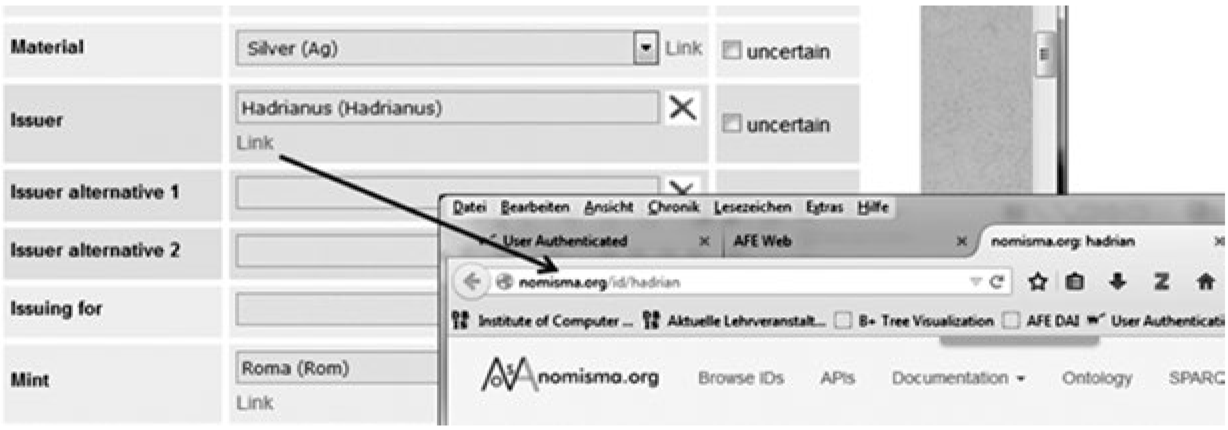


Fig. 3. The zero star mapping can be used to support data entry by providing a link to the mapped thesauri.

particular way. This is because modelling has to do with *design*, which to some extend depends on the designers' favoured way of doing things, but it is also due to more specific reasons, which should be recorded. If they are not, it is possible that next time the alterations are reversed.

In our situation we even postponed parts of the cleaning. The reason for this was to shorten the time frame for this first phase, and to come up quickly with a prototype to show the possibilities. Where the resulting application is 100% definite, it is more expensive. In other cases one can benefit from such a flexible approach, as it is not necessary to re-alter cleaned data if requirements change.

4.2 Mapping to existing thesauri (zero star)

In this second phase we enriched our thesauri with a mapping to existing ones. In our case this was mainly Nomisma.org, which provides URLs for various concepts such as mints, denominations, or authorities. On the database side we simply added a column to the thesauri table, which contains the Nomisma.org name. This name combined with the namespace (http://nomisma.org/id/) builds the URL reflecting the corresponding concept. In some cases we had items in our thesauri that were not yet covered by Nomisma.org. In such cases we just left the entry empty (void). In this way the system is not affected at all.

Within the system, we used this mapping to provide links to the Nomisma.org representation of the concept during entry of information on coins. Once a user has selected an item for a field, the corresponding link is presented next to it and the user can double-check if he/she was thinking of the right value. This is especially useful if students or those less experienced are assigned to enter data.

Thus this mapping brings direct benefits, even if data are not yet LOD. This internal mapping, however, will later also be used for generating LOD. The effort that one needs to invest here will be spared later on. Furthermore, with the mapping included in the relational database, something that is quite easy to understand, it can also be easily maintained later. The alternative would be to have it defined as part of the mapping itself, which is explained in phase 4.

4.3 Communicating with your domain community

This is simply the main human part or factor of LOD. The intention of LOD is to share and communicate with others. In order to do so, it is desirable to be able to talk the same language (or at least a similar one). This might sound easy at first, because each research domain already has some predefined basic terms. When they progress beyond the basic terms, however, research disciplines are often built on hypotheses that are barely provable but still taken for granted, until somebody explores something new that, at least in their view, does not fit the current state of the art. Research also means arguing. In some cases the frontiers of argument are very hard and we are back to the sociological challenges: fear of losing power and being unwilling to change one's habits.

The goal is to start by defining the basic (hopefully uncomplicated) parts. In many case, standards already exist (e.g. the existing thesauri mentioned above). Even when there are different standards, or they exist only on the level of hypotheses, LOD technologies are only a tool to describe or encode things. It is quite simple from a technological perspective to model and define a mapping between different standards, or to use different hypotheses, but the more uniform it is, the easier it will be to implement and understand.

The process of agreeing on how to model things occurs at different levels for different domains. In order for the LOD that will be put online to be really useful, and therefore be used by others (which then results in higher visibility), it is necessary to identify the target group and the most relevant community and how they model things, otherwise an additional mapping would be needed, which might cause errors or simply requires more effort from users of the LOD provided.

4.4 Implementing the relational DB to RDF mapping

Once it is clear from the previous step what the mapping target should look like, it is quite easy to define the corresponding mapping for the relational data to RDF. Various implementations exist (W3C 2012) along with background information about this task (W3C RDB2RDF Working Group 2012), but it is still something that belongs in the hands of an IT expert. We expect that in future this task will be better supported by graphic tools that will also allow non-IT experts to perform the task.

5 Our work so far and the next steps

We applied the methodology described above on several cases. The first one was the coin find database of the Römisch-Germanische Kommission (RGK), part of the Deutsches Archäologische Institut (DAI). In this case one database existed. The existing data needed to be cleaned up and also transformed in order to be compliant with the 1st normal form. It turned out that this is a time-consuming task and should not be underestimated. In order to support this step — and not reinvent the wheel each time — we used a free Extraction – Transformation – Loading (ETL) tool called Talend Open Studio community edition (Talend 2015). Like many other ETL tools, Talend Open Studio allows one to break down the ETL process into smaller sub-steps that are graphically combined to the overall workflow. In addition, it comes with different predefined routines or algorithms for mappings or identification of duplicates. Needless to say, whether such a tool makes sense depends on the complexity and the amount of data, and the experience of the person in charge of this step.

The same relational database structure generated for the RGK was later also used by the project 'Finds of Roman coins from Poland' (FRC PL 2015) which is dedicated to the registration of finds of Roman coins in Poland and territories historically associated with Poland over the past 100 years. As no previous data existed for the Polish project, they were able to begin immediately and only minor changes for additional requirements of the project needed to be included.

We are currently also working on Romanian coin find data provided by Christian Gazdac, as well as on data for the project 'Der spätantike Münzhorizont in der Rhein-Neckar-Region – Dokumentation und historische Interpretation' at the University of Heidelberg (Börner 2015). In both cases data exist and are based on different sources with different structures. The cleaning and ETL step is also needed in these cases.

As for the other steps, we already undertake them or constantly repeat them, for example communication with the domain community. Thus the RGK established the European Coin Find Network (ECFN 2015), a cooperation between institutions engaged in researching and recording coin finds from Europe with the aim of encouraging dialogue between them. We are also involved in the work of Nomisma.org. This means that there is a lot of synergy that can be leveraged when a similar project in the same domain is reimplemented.

For the projects we currently handle, we can even reuse the mapping from the relational Database to a SPARQL endpoint, as they all share the same relational schema. Since the target modelling of this mapping is identical, queries can be sent simultaneously to different SPARQL endpoints, and thus a user can query different databases at the same time. We are currently working on one such generic portal to query different sources at the same time. We are also looking at other systems that are based on a different schema in order to prove that this is independent of the relational schema. We do not expect major problems in such cases, especially if the thesaurus mapping (step 2 of the methodology) can be included into the relational schema. As long as the SPARQL endpoints speak the same language, it should be easy to combine and merge them. The next section will discuss more closely the problems that arise when this is not the case.

For the mapping itself we used the D2RQ-language (Cyganiak *et al.* 2012), which is script-based and needs some experience. In some complex cases we generated views on the level of the relational database in order to reduce the complexity of the mapping file.

6 Problems based on different modelling approaches

It is possible that there are different SPARQL endpoints representing semantically equal things, but a completely different modelling is used. In such cases we can say that they are simply speaking a different language. In the world of LOD, however, we talk about ontologies rather than languages. Within an ontology the classes and properties, as well as their hierarchies and constraints, can be defined. Many ontologies cover certain areas on different levels, from very broad to very specific. The intention here is to reuse them when appropriate and avoid reinventing the wheel. The Nomisma.org ontology, for example, does not define a class for persons. Persons defined within the Nomisma.org ID namespace use *foaf:Person* (a class from a commonly known and widely used ontology). Naturally, using any other person class together with

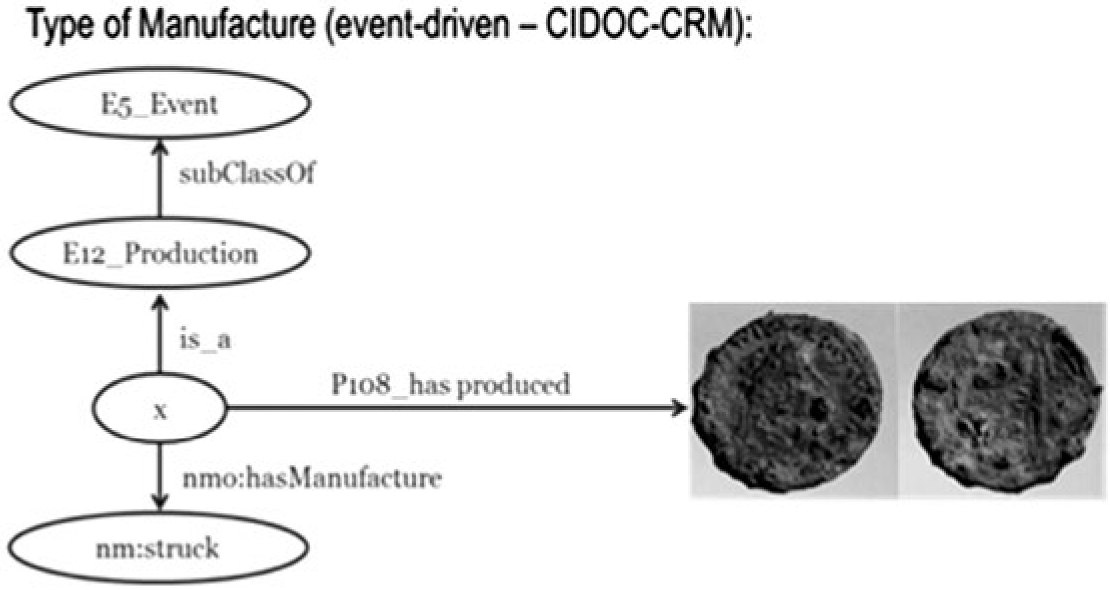


Fig. 4. Event-driven (CIDOC-CRM) modelling of a coin that was struck.

the Nomisma.org ontology is not prohibited, but someone who expects the usage of *foaf:Person* might have trouble dealing with it. This is a common problem in the LOD world, although there are ways to deal with it, e.g. by using appropriate OWL or SKOS statements describing the relationship between the two person classes.

This issue, however, already shows that modelling in the LOD world is, because of its flexibility, more complicated than the well-known modelling in the relational world, especially without links to the outside. When we think of modelling in the IT domain, sometimes the programming language used implies a certain modelling approach. There are object-oriented programming languages such as Java or C++, or functional programming languages such as Haskell. Each of these approaches has its pros and cons, and which looks most promising depends on the situation and persons involved.

One way to deal with this is to define rules on how to model things. This is the approach of CIDOC-CRM, which is much more than just an ontology; it also implies an event-driven approach to modelling things. Let us say, for example, that we want to model 'a certain coin was struck (a specific manufacturing technique for coins)'. In CIDOC-CRM this manufacturing technique should be bound to the manufacturing (hence production) event. One still can combine ontologies and therefore make use of the existing Nomisma.org ontology where the manufacturing technique as well as the property *nmo:hasManufacture* are defined, so in CIDOC-CRM it could look like Figure 4. This is especially useful if more information about the production is available, such as the place or circumstances.

There are other ways to model it, however. The object-oriented method would place the object in the centre, in this case the coin, and we could simply append the manufacturing technique. Figure 5 represents what the object-oriented modelling could look like. As can be seen, only one triple was used, while CIDOC-CRM needed three (excluding the *E12_Production* subClassOf *E5_Event* one – which is part of the ontology and not of the modelling itself).

This is not the place to discuss the pros and cons of all the different modelling approaches. In our view it depends on the people using it and what their way of thinking is, meaning that all kinds of modelling approaches would be allowed. To do so, the ontology must allow such flexibility. From the small example above, it is apparent that in the event-driven form the property *nmo:hasManufacture* was used with a domain instance of type *E12_Production*, while it was used with a coin in the object-oriented form of modelling. Many ontologies already define the domain and range classes for their properties, which would hinder such flexibility. When setting up the Nomisma.org ontology, we deliberately avoided generating any domain or range constraints to the properties in order to allow this flexibility.

We believe that the modelling has to follow the way of thinking of the users, and not the other way round. This of course causes inter-operability problems, but in our view it reduces the barriers to joining the LOD revolution. Time will show if we find the technical solutions to link different modellings, or if we all model and think in the same way in future.

7 Summary and conclusion

In our view sociological challenges are a barrier that need to be overcome to start the LOD revolution. With our methodology, based on small steps with limited influence on existing systems (as explained in section 4), most of the counter-arguments to the implementation of LOD are becoming obsolete, even if in many cases current systems do need a certain amount of cleaning and maintenance. This is probably the most time- and resource-consuming aspect, and needs appropriate support from IT experts. The persons responsible must understand that proper cleaning and modelling of their data is a mandatory requirement for any future development of their system.

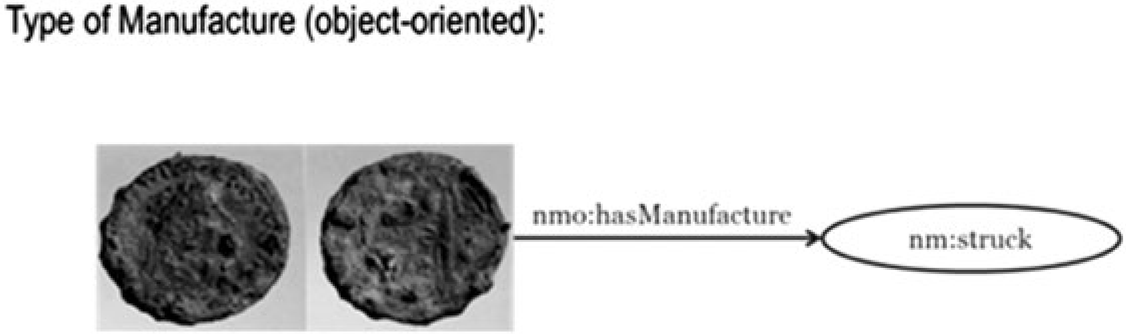


Fig. 5. Object-oriented modelling of a coin that was struck.

In our view, the key aspect of the successful introduction of LOD is probably that domain experts sit together with IT experts and that they learn from each other. For example, not only must domain experts appreciate and accept the possibilities and restrictions of the technology used, the IT experts must respect the fact that domain experts cannot be won over if they fear a loss of control or that sensitive data will no longer be protected in the new system. Normally, the community of domain experts has already agreed on certain concepts and ways of doing things. The more homogeneity there is the better, but even where there are differences between groups of experts, these differences can also be expressed. What is decisive in order to win over the target domain community, in our view, is that the current way of thinking of the domain experts should provide the basis for modelling their world. As noted in section 6, this might cause inter-operability problems, but in order to be accepted the modelling has to follow the people, not the other way round.

Bibliography

Antike fundmünzen in Europa 2015. [Online] http://afe.fundmuenzen.eu/. [Accessed: 29 june 2015].

Berners-Lee, T. 2006. *Linked Data - Design Issues* [Online] http://www.w3.org/DesignIssues/LinkedData.html. [Accessed: 29 june 2015].

Börner, S. 2015. *Der spätantike Münzhorizont in der Rhein-Neckar-Region* [Online] http://www.uni-heidelberg.de/fakultaeten/philosophie/zaw/sag/smh.html. [Accessed: 29 june 2015].

Cyganiak, R., Bizer, C., Garbers, J., Maresch, O., Becker, C., 2012. The D2RQ Mapping Language [Online]. D2RQ Mapp. Lang. D2RQ Platf. URL http://d2rq.org/d2rq-language [Accessed: 29 june 2015].

Database normalization [Online] https://en.wikipedia.org/wiki/Database_normalization. [Accessed: 11 november 2015]

ECFN 2015. *The European Coin Find Network* [Online] http://www.ecfn.fundmuenzen.eu/index.php/. [Accessed: 29 june 2015].

FRC PL 2015. *Finds of Roman coins from Poland* [Online] http://frcpl.uw.edu.pl/. [Accessed: 29 june 2015].

Müller, H., Freytag, J.-C. 2003. Problems, Methods, and Challenges in Comprehensive Data Cleansing. Technical Report HUB-IB-164, Humboldt University, Berlin, 2003. [Online] http://www.informatik.uni-jena.de/dbis/lehre/ss2005/sem_dwh/lit/MuFr03.pdf. [Accessed: 29 june 2015].

OCRE 2015. *Online Coins of the Roman Empire* [Online]. URL http://numismatics.org/ocre/. [Accessed: 29 june 2015].

TALEND 2015. *Open Studio Integration Software Platform* [Online] http://www.talend.com/products/talend-open-studio. [Accessed: 29 june 2015].

W3C 2012. *Implementations - RDB2RDF* [Online] http://www.w3.org/2001/sw/rdb2rdf/wiki/Implementations. [Accessed: 29 june 2015].

W3C RDB2RDF WORKING GROUP 2012. *RDB2RDF - Semantic Web Standards* [Online] http://www.w3.org/2001/sw/wiki/RDB2RDF. [Accessed: 29 june 2015].

Homogenization of the Archaeological Cartographic Data on a National Scale in Italy

Giovanni Azzena
azzena@uniss.it

Roberto Busonera
rbusonera@uniss.it

Federico Nurra
fnurra@uniss.it

Enrico Petruzzi
epetruzzi@uniss.it

Department of Architecture, Design and Urbanism (DADU) – University of Sassari, Italy

Abstract: For decades now standardization, homogenization, and harmonization of digital archaeological cartographic data in Italy has been a major topic of debate.

The complex organization of state agencies, heterogeneously structured on different operational levels causes a disruption of the archaeological georeferenced information, one of the main problems that the SITAN (National Archaeological Geographic Information System) project aims to simplify and bring back to shared tools and languages. The paper will focus on the peculiarities of the 'producers of information', the different typology of data acquired and yet to be acquired, the possibilities of using them, and on forms of cooperation undertaken or in progress with different actors operating in the Sardinian regional context.

A turbulent environment, in which the difference is more acute between protection of public property and the profit of private interests — a heated public debate strongly felt and discussed through the media.

Keywords: Ancient topography, archaeological cartography, SITAN, standard

Introduction (G.A.)

Standardization, homogenization, and harmoniza-tion of the archaeological mapping data on a digital base are issues that, in Italy, have been debated over many decades.

In the Code of Cultural Heritage and Landscape[1] there is a particular motivation for the revitalization of cartographic activities of the archaeological heritage[2] resulting from a collaboration between the state and the regions to which some fundamental aspects on 'landscape care' are delegated. According to article 156 of Legislative Decree no. 42/04, it is expected that the regions and the Ministry of Heritage and Culture will collaborate in the drafting of Regional Landscape Plans and cooperate in the performance of protection of the cultural heritage.

In this context, in 2004 the Autonomous Region of Sardinia (RAS) was the first in Italy to adopt a Landscape Plan,[3] paying particular attention to the creation of an original, historical and geographical alphanumeric database, generally based on specific categories of data already defined by the ICCD (Central Institute for Cataloguing and Documentation).[4]

The practical application of this system, especially as regards the extremely detailed scale of local archaeological surveys, has showed how basic methodological approaches are rarely integrated, a fact that produces a complex structure in the cooperation between different state agencies, differently structured on various operating levels, and causing serious disruption of the archaeological georeferenced information.

This contribution comes as part of a larger project, the creation of a National Archaeological Geographic Information System (SITAN), and attempts to provide a clear and complete illustration of the problems faced, starting with survey, interconnection, and dissemination of information about the 'producers of archaeological data' active on the island.

1 Heterogeneity of data and the need for standardization (R.B.)

To synthesize the complex cultural panorama of the choices that have developed over time in the Italian archaeological field is very difficult. It is, however, possible to highlight the gradually prominent role of computing, especially from a geographical point of view, responding promptly to the needs of archaeological practice.

But the capabilities and possibilities reached through these resources have quickly turned into one of the major problems affecting the whole national archaeological panorama.

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[1] D.Lgs. 42/04 – Code of Cultural Heritage and Landscape.
[2] Art. 2, paragraph 2, of Legislative Decree no. 42/04.
[3] PPR of RAS was approved by a resolution of the Regional Council no. 36/7 of 5 September 2006, following the L.R. no. 8 of 25 November 2004.
[4] http://www.iccd.beniculturali.it/

After a positive start, characterized by the creation of a methodology to enliven and develop a technological approach to the historical and archaeological sciences, the thread of a new systematic approach that could combine good initiatives into a solid foundation of common and shared knowledge has been lost (Azzena 2009: 169).

These issues comes mainly from the large fragmentation of initiatives, which caused not only the loss of the potential offered by computer support, but the significance of a geographic and mapping approach to the archaeology and history of the cities and territories. This possibility has been in existence since 1870 (Azzena 2009: 170) and was finally realized by the creation of a unique National Archaeological Geographic Information System.

A 'progress report' of sorts on the state of the national archaeological and cultural heritage has been produced since 2007 by the 'Commissione paritetica per la realizzazione del Sistema Informativo Archeologico delle Città Italiane e dei loro Territori' followed, in 2009, by one from a second Committee.[5]

Because of the need to deal with the wide heterogeneity of data, caused by an apparent lack of coordination between the various research initiatives, the starting point of the project was the creation of 'geographical' information support for 'the preparation of a document containing the interoperability standards between systems, aimed at the identification of the essential requirements for GIS in archaeology in relation to the purposes of protection and knowledge' (Carandini 2008: 200).

The second Committee continued on the path taken by the previous one, in an effort to identify concrete actions for the creation and adoption of a standard for the national archaeological heritage GIS.

The adoption of the Landscape Plan of the Region of Sardinia, the first in Italy to conform with the guidelines laid down by the European Convention for the Landscape (Firenze 2000) and according to what is defined by Legislative Decree 42/04 — Code of Cultural Heritage and Landscape — seemed to give new energy to the activities of documentation of archaeological heritage in the form of GIS coordinated, planned, and linked to the 'co-planning' between the state and the regions.[6]

Unfortunately we also have to deal with an ongoing fragmentation of initiatives at regional level; this is still far from a systematic approach and is not directed towards a common knowledge base.

In Sardinia local governments have proceeded independently, creating different local surveys, often without scientific homogeneity and producing a confusing array of analytical equipment, similar to the archaeological 'core-zone' areas created in the Regional Plan, but rarely able to help to understand (and therefore design) contexts.

It seems to have established a consolidated cultural and, consequently, legislative attitude, from which the idea derives that the informative apparatus should be 'site-oriented', with clear implications for the practice of protection. A situation no longer limited to research activity, but also extended to those related to the adoption of management Landscape Plans and those of urban and land management.

Because of its recent planning history,[7] the region of Sardinia is a particularly favourable environment for the practical application of this system.

The project 'Creation and activation of the Sardinian pole of the Information Network for the national collective construction of web GIS of Italian archaeological heritage' aims to be a permanent and constantly updated reference for exchanging information on the archaeological heritage at different national and international levels (Figure 1).

2 The Structure of Data (E.P.)[8]

The structure of the SITAN system is based on the Univocal Identifying Code or 'CUI', an independent self-generating code, that can be related to all possible developments of the platform.

Firstly, the CUI is composed of the ISTAT code (National Statistics Institute)[9] that indicates the region, province, and municipality in which the archaeological entity is located; secondly, by the geographical coordinates in degrees (giving six numbers after the decimal point); thirdly, by a random number or letter assigned by the system to avoid duplication due to the overlap of more than one element to identify (e.g. Monte Baranta 200900480839626440636566A).

To the CUI are associated, as well as the geometrical apparatus, the alpha-numeric information represented by a minimum set of obligatory values defined by the 'Alphanumeric Label', which represents the basic level of information extended to all categories and based on the items required by the 'Information Module' (MODI), as defined by the ICCD (Central Institute for Catalogue and Documentation).[10] The 'Alphanumeric Label' is the connecting link between SITAN and the system of cataloguing and designation of the cultural heritage of MIBACT.

Compared to the synthesis achieved by the Sassatelli Committee (2011: 98–102), the Sardinian experiment opted for a further simplification of the information based on the minimum set of data acquisition required by MODI, which has decreased from 26 to 16 items of which 6 are generated directly from the system on a geographical basis and only the remaining 5 are mandatory. It was decided to match each dataset to an

5 The 'Committee for the development and drafting of a project for the construction of the geographic information system of the Italian archaeological heritage', established by D.M., December 22 2009. In this regard see Sassatelli 2011: 99–102.

6 Legislative Decree 42/04, Art. 1 Section 3. Art. 5 requires that the regions, municipalities, metropolitan cities, and provinces cooperate with the Ministry of Heritage and Culture in the functions of cultural heritage protection.

7 The Sardinian Regional Law of 25 November 2004, no. 8, with the introduction of new Article n. 11 of the regional planning law no. 45/1989 has regulated the procedure of the Regional Landscape Plan (PPR) and has ordered that the municipalities approve their urban plans (PUC) as required by PPR.

8 The structure of the system, which is currently being experimented on, processed by the Sassatelli Committee is defined in the 'Final Committee Report' in which G. Azzena took part as responsible party for the 'Sardinian node'.

9 www.istat.it/it/

10 www.iccd.beniculturali.it/

Fig. 1. The archaeological research network.

apparatus of metadata in accordance with ISO 19115: 2005, in order to have some sort of identity card of the actual drafters of the data and to have a functional reference to increase the information of each datum in SITAN. Each data set is linked to a metadata apparatus, a sort of ID card for material extenders of the datum and a functional reference in the exploration of information of each element present in the system.

The system is then included in the so-called 'Areas of investigation' (or 'Identifiers') systems of primary identification description; these are exclusively aerial, geographical, and topographical references that represent the minimum level of knowledge, called the 'Maximum Common Divisor' by the Sassatelli Committee, and are divided into five categories.

The 'Identifiers' are listed below:

1. Area of extended deposits

The synthesis between different Identifiers is achieved through the 'Area of Extended deposits'. The overlapping of the levels below leads to a complex network of archaeological phenomena and links among identifiers.

2. Area of general investigation

Archaeological surveys, graduate dissertations, and all investigations that do not include an archaeological excavation — a geometric minimum value that can be either positive or negative.

3. Area of excavation

Excavation (productive/unproductive):

All research including archaeological excavation. There could be two-dimensional or three-dimensional elements as well as metric values; those including heights must be expressed as geometric entities.[11]

4. Area subject to direct restriction

Direct/indirect limit:

Direct archaeological limitation set by decrees, 'Galassine',[12] archaeological areas, and parks.[13] In force for the framework agreement between the archaeological conservation agency of Sardinia and DADU, we proceeded with the experimental data input of the database in order to validate the system.

5. Area subject to different kinds of archaeological restriction

Area subject to other types of archaeological restrictions as they are outlined by regional or local administration. This is a category similar to the previous one, differentiated only by the type of producer of limitation date.

Within these areas, through a traditional approach to archaeological cartography with well-defined topographical elements, the category of archaeological sites and the minimum unit of archaeological evidence identified in the area through direct verification based on a bibliographical trace was introduced by the Sassatelli Committee into the unpublished documentation or in historical cartography.

The Sardinian experiment calls for this level of detail on a regional scale, but we wish to clarify that thanks to the work undertaken in collaboration with the Archaeological Superintendence for monuments and other heritage for the area of Porto Torres, we have a basis of information that allows the representation of the datum up to a single stratigraphic unit (Gottarelli 2011: 103–105).

3 Big producers of Data (E.P.)

The crucial steps for the efficacy of the Spatial Data Infrastructure (SDI) are the categorization by the georeferenced data producers on the island and the establishment of framework agreements for the development of an effective synergy between research and conservation agencies.

It is in this context that the Department of Architecture, Design and Urbanism of Alghero has signed an agreement with the Sardinian Department of Archaeological Heritage, to organize in a systematic way a real collaboration and exchange of information, which represents the starting point for the involvement of other institutional, economic, and social actors.

Fundamental to the structure of the agreement, from a regulatory point of view, is the Italian Legislative Decree no. 32/10 (Implementation of Directive 2007/2/EC) that establishes an Infrastructure for Spatial Information in the European Community (INSPIRE),[14] Legislative Decree no. 82/05 (Digital Administration Code), and Legislative Decree

[11] The areas of excavation defined here have been found in the urban area of Porto Torres, starting with a previous project with Nurra and Petruzzi (2013).

[12] Law of 8 August 1985, no. 431.

[13] This item in particular refers to point 81 of the CNIPA repository (National Computer Center for Public Administration).

[14] http://inspire.ec.europa.eu/

no. 42/05 (Establishment of the public connectivity system and the international network of the Public Administration), which, pursuant to Article 10 of the law of 29 July 2003, no. 229, applies regulations concerning the obligations for public administrations on the use of digital technologies and the management of databases.

Based on these directives and on the pattern laid down by the Ministerial Committees, the project has set protocols OGC XML, in particular OGC KML,[15] for the technological definition of the minimum metadata of intercommunication — the selection of technological standards of representation, protocols, and syntax that formalize the contents — and storage formats and formats of exchange and communication.

The Framework Agreement constitutes the paradigm of reference for entering into conventions with other agencies; for the use of facilities outside the university for supplementary teaching (Art. 27 DPR 383/80); for consultancy contracts and community projects in partnership; for conducting training activities (summer schools, workshops, seminars) and conferences on topics of common interest.

This path of collaboration based on the sharing of methods and instruments for the maintenance and use of archaeological data between the University of Sassari and The Sardinian Department of Archaeological Heritage, represents a very important step towards the knowledge and conservation of Italian archaeological heritage. The agreement includes duties and responsibilities and establishes the value of the results of the studies. It is based on the principle of 'best practice' for the process of unification and standardization between the projects currently undertaken on the national territory, and on the definition of the codices, terminology, and minimum requirements, with the intention of extending it to the widest possible number of subjects.

As mentioned above, the effort to achieve European directives on digital infrastructure, the adoption of Open Source and Open Format tools, as well as the creation of a database are fundamental parts of the Framework agreement.[16]

The objective, too long delayed, of the creation of an Italian Archaeological Map,[17] the first and necessary basis for any activity within the field of archaeological heritage, will only be achieved through the breaking down of all of the barriers that until now have limited the ownership of knowledge, areas of influence, and strongholds of competence, from time to time redefined in more or less tacit strategies, the only victim of which has been, and continues to be, the Italian national heritage (Azzena 2004: 191–195).

4 The Maximum Common Divisor (F.N.)

In archaeology, the study and analysis of so-called previous data (current and historical archives; specialist publications; historical, economic, geo-morphological, agronomic data; nature, landscape, etc.), the collection of data from direct analysis (excavations and rescue excavations, data from preventive archaeology, intensive and extensive, systematic and unsystematic surveys, archaeological censuses and investigations under the surface, etc.), are an abundant but heterogeneous source of information.

Most of these data have a common feature, however, which allows us always to place them in correlation: the position in space and time. The first is characterized by a pair of precise plane coordinates and taken from an altitude; the second, from a more or less precise numeric string. Thanks to this common feature, each item found, appropriately associated with a common Reference System (spatial and chronological), can be mapped.

Its location, in space and time, is the primary condition for the single datum to come into contact with others and with the environment, thus becoming effectively analysed and, at the same time, summarized. To achieve this result, interaction between basic data and geographical databases is essential; these are in their turn representative of multiple themes and variables.

In other words, it is no longer possible to delay the close communion between operational and scientific research institutes, institutions of protection, and the management of the territory, which in any case have begun to be produce their own cognitive and projective data, and different cartographic scales also of a historical-cultural and archaeological character. Above all and at all levels, one cannot delay the subsequent sharing of data — a democratization of information that contributes to the creation, definition, and promotion of the awareness essential for the purpose of a shared protection of the cultural heritage, which today has finally been achieved thanks to the contribution of the web.

A minimum amount of knowledge can therefore be derived from the information of the Carandini (2008: 199–207) and Sassatelli (2011: 99–102) Committees.

The attributes, terminology, and common lemmas which define the so-called 'Greatest Common Divisor' (Azzena 2011b: 38), must be the long-awaited standard for the treatment of archaeological data, according to the National Archaeological Geographic Information System (SITAN).[18]

From a strict geographical point of view, a projected reference system that complies with directives INSPIRE[19] and ISO TC211,[20] the UTM-WGS84 zone 32, Northern Hemisphere (EPSG:[21] 32632), has been chosen. Much of the acquired data in fact usedthe system of geographical native Roma40, projection 'Gauss-Boaga', West zone (EPSG: 3003). The first step was therefore to standardize the data to a single SRS (Spatial Referencing System) through appropriate coordinate transformations and projections.

5 Data Implementation and Constraint Issues (E.P.)

The collaboration with the archaeological Superintendence has set as a necessary starting point the complex issue of archaeological constraints, firstly, because it represents the most pressing and practical problem to be solved for obtaining

[15] www.opengeospatial.org/
[16] See below §8.
[17] For a history of the archaeological cartography of Italy see Castagnoli 1993: 5–81.

[18] See above §3.
[19] http://inspire.ec.europa.eu/
[20] http://www.isotc211.org/
[21] http://www.epsg.org/

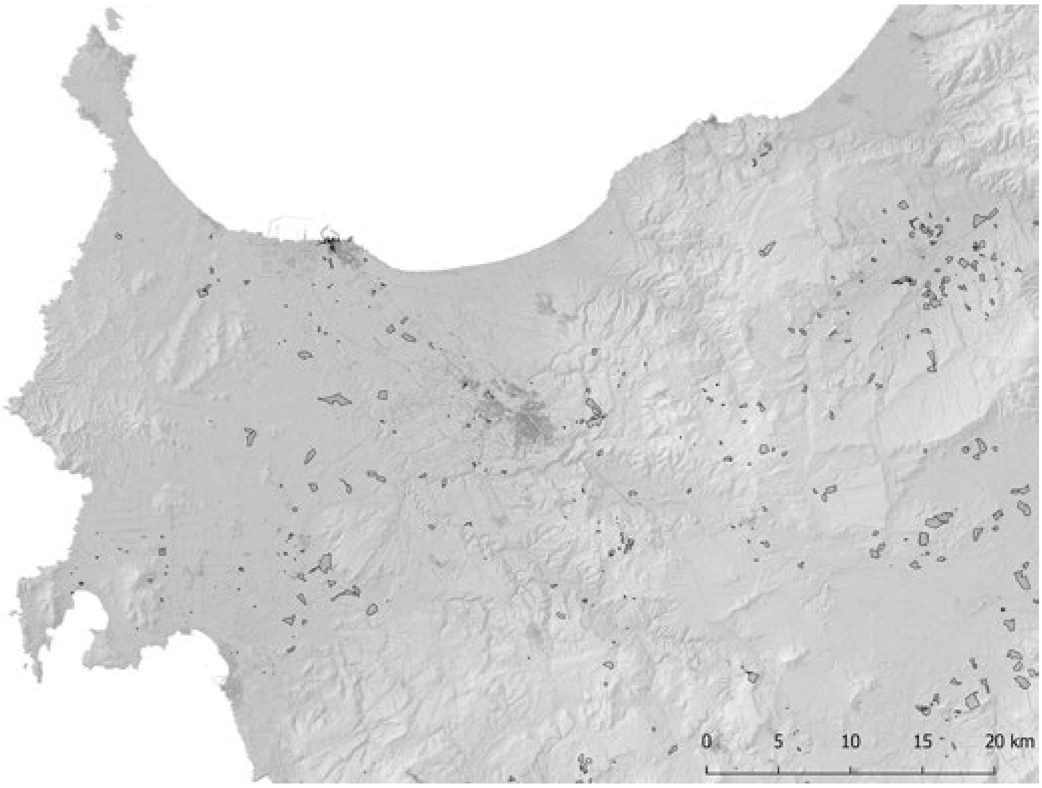


Fig. 2. Archaeological constraints in north-west Sardinia.

knowledge and for the protection of cultural heritage. Secondly, because of the complexity of the subject and for increasing the possibility of experimentation in relation to both the technical and administrative aspects of the management of territory: possibilities for expansion and sharing of knowledge of archaeological heritage, heterogeneity of knowledge at source, awareness and privacy of data, complexity of legal questions, transformation of land and territory, changes of ownership.[22]

The opportunity provided by the revision of the Regional Landscape Plan (PPR), was an exceptional field of experimentation. In order to assess, digitize, and georeference 'Identifiers', the implementation of the Geo-DB of the ministerial archaeological constraints of the province of Sassari, in North West Sardinia has been carried out.

The decree of constraint includes: the reference standard; the municipality where the constraint is located; the report on the reasons for imposing it; the cadastral references and, often but not always, a reference for the cartographic register; the minutes of notification to the owners of the cadastral maps affected by the constraint decree and in some cases the note of transcription of the Decree to the Conservatory for the Land Registry. The procedure starts with the breakdown of the document in order to identify all relevant information useful for the acquisition of information elements and their georeferencing.

The operation of geoinformatic acquisition of the constraints area have followed the following procedure:

[22] See below § 7.

- Building a GIS Project specifically structured for the needs of implementation of SITAN;
- Use of digital mapping reference (IGM Series 25,[23] CTR RAS,[24] Cadastral Sheets and Particles, multitemporal orthophoto);
- Geo-referencing of a cadastral excerpt based on the reference map;
- Construction of a vector layer structured in accordance with the 'Joint Committee for the development and drafting of a project for the construction of the Geographic Information System of the Italian Archaeological Heritage (DM 22 December 2009)';
- Digitization of the extent of the constraint and storage of the same on a PostgreSQL DB Server.[25]
- More than 1000 archaeological restrictions areas were analysed and digitalized in Central and North Sardinia.

The elaboration of data has shown different kind of issues to be considered:

[23] WMS service: http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/raster/IGM_25000.map

[24] WMS service: http://webgis.regione.sardegna.it/geoserverraster/ows?service=WMSandrequest=GetCapabilities

[25] http://www.postgresql.org/

- One of the biggest problems is the unavailability of the historical cadastre (register of property) which is linked to the incorrect position set by archaeological restrictions. The modification of properties as a result of sales, inheritance, etc. makes the definition of the restrictions even more difficult. The procedure for access and consultation of the historical cadastre in order to reconstruct the history a particular property to reach an accurate definition of the archaeological restrictions has been started.

- The progressive subdivision of the property means that in some cases a monument lies completely outside the cadastral maps indicated or is only partially included in it. In other cases, the property indicated in the decree of restriction no longer exists, and an investigation into the historical cadastre is essential.

- In many cases the definition of the restriction on a cadastral basis leads to errors in the definition of the boundaries. They were placed over very extended areas that included the monument as a whole but only in a marginal way, sometimes without regard to the relationship between the environmental conditions and the archaeological potential of the area.

- In other cases, despite the existence of a high number of archaeological elements attested by various studies there are no constraint decrees, which is a very dangerous situation for the archaeological heritage.

The definition of SITAN identifiers is complicated for a variety of problems:

Use and overlapping of different cartographic bases. The cadastre in shape file format provided by the Sardinian local government[26] does not correspond with other base maps. This purely technical issue implies a more complex reasoning about the nature and validity of the base maps. If the cadastral boundaries are the references on which is structured the technical and legal appraisal for the demarcation of the restriction, how is one to proceed in the case of an obvious offset of this cartographic base? Who determines which cartographic basis is correct?

Another problem that occurs is the absence of both archaeological and cadastral plans.

In a high number of restriction decrees the number of the property of archaeological interest is indicated only in the report but without any cartographic reference.

In these cases restrictions are defined without a critical analysis of the real situation of the boundary. It is not possible to verify where the temporary boundary is actually located. The absence of toponomastic elements and the impossibility of identifying monuments on an aerial photograph requires us to operate without any kind of reference points in the territory.

6 Protection and land management (R.B.)

The Italian model of management and protection of the cultural heritage is based on some essential elements that specifically aim at the identification of the archaeological entity[27] that has to be protected for the purposes of public use.[28]

On might query both the conceptual and the operative point of uploading an illogical archaeological map (from instrument to result, starting half way to reach the target.[29] There is a need to overcome the idea of an archaeological datum as a single 'object' to protect.

In the constant conflict between the need for protection and conservation of ancient heritage and urban and territorial planning, the 'Sardinia case' shows the limits that various practices currently cannot overcome.

The need to identify and locate in space individual archaeological evidence is inherent in the provision of the law, but by its nature, the graphic sign will only point to an archaeological presence, leaving out the various aspects related to data communication capable of conferring operability to the information obtained from different researches (Azzena 2004: 191).

It is essential that the draft and its subsequent publication is simple and straightforward in order to represent an interpretive and useful step towards the involvement of other specialized skills, properly developed and coordinated.

A synthesis is needed that would put a stop to alleged trivialization of data, and would offer the immediate possibility of defining a meta-language (Azzena, 2004: 195) on which archaeologists, architects, and planners can 'lay the foundations for a project aimed at understanding the patterns of life settlement expanded on it and to promote new forms of sociability rooted in its past and projected into the future' (Tagliagambe 2004: 223–224) (Fig. 3).

7 An ethical goal: Open Source and Open Data (F.N.)

For the acquisition of data of a different cartographic nature we have opted for the use of GIS tools. The choice fell on open source software, in line with the ethical choice of openness behind the whole project.

We chose the software QGIS[30] and its plugin, which perfectly meet the needs of digitization required by the project (Gottarelli 2011: 103–5). The data was stored using a DB server PostgreSQL[31] with a PostGIS[32] geographic interface.

[26] http://www.sardegnageoportale.it/index.html

[27] Starting from the definition provided in Art. 2, paragraph 2 of the Code of Cultural Heritage and Landscape until the 'rhetoric of the ruin'. For this see Choay 1995, Augé 2004, Scarrocchia 2011, and Azzena 2011a. For the relationship between current legislation on archaeological conservation policies see Ulisse 2009, and also Settis 2007, 2010.

[28] In reference to Legislative Decree no. 42/04, Art. 3, paragraph 1, see Busonera 2013. A clear interpretation of the Italian and, more generally, European model of protection is in Ulisse 2009.

[29] '…the archaeological map is the natural basis for all topographical research, but not the purpose of the research' (Mansuelli 1957: 299–301). 'Then it seems appropriate to reiterate that the archaeological map is mainly a cadaster!' (Azzena 2004: 188).

[30] http://www.qgis.org/it/site/

[31] http://www.postgresql.org/

[32] http://postgis.net/

Fig. 3. Urban development in relation to archaeological constraints.

Data acquisition has raised the issue of disclosure, distribution, and use of data. In a first phase it was decided to run the data through the format Keyhole Markup Language (KML), as required by the Sassatelli Committee (2011: 99–102), using the platform of Webmapping Google Maps[33] through its Google Maps Engine (GME),[34] commonly used on browsers and compatible with Google Earth.[35]

Google tools (as well as other large private providers), however, although free, are subject to a license agreement that binds the data to the provider, and therefore do not allow open licenses (such as Creative Commons,[36] Open Data License, etc.) and provide no guarantee for the archiving, preservation, distribution, and reuse of data.

The research was therefore directed towards different instruments. Interest has been directed to the community of open web mapping, particularly OpenStreetMap (OSM),[37] trying to find an 'interpretive key' of the data acquired according to the SITAN standard[38] towards a transfer to the OSM format, through the conversion tools available in the network. To do this the PostGIS database was drawn up through the editing software JOSM,[39] implementing the appropriate 'keys' and 'values' already available[40] and the necessary topological validation functional to the data entry into the system (Fig. 4).

This structure proved to be capable of identifying the data acquired according to categories already defined by the community: 'historical: archaeological_site', 'historical: ruins' and 'historical: heritage' (with various 'tags' and 'sub-tags' e.g. 'Period: ancient_rome'), identifying, for example in the case of archaeological constraints, a 'boundary: administrative', or an entity not visible or detectable on the ground but legally present. The strength of the data structure of OSM is constantly evolving and therefore provides endless possibilities for the adaptation and structuring of data (Fig. 5).

In addition, the structure already codified by OSM provides a 'ready to use' solution to the old problem of the relationship between archaeological objects and linked data in the network,[41] as the entities of OSM are already structured and defined according to semantics and terminology, using a

33 https://www.google.com/maps
34 https://mapsengine.google.com/
35 https://www.google.com/earth/
36 http://creativecommons.org/
37 https://www.openstreetmap.org/
38 See above §3.

39 https://josm.openstreetmap.de/
40 http://wiki.openstreetmap.org/wiki/Tags
41 i.e. http://www.ariadne-infrastructure.eu/ and http://www.europeana.eu/portal/

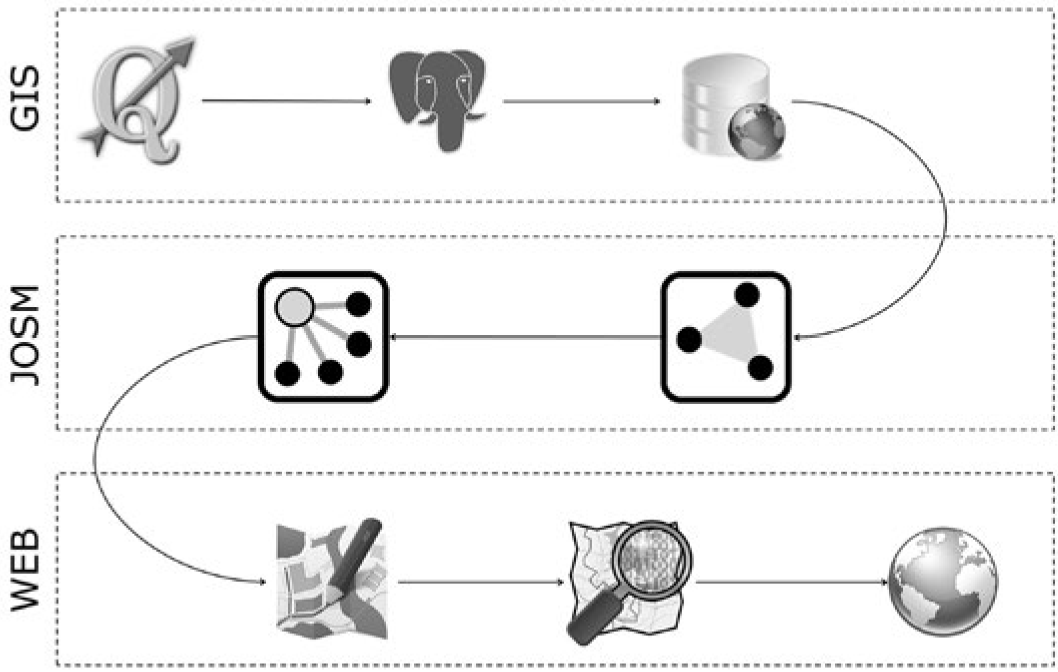


FIG. 4. SCHEMA OF THE ACQUISITION AND PUBLICATION OF ARCHAEOLOGICAL DATA IN THE SITAN PROJECT.

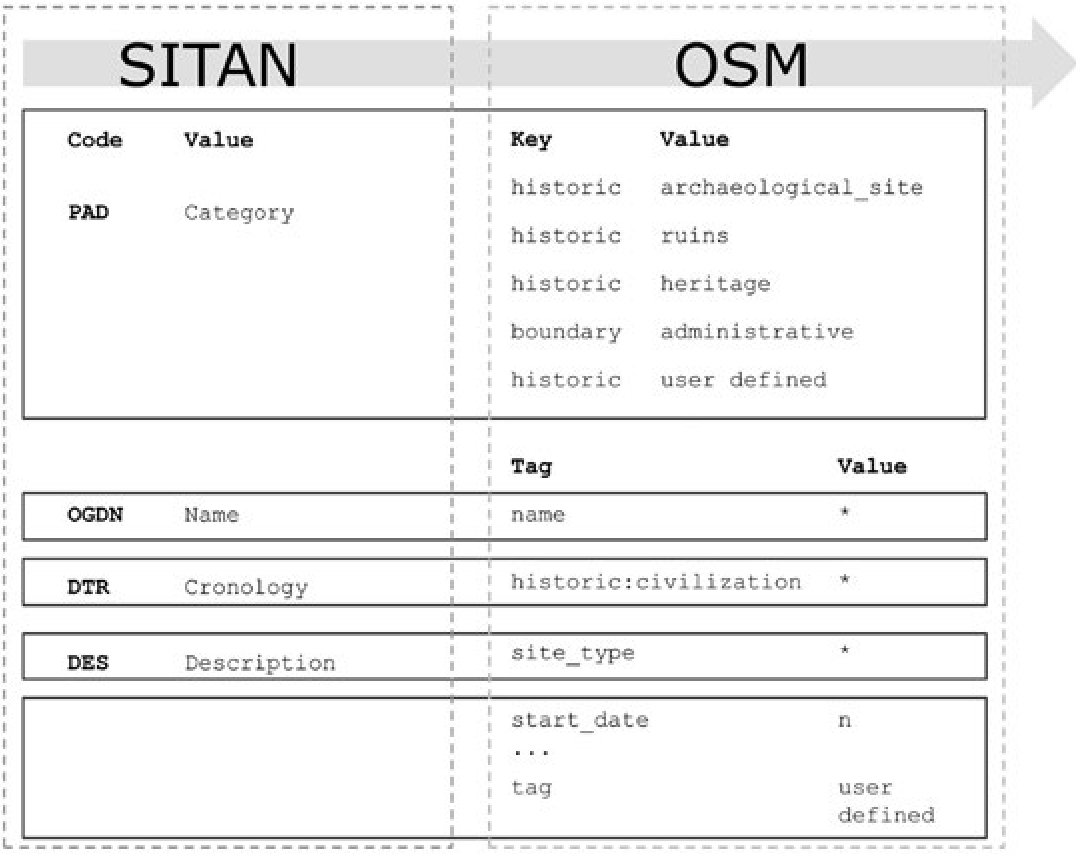


FIG. 5. A PROPOSAL FOR DATA MIGRATION FROM THE SITAN TO THE OSM FORMAT.

standard already prepared for the revolution that is sweeping the web: the web of objects or the semantic web.[42]

The idea of transferring to OSM also has several precedents: in particular, the transfer of SITAN data arose following recent steps by the Autonomous Region of Sardinia, which offered its open map data for the implementation of the OSM platform.[43] As well as the RAS, other administrations at national and international level, such as the French Cadastre office, opted for an open form of spread of information by OSM.[44]

This offers a new scenario regarding to the interchange of archaeological data on a global basis: the possibility that the continuous implementation of a basis of geo-referenced data, even in its minimal form, identifying a 'Greatest Common Denominator' of archaeological data[45] may be valid not only on a national scale, but also on an international one.

8 Conclusions (G.A.)

It is clear that the best and most urgent perspective for a real advancement of this research relates to attempts at the homogenization of an enormous amount of data so far obtained thanks to the collaboration of various public institutions within the region.

In order to have a knowledge base on which to found the necessary investigations on a detailed scale, the homogenization of data is certainly an important starting point and in that sense we must reflect whether the difficulties represent the mark of a consolidated cultural and consequently legislative orientation, from which comes the idea that an informative apparatus dedicated to the 'historic' landscape can be interpreted only as 'site oriented'.

Currently the focus is on traditional protection as well as 'innovative', precisely because it is activated by contrasting but rarely coordinated initiatives, which, besides being basically weak and confused, appears to be inadequate to support the actions of the 'respectful' planning of historical and archaeological elements in the territory.

A widespread and varied knowledge, extended in this case beyond national borders, is therefore an undoubtedly solid base from which to start; it can be used in different ways and with multiple functions on a continental and global scale.

The international research context, despite the interest shown by the European Union towards the processes of standardization and inter-operability of archaeological data,[46] does not seem oriented towards the problem of the precise location of archaeological data. This creates great difficulties in the definition of cartographic support on a continental scale.

The transposition of the INSPIRE Directive,[47] which is able to offer a valuable contribution in this sense, is highlighting the difficulties of implementing the system outside the government bodies involved in the territory and therefore particularly in the field of archaeology.

The European directive for the infrastructure of spatial data is applied, with respect to the infrastructure of data produced by institutions directly related to state or regional authority and consequently, does not affect those who produce cartographic archaeological data outside the bodies of the Ministry (universities, private institutions, etc.).

Reflecting on the possibilities and modalities of data sharing is undoubtedly extremely important, a sine qua non for a real opportunity to spread information and knowledge about local archaeology, but it might be useful to ask whether it is this concept that must be structurally and fundamentally changed even before heading for new frontiers, and thus changed is it misleading because it is still premature, with or without technological support.

Bibliography

Augé, M. 2004. *Rovine e macerie. Il senso del tempo*, Torino, Bollati Boringhieri.

Azzena, G. 2004. Tancas serradas a muros. Tracce di incomunicabilità nel 'linguaggio' dell'archeologia, tra tutela, archeologia del paesaggio, e pianificazione territoriale. *Archeologia e calcolatori*. 15: 185-97.

Azzena, G. 2009. Punto di non-ritorno (Cartografia numerica, sistemi informativi territoriali, analisi spaziale). *Archeologia e Calcolatori* 20: 169-77.

Azzena, G. 2011a. History for places/La storia per i luoghi. in Maciocco G., Sanna G., Serreli S. (eds.), *The urban potential of external territories*. Milano, Franco Angeli.

Azzena, G. 2011b. Una logica prospettiva. In Serlorenzi M. (ed.), *SITAR Sistema Informativo Territoriale Archeologico di Roma. Atti del I Convegno (Roma 2010)*. Roma, Iuno.

Busonera, R. 2013. Il territorio dell'archeologia. 'Musei senza muri' per la tutela e valorizzazione del 'paesaggio storico'. *Planum. The Journal of Urbanism.* 27, 2. Available at: http://www.planum.bedita.net/planum-magazine/siu/xvi-conferenza-nazionale-siu-atelier-3 [Accessed: 29 june 2015].

Carandini, A. 2008. *Archeologia Classica. Vedere il tempo antico con gli occhi del 2000*. Torino, Einaudi.

Castagnoli, F. 1993. *Topografia Antica: un metodo di studio* I. Roma, Istituto Poligrafico e Zecca dello Stato.

Choay, F. 1995. *L'allegoria del patrimonio*. Roma, Officina.

Corns, A., Shaw, R. 2010. Cultural Heritage Spatial Data Infrastructures (SDI) - Unlocking the Potential of our Cultural Landscape Data. In *30th EARSeL Symposium - Remote Sensing for Science, Education, and Natural and Cultural Heritage*. Paris, Rainer Reuter.

Gottarelli, A. 2011. Il Progetto di Network della Ricerca archeologica. In Serlorenzi M., Jovine I. (eds.), *SITAR. Sistema Informativo Territoriale Archeologico di Roma. Potenziale archeologico, pianificazione territoriale e rappresentazione pubblica dei dati. Atti del II Convegno (Roma 2011)*. Roma, Iuno.

42 http://wiki.openstreetmap.org/wiki/OSM_Semantic_Network

43 http://www.sardegnageoportale.it/index.php?xsl=1598ands=267969andv=2and c=9166andt=1

44 http://wiki.openstreetmap.org/wiki/WikiProject_France/Cadastre

45 Cfr. §5

46 See for example the impact had by the projects EUROPEANA 2015 and Ariadne 2012.

47 The INSPIRE (Infrastructure for Spatial Information in Europe) is available in INSPIRE 2004; 2014. About Implementation in archaeology see McKeague *et al.* 2012 and Corns and Shaw 2010.

Manuseli, G.A. 1957 in Enciclopedia Classica, Sezione III. Archeologia e storia dell'arte classica, X, t. III (Geografia e Topografia Storica), Torino, S.E.I.

Mckeague, P., Corns, A., Shaw, R. 2012. Developing a spatial data infrastructure for archaeological and built heritage. *International Journal of Spatial Data Infrastructures Research* (2012): 38-65.

Nurra, F., Petruzzi, E. 2013. Passaggi di scala. Dal contesto urbano al territorio. Geo-informatica per l'individuazione e la tutela del paesaggio storico. In Galeotti, G., Paperini, M. (eds.), *Città e Territorio, tutela e valorizzazione del paesaggio culturale.* 1. Livorno, Debatte.

Sassatelli, G. 2011. La Seconda Commissione ministeriale per la formazione di un Sistema Informativo Territoriale Archeologico Nazionale. In Serlorenzi, M. (ed.), *SITAR Sistema Informativo Territoriale Archeologico di Roma. Atti del I Convegno. Roma-Palazzo Massimo (26 Ottobre 2010)*, Roma, Iuno.

Scarocchia, S. 2011. *Alois Riegl. Il culto moderno dei monumenti, il suo carattere e i suoi inizi*. Milano, Abscondita.

Serlorenzi, M. 2011. *SITAR Sistema Informativo Territoriale Archeologico di Roma. Atti del I Convegno. Roma-Palazzo Massimo (26 Ottobre 2010)*, Roma, Iuno.

Settis, S. 2007. *Italia S.P.A. L'assalto del patrimonio culturale*, Torino, Einaudi.

Settis, S. 2010. *Paesaggio costituzione cemento. La battaglia per l'ambiente contro il degrado civile*, Torino: Einaudi.

Spanedda, F. 2004. *Progetti di territori*, Milano, FrancoAngeli.

Tagliagambe, S. 2004. Postfazione. In Spanedda, F. (ed.), *Progetti di territori*. Milano, Franco Angeli.

Ulisse, F. 2009. *Tutela della cultura e cultura della tutela. Cartografia archeologica e legislazione sui beni culturali in Italia e in Europa*. Bologna, Ante Quem.

Websites

ARIADNE 2012. *Ariadne - Ariadne*[Online] http://www.ariadne-infrastructure.eu/ [Accessed: 29 june 2015].

CREATIVE COMMONS. *Creative Commons.* [Online] http://creativecommons.org/ [Accessed: 29 june 2015].

EUROPEANA 2015. *Europeana - Homepage* [Online] http://www.europeana.eu/portal/ [Accessed: 29 june 2015].

GEOPORTALE NAZIONALE. *Geoportale Nazionale – Home.* [Online] http://wms.pcn.minambiente.it/ [Accessed: 29 june 2015].

GOOGLE EARTH. *Google Earth.* [Online] https://www.google.com/earth/ [Accessed: 30 june 2015].

GOOGLE MAPS. *Google Maps.* [Online] https://www.google.com/maps [Accessed: 30 june 2015].

GOOGLE MAPS ENGINE. *Maps Engine.* [Online] https://mapsengine.google.com/ [Accessed: 30 june 2015].

INFRASTRUCTURE FOR SPATIAL INFORMATION IN THE EUROPEAN COMMUNITY 2007. *Inspire > welcome to inspire.* [Online] http://inspire.ec.europa.eu/ [Accessed: 30 june 2015].

INTERNATIONAL ASSOCIATION OF OIL and GAS PRODUCERS. *epsg > EPSG home*. [Online] http://www.epsg.org/ [Accessed: 30 june 2015].

ISO/TC 2011. GEOGRAPHIC INFORMATIC/GEOMATICS. [Online] http://www.isotc211.org/ [Accessed: 30 june 2015].

ISTITUTO CENTRALE PER IL CATALOGO E PER LA DOCUMENTAZIONE (ICCD). *Home – ICCD.* [Online] http://www.iccd.beniculturali.it/ [Accessed: 30 june 2015].

ISTITUTO NAZIONALE DI STATISTICA (ISTAT). *Istat.it* [Online] http://www.istat.it/it/ [Accessed: 30 june 2015].

OPENSTREETMAP. *OpenStreetMap.* [Online] https://www.openstreetmap.org/ [Accessed: 30 june 2015].

OGC. OPEN GEOSPATIAL CONSORTIUM. *Open Geospatial Consortium | OGC* [Online] http://www.opengeospatial.org/ [Accessed: 30 june 2015].

OPEN STREETMAP SEMANTIC NETWORK. *OSM Semantic Network – OpenStreetMap Wiki* [Online] http://wiki.openstreetmap.org/wiki/OSM_Semantic_Network [Accessed: 30 june 2015].

OPEN STREET MAP WIKI. Tags – OpenStreetMap Wiki. [Online] http://wiki.openstreetmap.org/wiki/Tags [Accessed 30 June 2015].

POSTGIS. SPATIAL AND GEOGRAPHIC OBJECT FOR POSTGRESQL. *PostGIS – Spatial and Geographic Objects for PostgreSQL.* [Online] http://postgis.net/ [Accessed: 30 june 2015].

POSTGRESQL. *PostgreSQL: The world's most advanced open source database.* [Online] http://www.postgresql.org/ [Accessed: 30 june 2015].

QGIS. UN SISTEMA DI INFORMAZIONE GEOGRAFICA LIBERO E OPEN SOURCE. *Benvenuto all'interno del progetto di QGIS!* [Online] http://www.qgis.org/it/site/ [Accessed: 30 june 2015].

SARDEGNA GEOPORTALE. *Sardegna Geoportale – Home page*. [Online] http://www.sardegnageoportale.it/ [Accessed: 30 june 2015].

SARDEGNA GEOPORTALE. Sardegna Geoportale – *Agenda – Notizie – Import Edificato della Regione Sardegna su OpenStreetMap* [Online] http://www.sardegnageoportale.it/index.php?xsl=1598ands=267969andv=2andc=9166andt=1 [Accessed: 30 june 2015].

WIKIPROJECT FRANCE/CADASTRE. *WikiProject France/Cadastre – OpenStreetMap.* [Online] http://wiki.openstreetmap.org/wiki/WikiProject_France/Cadastre [Accessed: 30 june 2015].

The GIS for the ‘Forma Italiae’ Project. From the GIS of the Ager Venusinus Project to the GIS of the Ager Lucerinus Project: Evolution of the System

Maria Luisa Marchi
marialuisa.marchi@unifg.it

Giovanni Forte
gianniforte76@libero.it

Department of Humanities. Literature, Cultural Heritage, Education Sciences, University of Foggia, Italy

Abstract: This paper presents the research method applied to the ‘Archaeological Map of Italy – Forma Italiae’ project, comprising to date, the Ager Venusinus project (completed) and the Ager Lucerinus project (ongoing).

The idea of an archaeological map of Italy dates back to 1889. Giuseppe Lugli's publication in 1926 of the first volume of Forma Italiae represents the continuation of the initial royal project. Many decades later, with the advent of information technology and satellite observing systems as well as GPS, a ‘new era’ of archaeological mapping had begun and the ‘Forma Italiae’ started to develop the first Territorial Information System of archaeological material in Italy.

This project represents one of the first applications of both GIS (Geographic Information System) and GPS (Global Position System) in archaeology. Between 1989 and 1992, studies and experiments were carried out on automatic systems for the acquisition, calculation, and management of archaeological data relating to the Carta Archeologica d'Italia (Forma Italiae).

It is important to keep in mind that in the GIS (Carta Archeologica d'Italia: Archaeological Map of Italy – Forma Italiae) all archaeological elements, both monumental and structural as well as a scatter of material on the surface, are georeferenced, their shapes and sizes perfectly represented.

Our project sought to put together many experiences, including some from the past, as part of a ministerial initiative resulting in the establishment of a committee; furthermore, it sought to extend the discussion that for many years concerned primarily academic institutions in the sectors dealing with protection and archaeological prevention. The project, as a whole, made possible the creation of a large integrated system for a more thorough knowledge of Italian cultural heritage. Although it has been designed for prevention and protection, it simultaneously serves as the basic instrument for the understanding and enhancement of the cultural resources of the territory. In discussions about preventive archaeology and about the so-called ‘archaeological risk’, it is very useful to create a databank of the known archaeological heritage. The correct application of the most advanced technologies (such as GPS and dedicated GIS) enabled a precise referencing for each of these, along with a rapid creation of thematic cartographies.

For this purpose, a computerized system for data management was used, composed of a GIS platform associated with an alphanumeric archive and designed soon to become a webGIS.

Keywords: Archaeological map, GIS, GPS, ancient topography, Webgis

Introduction

This paper presents the research method applied to the ‘Archaeological Map of Italy – *Forma Italiae*’ project (Fig. 1), comprising to date, the Ager Venusinus project (completed) and the Ager Lucerinus project (ongoing) (Fig. 2). This project is a joint effort of the University of Rome ‘La Sapienza’ Cartographic Laboratory of Experimental Archaeology and the Cartography Laboratory of the University of Foggia.

The idea of an archaeological map of Italy dates back to 1889 when a royal degree created the ‘Bureau for an Archaeological Map of Italy’. Giuseppe Lugli's publication in 1926 of the first volume of *Forma Italiae* represents the continuation of the initial royal project (Castagnoli 1978: 78–80; Azzena 2002: 149–52; Sommella 2009: 47–59). Many decades later, with the advent of information technology — Satellite Image analysis and GPS — a ‘new era’ of archaeological mapping began, and the ‘*Forma Italiae*’ started to develop the first Territorial Information System of archaeological material in Italy.

This project represents one of the first applications of both GIS (Geographic Information System) and GPS (Global Position System) in archaeology (Sommella 1987) and one of the first working with GPS (Fig. 3). Between 1989 and 1992, studies and experiments were carried out on automatic systems for the acquisition, calculation, and management of archaeological data relating to the Carta Archeologica d'Italia (*Forma Italiae*) (Sommella 1989). Currently we use GPS for all archaeological sites. The correct application of the most advanced technologies (such as GPS and dedicated GIS) enabled a precise referencing for each of these, along with a rapid creation of thematic cartographies (Sommella 1992; Azzena, Tascio 1996: 281–97; Marchi 2010: 25–8; Marchi, in press) (Fig. 4).

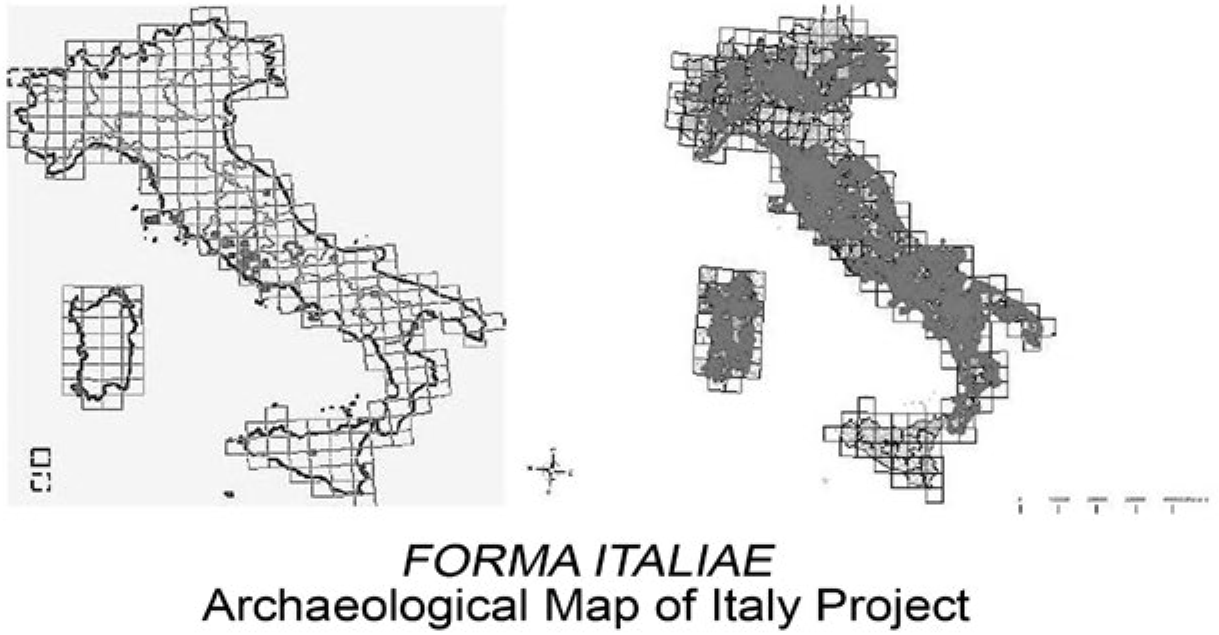

FORMA ITALIAE
Archaeological Map of Italy Project

FIG. 1.

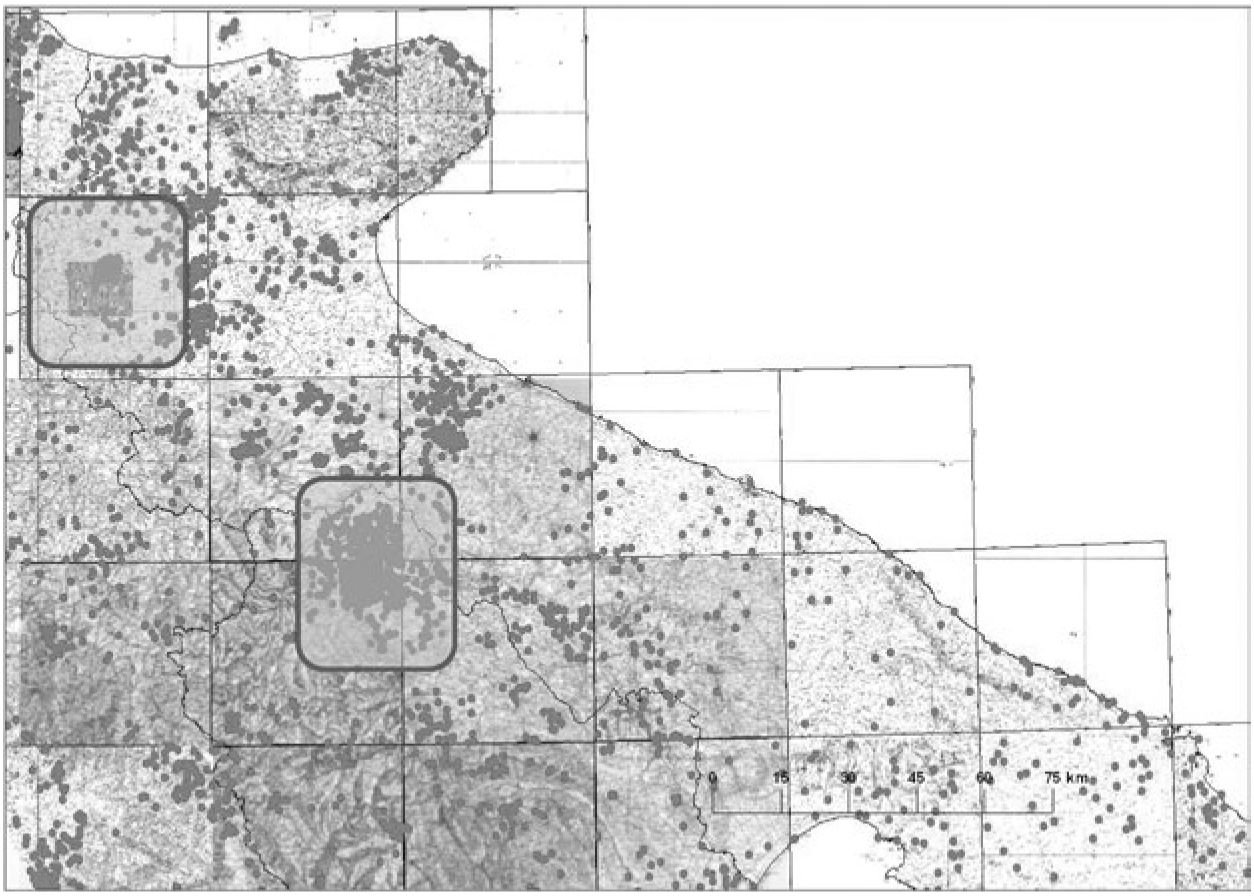

0
15
30
45
60
75 km

FIG. 02.

Fig. 3.

The data archive of this project could also serve as a learning foundation and a starting basis for all those who work in the area and may contribute towards a greater efficiency of preventive archaeology tools.

For this purpose, a computerized system for data management was used, composed of a GIS platform associated with an alphanumeric archive and designed in a short time to become a webGIS.

The importance of an archaeological heritage database is reinforced by the discussion on preventive archaeology and more generally on 'archaeological risk', a topic currently considered of great relevance.

1 The Ager Venusinus project (M.L.M.)

While not being a determining factor, the experience of research in the Ager Venusinus gained in 20 years has facilitated much, as explained above, especially since information technology began to be integrated in most territorial documentation.

Experimenting with the 'automatic' passage of information from a direct reading of the land to an operational project but without specialist interpretation was started in topographical research as well as in the selective reading of both urban and territorial themes (Sommella 2009; Azzena 2009) (Fig. 5). This was one of the first archaeological projects in Italy to use GIS, experimenting database input and GIS applications. Our project included the creation of a dedicated GIS (Carta Archeologica d'Italia: Archaeological Map of Italy – *Forma Italiae*) (Azzena 2004; Marchi, Mazzei 2012; Marchi, in press).

All archaeological elements, both monumental and structural as well as scatter of material on the surface are georeferenced, their shapes and sizes perfectly represented (Fig. 6). It is important to keep in mind that having the entire project with all its analytical data in the GIS makes cartographic references and indications of scale superfluous.

Archaeological points have been catalogued by providing data in site reports/bibliography and site/recognition reports appropriately processed using a process based on lengthy experimentation with computerized cartographic methods, and data based on many years of data-processing experience. The contents are adjusted to the stability parameters of the MiBAC[1] Joint Committee (Carandini 2008) and compatible with the ICCD[2] cataloguing standards, especially with regard

1 MiBACT (Ministero dei Beni e delle Attività Culturali e del Turismo) – Ministry of Cultural Heritage and Tourism.

2 ICCD – (Istituto Centrale per il Catalogo e la Documentazione) – The Central Institute for Cataloguing and Documentation within the Italian Ministry of Heritage and Culture (MIBAC), defines procedures, standards and tools for the Cataloguing and Documentation of national archaeological, architectural, art history, and ethno-anthropological heritage in agreement with the Regions.

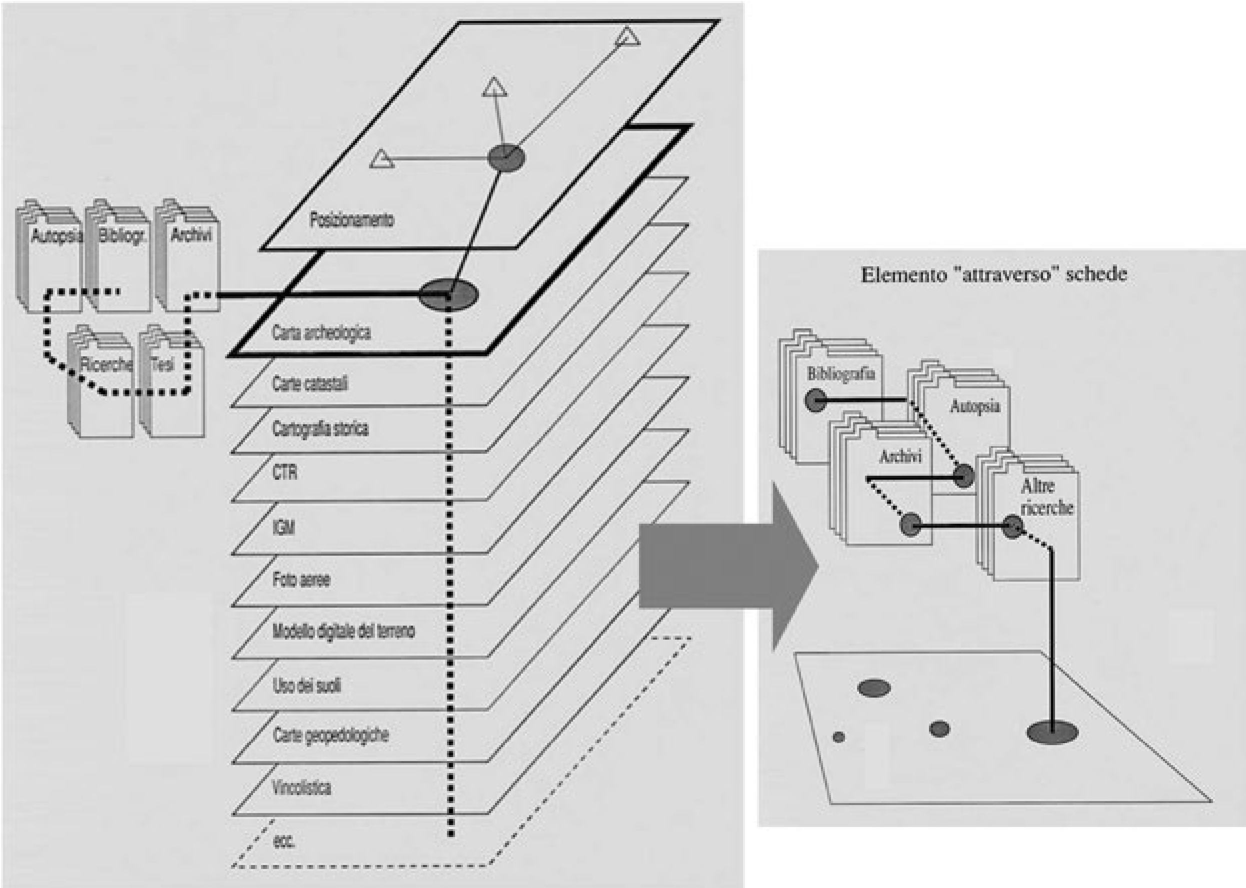


FIG. 4.

to the identification parameters. All the items in the report are found in dictionaries contained in the drop-down menu, and these are also processed on the basis of the ICCD directive and the lengthy experience acquired from modelling experiments (Azzena, Tascio 1996).

One of the most important factors is the input of archaeological constraints as preferences (Marchi, Mazzei 2012).

The large volume of data collected (over 3000 reports) between the end of the 1980s and 2000 has facilitated the refining of methods and techniques in a continuously evolving system.

Our project was also one of the first to work with GPS (Global Position System) (Azzena 1992: 747–76). Between 1989 and 1992, studies and experiments were carried out on automatic systems for the acquisition, calculation, and management of archaeological data relating to the *Forma Italiae* (Sommella 1987; 1989).

This method was also used in the project 'Bibliography for the archaeological map of the Province of Rome' (Amendolea 2003; Marchi 2005) and in the 'Project Census for an Archaeological Map of Italy' (Marchi 2012).

The 'Project Census for an Archaeological Map of Italy', was carried out over several years (2002–2008) to create a scientific and technical instrument which uses the method of the 'Archaeological Map' of Italy, on input from the Ministry of Cultural Heritage and Activities, in collaboration with Sapienza University of Rome with the participation of the University of Foggia, and was carried out in several operative phases.

The Project enabled the realization of a large integrated system for heritage protection and an essential instrument for better knowledge and greater valorisation of the Italian cultural heritage.

The programme provided a 'Register', based on the inventory and georeference of bibliographic and archival data. The census of the archaeological records is based on published data for which a topographic localization on a map is possible. To insure the reliability of the data, which should be verified on site, the archaeological elements were selected based on two levels of reliability: geo-referencing and general localization. The project led to the count of almost 30,000 archaeological sites, chronologically ordered from Prehistory to the high Middle Ages (Fig. 1).

The mass of data gathered (more than 3000 items for the Ager Venusinus project and 1200 points for the Ager Lucerinus project) allowed us to refine techniques and methods for constructing a database. We experimented with many formats for entering data, both from sites and materials.

The digital information collected makes possible the distribution analysis of archaeological finds as a function of chronological phases, as well as the study of settlement

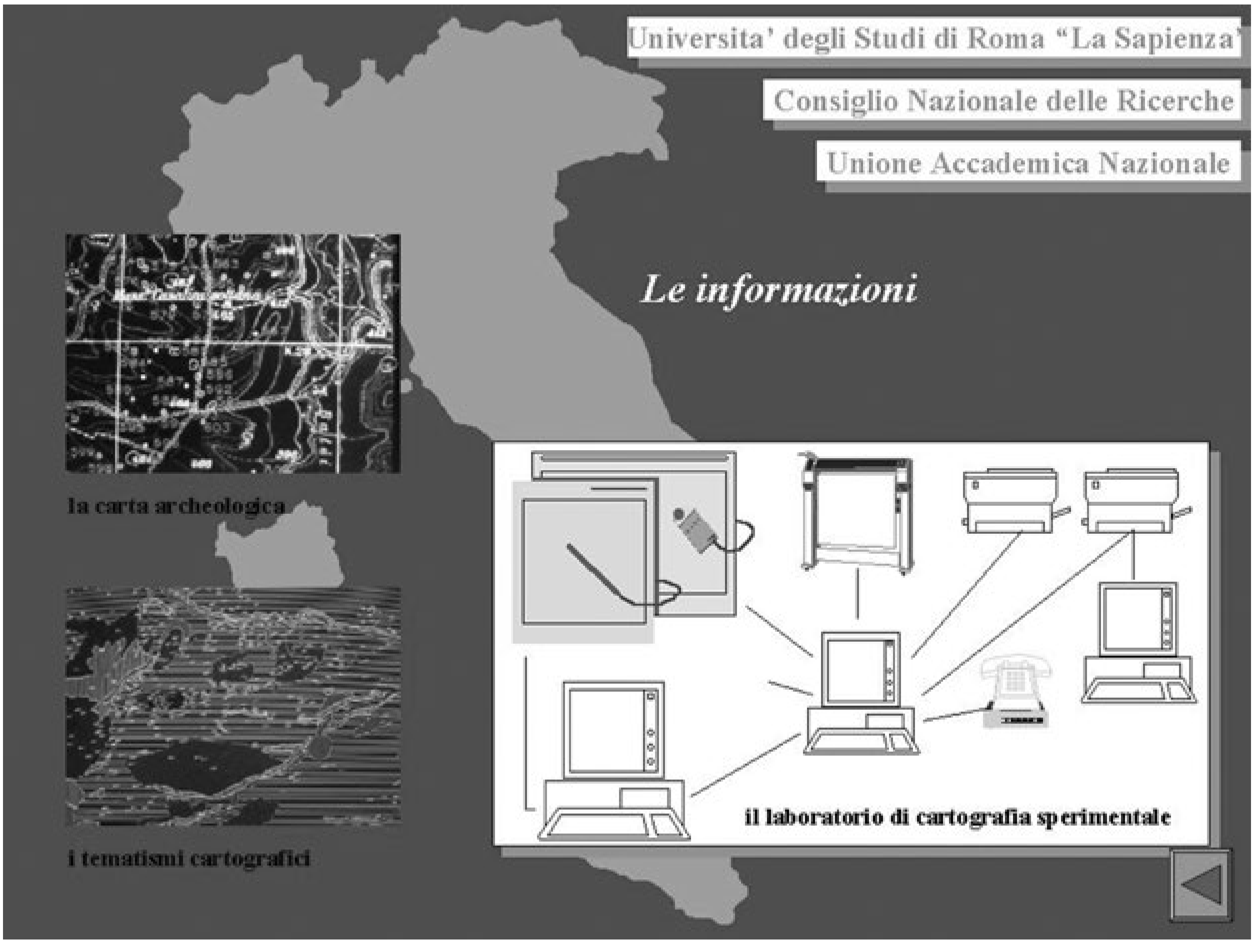


Fig. 5.

dynamics of the historic landscapes, and provides indicators of hidden or unexpected characteristics found when complex territorial systems are analysed.

The system facilitates in-depth investigation of the distribution maps of various settlements and their relationships with other sites, as well as the exploitation of spatial analysis techniques together with other information sources so that extremely useful critical items can be caught in the territorial planning phase. This GIS project has proved to be useful in scientific research and for the protection of the cultural heritage. Moreover, it must be emphasized that the GIS presented is the result of a very lengthy process of experimentation and the examples only represent some of the potential that the system offers to researchers. This is only the starting point of the research and not its final aim, which is the historical reconstruction of the territory and its landscape (Fig. 7).

2 The Ager Lucerinus project (G.F.)

The Ager Lucerinus project (Fig. 8) concerns a territory the ancient landscape of which was varied and articulated. The archaeological map produced is a valid instrument for the protection of an area continuously threatened by the spread of wind farms. Indeed, the GIS data processed by the Archaeological Cartographic Laboratory in accordance with the Superintendence for Archaeological Heritage in Puglia was used as a support for the Puglia Regional Territorial Landscape Plan (PPTR).

Characteristics and peculiarities of the GIS are again the 'Archaeological Map of Italy – *Forma Italiae*'. In the initial phase, we used a multiple source data retrieval approach (bibliographic, archival, epigraphic, archaeological, etc.), recording much of the information, reducing it to generic symbols and distinguishing only location type (precise or generic), but the scarcity of material gathered in the early stage of the project made clear the need for a more detailed survey of the territory itself.

The cartographical base reference is 'Carta Tecnica Regionale'[3] at the scale of 1:10000 and supported by regional ortho-photography. We also use the cadastral map, indispensable as a protective measure, but this is seldom used in the operational phase because it lacks altimetric references and is often completely anachronistic.

As previously confirmed, the 1:25000 scale IGM[4] map is an unsurpassed base reference for the global picture and is more

[3] Just as for the Geoportale Nazionale, in this case reference has been made to the free services available on the web site http://www.sit.puglia.it

[4] IGM (Istituto Geografico Militare) - the Italian military geographical institute.

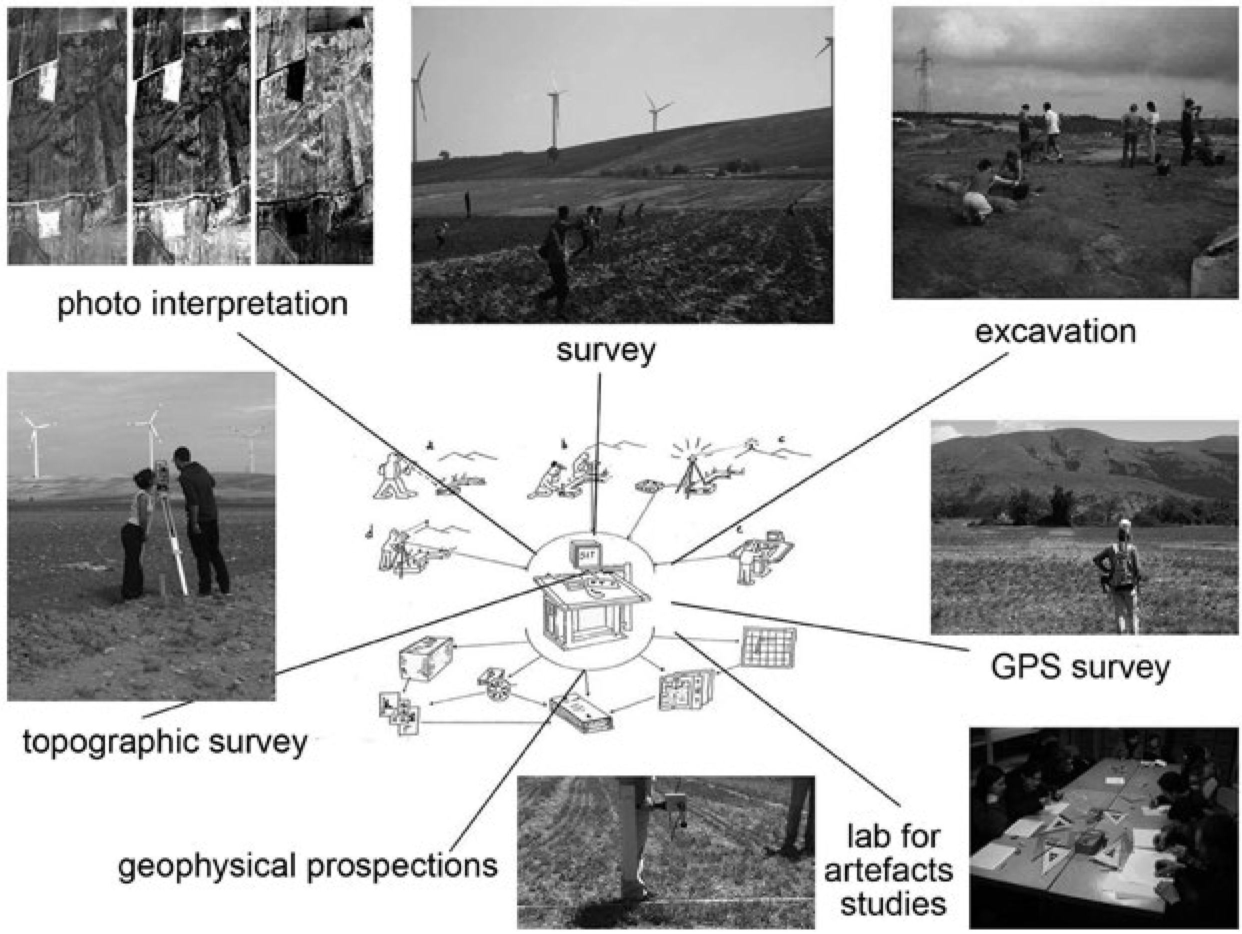


FIG. 6.

useful in some situations as historic cartography rather than as a direct reference in the field.

Aerial photographs were essential for the identification of archaeological evidence, such as crop marks, in the territory. The material from the RAF photographic coverage for the area (1943–47) and from IGM were unquestionably useful.

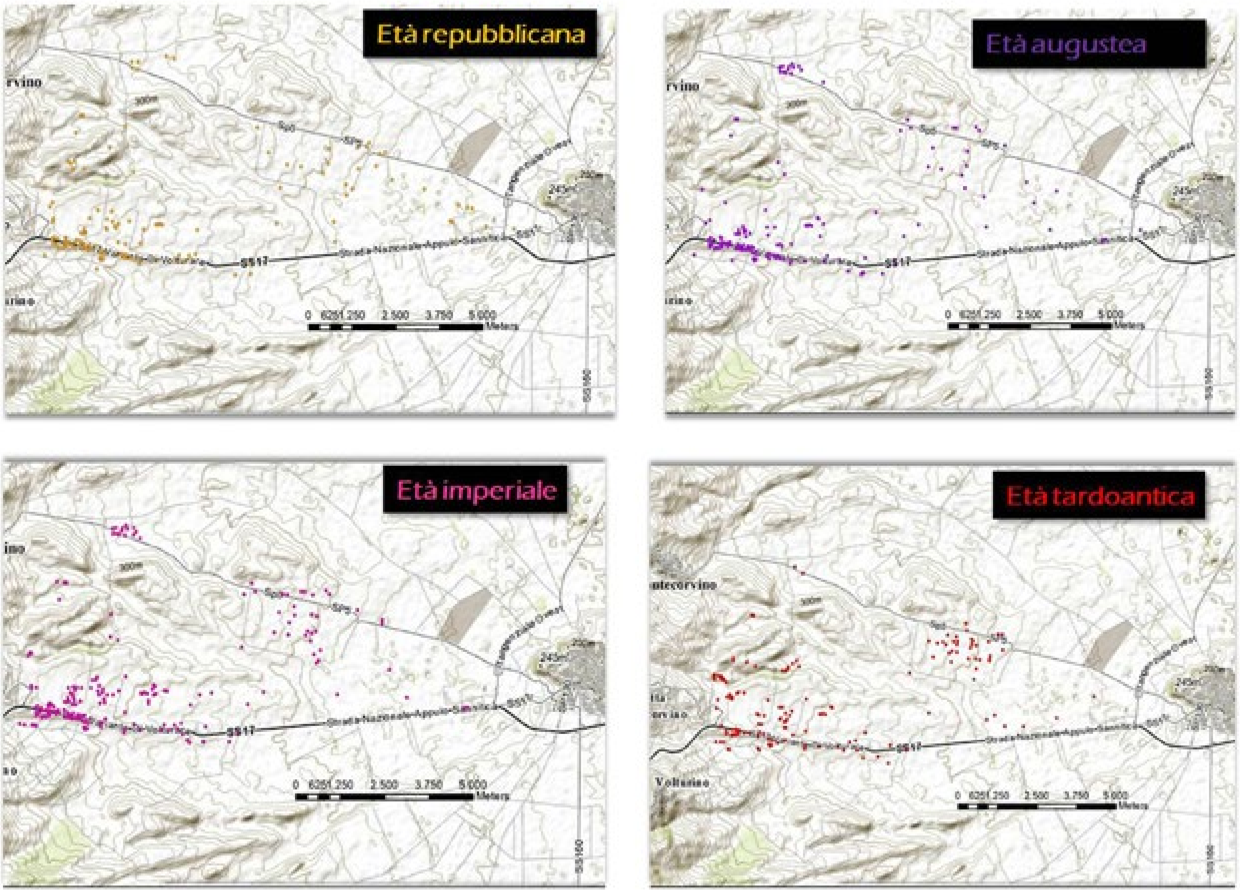
The aerial coverage currently available (1954; 1988–89; 1994; 1998; 2000; 2004; 2007; 2010) was compared in order to check how the legibility of traces through time. The interpretation and, where possible, the geo-referencing of the historic cartography are essential for the recovery and analysis of items in the landscape, especially in the historic reconstruction of infrastructures such as the road network, or geomorphological evolution and changes in the landscape. Therefore, a series of historic maps were also regenerated, georeferenced, and analysed during the project, including precious historic maps such as the Rizzi Zannoni, the 'Locations' of the 'Foggia sheep Customs House', and all of the IGM cartography (Fig. 9).

2.1 The GIS for the Ager Lucerinus project

The various applications of information systems in the archaeological-topographical domain are, above all, an instrument that solves a wide range of problems with management and data analysis methods. What characterizes an archaeological GIS is not so much its content or the managed data but its ability to interpret the data.

The GIS used in the study presented in this paper is also based on three-dimensional models. These show one of the most important variables in the understanding of ancient behaviour: the landscape and the human interaction with it.

It should be noted that some of the above-mentioned series of aerial photographs available for GIS analysis, are directly available online through the OGC (Open Geospatial Consortium). Previously known as the OpenGISConsortium, this is an international non-profit organization based on a voluntary agreement that defines technical specifications for geospatial and location-based services. In particular, the method used to implement the Ager Lucerinus project not only made use of aerial photographs but also WMS, WFS, and WCS services present in the National Geoportal (www.pcn.minambiente.it). Using a procedure in the project GIS software (i.e. proprietary ESRI ArcGis, Geomedia, and free QGis) through which the information layer can be coupled and projected on the fly (only with an Internet connection) inside the project presented in this paper as a normal information layer. In addition to clear financial benefit and time saving, this procedure obtains updated georeferenced data at a very high standard. Geomagnetic or electromagnetic prospections are also carried out in some cases in order to add further


Età repubblicana
Età augustea
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0 625 1.250 2.500 3.750 5.000
Meters

Fig. 7.

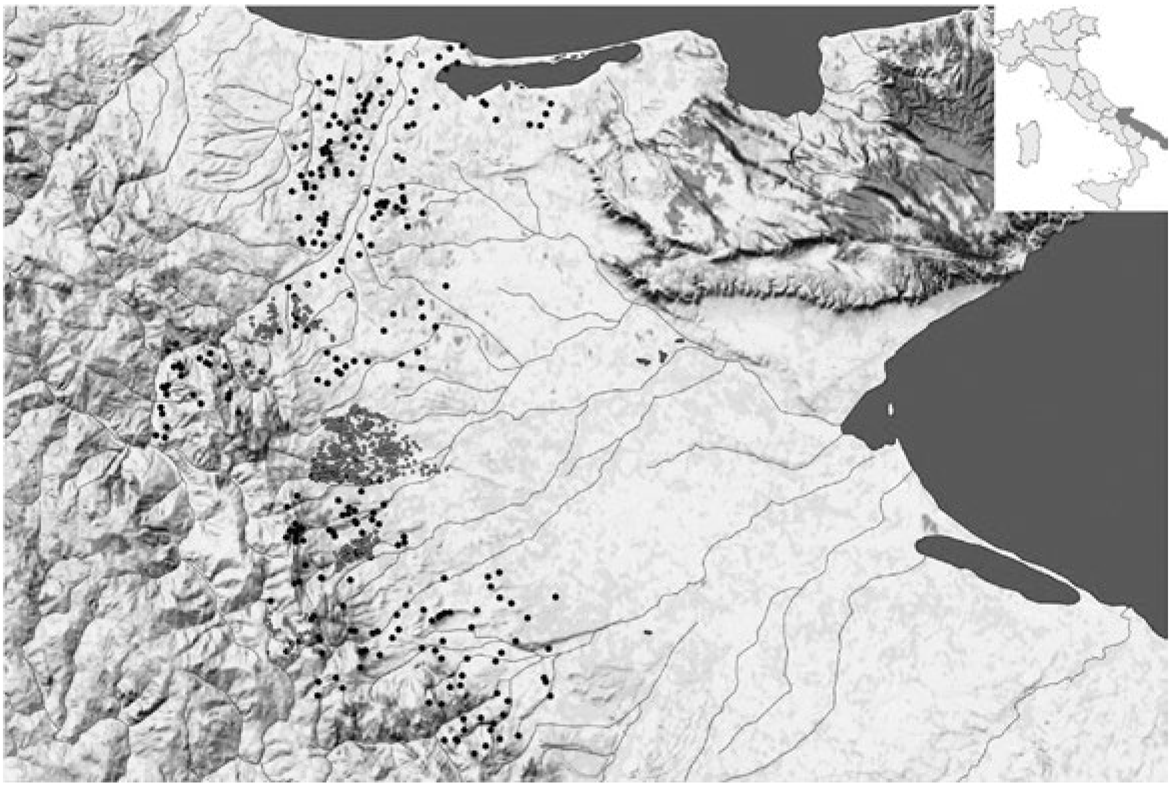

Fig. 8.

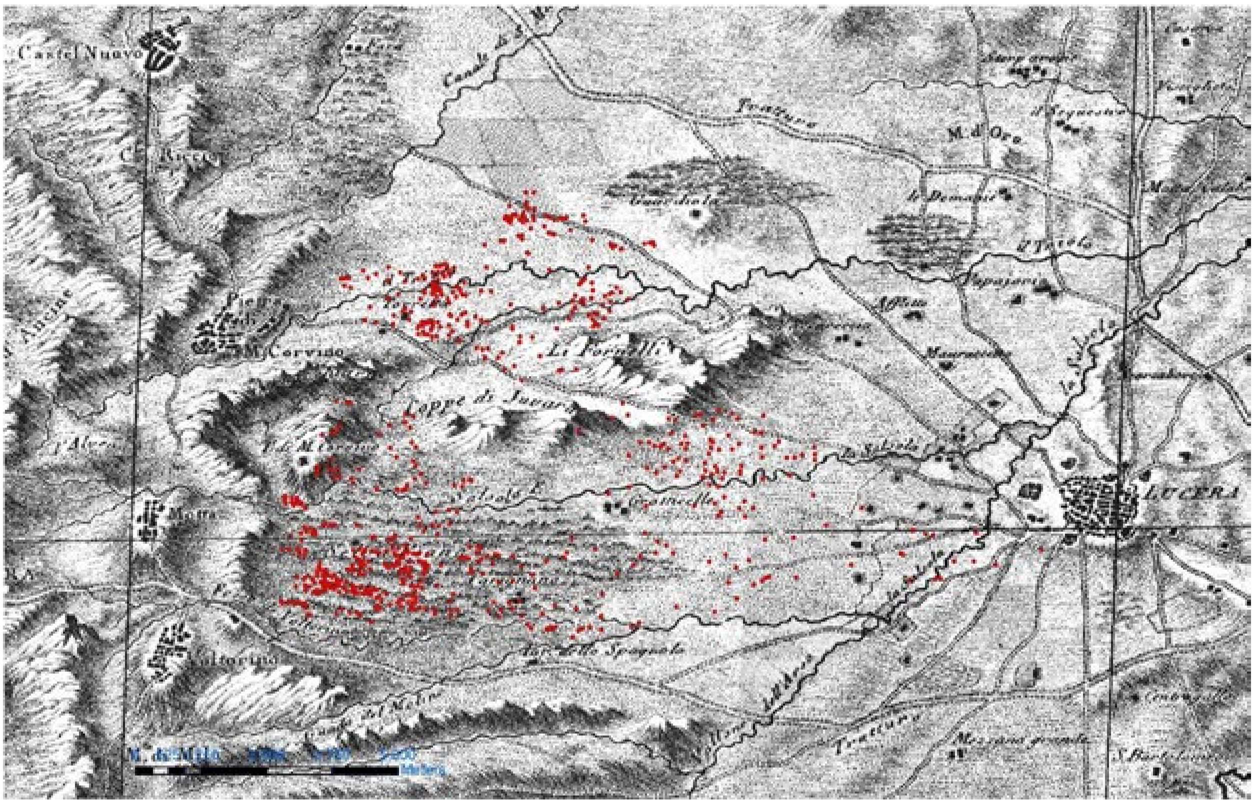

FIG. 9.

information on buried features, often contributing precious items in the reconstruction of building plans.

In addition to the recognition investigations, topographical sampling is always carried out so that finds are identified using GPS.

Most sites were indicated by dense scatter of material on the surface. In these cases our data collection efforts necessarily had to allow for maximum visibility of the terrain, which depended on the type and stage of cultivation. This approach allowed us to create a map of visibility of the territory.

Where grapes and olives are farmed, but also where fields are not farmed, the best periods are winter and spring. We classified the areas where we found scatter according to size and density of scatter. It is important to note that when indicating the size of an area, we considered only the zone with the greatest concentration of material, where excavation was most likely to reveal structures. We were able to define the types of settlements (rural structures, farms, *villae*, *vici*) by combining the following types of data: size of the area, characteristics of the scatter, that is, whether it consisted of construction materials (bricks and tiles, building stone, clay, etc.) or decorative elements (floors, plaster) (Marchi 2010).

The attention given to the DTM (Digital Terrain Mode) processing obtained by interpolating the contour lines has facilitated hypothetical three-dimensional reconstruction of the ancient landscape and therefore its 'virtualization'. It also makes it easier identify systematic forms of anthropic settlement and to formulate further research hypotheses about the presence of human life and buildings in a determined altimetric position, or its slope and exposure in relation to the surrounding environment.

In particular, time has been dedicated to creating a geodatabase in the ArcMap environment.

The geodatabases not only support feature class, rasters, and attributes, they also allow advanced GIS data behaviour and integrity rules to be implemented using types of data such as the topologies, networks, raster catalogues, terrain, specific rules for cadastral data (cadastral fabric), relationships, subtypes, and domains. The geodatabase unites 'geo' (spatial data) with 'database' (data repository) to create a central repository to manage and memorize the spatial data. This makes it possible to save the GIS data on a central server in order to facilitate easier management and rapid access. The construction of a geodatabase allows a very detailed implementation of the data input and therefore the equally detailed running of queries in the GIS constructed in this way. In other words, the more complex, the more detailed, and the more organized the attributes of any type implemented in the geodatabase are, the more detailed, accurate, and exhaustive will be the answers produced by the software, making it possible to create the assumptions for an interpretation as objective and immediate as possible.

Bibliography

Amendolea, B. 2003. *Repertorio bibliografico per la Carta Archeologica della Provincia di Roma*, Roma.

Azzena, G. 1992. Tecnologie cartografiche avanzate applicate alla topografia antica. In Berardi M. (ed.), *Archeologia del* *paesaggio*, *IV Ciclo di Lezioni sulla Ricerca applicata in Archeologia, Certosa di Pontignano (Si), 1991*: 747-76. Firenze.

Azzena, G. 2001. *Verso* lo standard: riflessioni in margine al caso della FIAT di Melfi. In Guermandi M. P. (ed.), *Rischio archeologico: se lo conosci lo eviti*, Atti conv. su cartografia archeologica e tutela del territorio, (Ferrara 2000): 77-86. Firenze.

Azzena, G. 2004. Quale SIT per la Carta Archeologica? Orientamenti (e dubbi) nell'esperienza della Forma Italiae. In ROsada G., Cerchiaro K. (eds.), *Topografia archeologica e sistemi informativi. Atti del Convegno Nazionale (Borgoricco 2001)*: 85-7. Roma.

Azzena, G, Tascio, M. 1996. Il sistema informativo territoriale per la Carta Archeologica d'Italia. In Marchi M. L., Sabbatini G. (eds.), *Ager Venusinus II, Forma Italiae 43*: 281-97. Firenze.

Carandini, A. 2008. *Archeologia Classica*, Torino.

Castagnoli, F. 1978. La carta Archeologica d'Italia, PP 33: 78-80.

Marchi, M. L. 2010. *Introduzione. Una nota di metodo* In Marchi M. L., Sabbatini G. (eds.), *Ager Venusinus II, Forma Italiae 43*: 25-8. Firenze.

Marchi, M. L. 2005. Il sistema informativo territoriale archeologico della Provincia di Roma. Il Contributo dell'Università. In *Beni Culturali e catalogazione integrata*, *4° corso di formazione e di aggiornamento per il personale dei Musei Civici*: 80-1. Roma.

Marchi, M. L. 2012. Project for the Census of the archaeological presences in Italy. In *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin*, *5° Congresso Internazionale su Istambul 2011*: 274-7. Roma 2012.

Marchi, M. L., Mazzei, M. 2012. Un Sistema informativo territoriale per i Beni Culturali: Il GIS del Progetto Censimento per la 'Cartografia Archeologica d'Italia', Digitalia, 1:106-12.

Marchi, M. L., Muntoni, I. M., Forte, G., De Leo, A. 2015. Dalle ricerche topografiche all'archeologia preventiva. Il GIS del 'Progetto Ager Lucerinus': modelli di indagine e strategie di intervento nei Monti Dauni. *Archeologia e Calcolatori* 26.

Marchi, M. L. (in press). 'Carta Archeologica d'Italia - *Forma Italiae*' project: Research method. In *3rd International Landscape Archaeology Conference 2014, Rome, Italy, 17–20 september 2014*.

Sommella, P. 1987. Cartografia archeologica computerizzata. In F. D'Andria (ed.), *Informatica e Archeologia Classica. Atti del Congresso Internazionale (Lecce 1986)*: 17-30. Lecce.

Sommella, P. 1989. *Forma Italiae*. Un progetto scientifico e uno strumento operativo. In Pasquinucci M., Menchelli S. (eds.), *La Cartografia archeologica. Problemi e prospettive. Atti del Convegno Internazionale (Pisa 1988)*, *Pisa, Amministrazione Provinciale*: 291-305.

Sommella, P. 1992. Tecnologie avanzate e Beni Culturali. La cartografia. In *Calcolatori e Scienze umane. Atti del Convegno (Roma, Accademia Nazionale dei Lincei-Fondazione IBM, 1991)*: 25-32. Roma, ETAS.

GIS, An Answer to the Challenge of Preventive Archaeology? The Attempts of the French National Institute for Preventive Archaeology (Inrap)

Anne Moreau
Institut National de Recherches Archéologiques Préventive, Direction Scientifique et Technique,
Laboratoire Archéologie et Territoires,
UMR7324-CITERES, Université de Tours, France

Abstract: Preventive archaeology has to deal with several goals, as a human science, as part of the planning process, and finally as a vector of cultural heritage. To achieve the different aims above, archaeological data have to be manipulated and represented in different ways, according to the target public. In this context, GIS is a way of satisfying all the needs and obligations. That is why the French National Institute for Preventive Archaeology has launched an important programme to promote the use of GIS among archaeologists. Besides the technical question raised by such a programme, the main issue is that of the harmonization of spatial data collected in order to allow the sharing of data between archaeologists. This involves defining a common part of data required for all archaeological operations and the parts of data that is a matter for archaeologists. Defining standards while allowing some latitude: that is the real challenge.

Keywords: Preventive archaeology, GIS, Data, Harmonization

Introduction

In France, preventive archaeology is essentially state-run but since 2003, private companies have been involved too. This context has led to the introduction of GIS (Geographic Information System) and its widespread use. GIS is nowadays one of the common tools that archaeologists use to manage, analyse, and explore the archaeological data.

The French National Institute for Preventive Archaeology started considering the use of GIS in preventive archaeology in 2006 (Rodier, Ciezar, Moreau 2011). Since then, the institute has launched an unprecedented programme to promote the use of GIS and train archaeologists in the new practices involved. But going from a local application of GIS to rolling it out for use by thousands of archaeological projects has brought up several problems, such as the definition and the harmonization of data collecting in order to allow the sharing of data.

1 The French archaeological process

Integrated within the town and country planning process since the 1970s (Demoule 2007; Soulier 2012), the archaeological process is well defined: development projects are sent to the regional archaeology services of the state, which examine them. According to the known archaeological context, they decide whether an archaeological operation is needed or not. If so, an assessment — the diagnosis — takes place. This assessment can only be made by a state organization, the National Institute, or an approved local authority service. The diagnosis aims at detecting and characterizing the archaeological deposits.

After the diagnosis, the state may ask for an excavation or changes in the development project. In the case of an excavation, it is financed by the developer and carried out by the Institute, local authority service, or private company. Every step of the process is under the control of the state, which decides and defines the aims of the archaeological assessment or excavation and controls the archaeological operations in progress. The operators, public or private, define the means and the strategy to meet those aims. They must produce a final report at the end of the operation to be sent to the regional service.

2 The French National Institute for Preventive Archaeology

The French National Institute for Preventive Archaeology is a public institution created by the Law of 17 January 2001 and founded in 2002 (Demoule, Landes 2009). It replaced the former association for archaeological excavation (AFAN), which was the only operator of preventive archaeology before 2003. Due to this former situation, the Inrap is currently the biggest contributor to archaeological collecting.

The Institute is in charge of three main missions described as follows:

- it surveys the archaeological heritage threatened by development and infrastructural works
- it undertakes the study of the data collected, spreads the research results within the scientific community, and circulates archaeological knowledge to the general public with publications, exhibitions, etc.

The institute is organized into eight regional zones and about 45 centres are spread over the national territory and overseas territories (Guyana and West Indies). It comprises around 2000 archaeologists working on all archaeological periods from the Paleolithic to the present day. It carries out over 2000 diagnoses and 3000 excavations a year and tries to highlight this activity with publications.

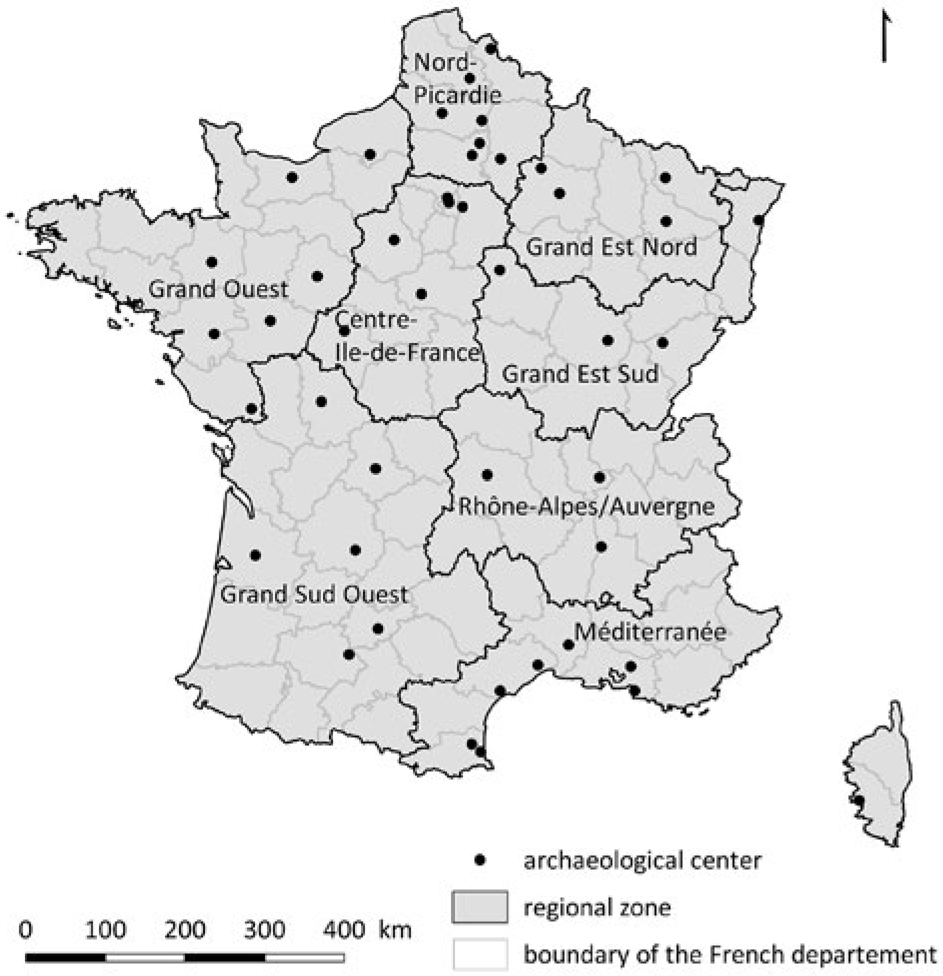

Fig. 1. Organization of the French National Institute for Preventive Archaeology.

3 The goals of preventive archaeology

Preventive archaeology must reach several goals, which do not all match:

- as a human science, archaeology must produce, explore, and publish data for research;
- as a patrimonial activity, it must respect the legal obligations of archaeological data management and conservation, and contribute to the knowledge and respect of the patrimonial heritage;
- as part of the town and country planning process, preventive archaeology must clear the ground of archaeological remains;
- as a vector of cultural heritage, it must communicate archaeological knowledge to the general public.

Preventive archaeology has to reach several goals but archaeologists only have one opportunity to collect the data. To meet the different aims above, archaeological data have to be manipulated, represented in different ways. Several restitutions of data must be produced, according to the target public.

Furthermore, archaeologists must find ways of easily sharing the data produced:

- between archaeologists of every institution or community to contribute to science; between archaeologists working on the same archaeological process;
- between archaeologists and the regional state services responsible for the control of the operations and, finally, the drawing of the national archaeological map;
- between archaeologists and developers; between archaeologists of different institutions (the assessment of a site can be carried out by the Inrap, and the following excavation by a private company or a local authority);
- between archaeologists and the general public or other public institutions interested in archaeological data.

Finally, other difficulties should be mentioned: the variety of practices within the Institute and elsewhere, the variety of archaeological recording systems within the Institute and other places, and the competitive context which increases the mistrust between researchers and the different institutions.

All these elements are as many barriers to archaeological practices for a scientific purpose.

4 Promoting the use of GIS

In 2011 the Institute started to train archaeologists in order to develop the use of GIS. It was first decided to systematize the use of GIS at the level of the operation whatever the type of excavation. How are the archaeological remains organized on the surface investigated?; this question determines the scale analysis and allows a definition of the objects to be integrated in the GIS (Joliveau 1996: 101; Saint-Gérand 2005; Rodier, Saligny 2011: 43–4). The aim is to offer a tool for archaeologists and their daily work, to manage the operation, explore the data collected, and produce illustrations for the final reports (Rodier, Ciezar, Moreau 2013). All the archaeological professions are concerned with important influences on the work process currently applied, which involves changes in uses and habits.

To initiate the project, the Institute has invested in the training of archaeologists.[1] As they were aware of the difficulties involved in adapting to a new tool, several levels of methodology have been defined: the first step is to encourage archaeologists to collect, integrate, and systematically represent the archaeological spatial data in the GIS.

Tab. 1. Number of archaeologists trained since 2011.

Year	Number of trainees
2011	30
2012	89
2013	100
2014	153
2015	200*
total	572

*theoretical number, work in progress

Currently, over 25 archaeological centres are involved and over 500 archaeologists will be trained by the end of 2015.

Since 2013, resources made available by the Institute have also been used to help new users in their first steps with GIS. Qualified people were appointed to assist their colleagues in order to pool the achievements and skills among members of the Institute and make use of former achievements.

Apart from the issue of the resources to be invested, another essential issue was raised while developing the use of GIS among 2000 archaeologists producing data every day, that of sharing data between the researchers of the Institute.

5 Harmonizing the spatial data: Inrap's six layers and the catalogue of spatial data

Spreading the use of GIS and harmonizing the spatial data may represent a way of conciliating the different missions of preventive archaeology, partly solving the problem of the sharing of data in a context of heterogeneous practices. Indeed, since the advent and the spreading of GIS in archaeology in the 1990s, spatial data are frequently or even systematically considered. GIS brought up the spatial dimension of archaeological data.

Harmonizing the spatial data collected appears to be feasible because archaeological data are necessarily linked to space and because it is probably easier to reach general agreement on the way of representing spatial data. There are many ways of qualifying and characterizing the archaeological data but fewer ways of representing archaeological data in space.

In this perspective, the first attempt was to match practices by adopting common layers of spatial data as follows:

- 'perimeter': the surface which has to be investigated or dug in the case of an excavation;
- 'opening': dealing with all technological units, different technical holes dug in the ground (trenches…);
- 'polygonal observations': archaeological remains observed, recorded, located, spatially represented with polygons;
- 'punctual observations': archaeological remains or artefacts observed, recorded, located, spatially represented with points;
- 'samples': locations of samples, geomorphological observations;
- 'sections': location of sections represented by lines.

These six layers must be produced at the end of each archaeological operation. The map projection used for the whole data is Lambert93 (EPSG code 2154), based on the legal geodetic reference system RGF93, which is the French version of ETRS89.

The structure is a thematic one where each recording unit has its own spatial representation without spatial modelling (Rodier, Saligny 2011: 48–9). The shape file data format currently used involves a division of the objects into points, lines, and polygons. In addition, we have distinguished between the technical units, or archaeological gestures, and archaeological units: 'perimeter', 'opening', 'sections', 'location of samples' are the technical units, and polygonal observations and punctual observations are the archaeological units. The polygonal observations are the structures or 'features' (wall, grave, post hole, ditch, etc.). The punctual observations correspond to the *artefacts* (pottery sherd, flint, bone, metal objet, etc.) or even *ecofacts* recorded in the field.

The data structure is inspired by traditional archaeological field recording so that archaeologists can easily link the spatial data to their own databases. This level of manipulation of the spatial data is easy to understand. Furthermore, the layers are meant

[1] Archaeologists are trained with QGIS.

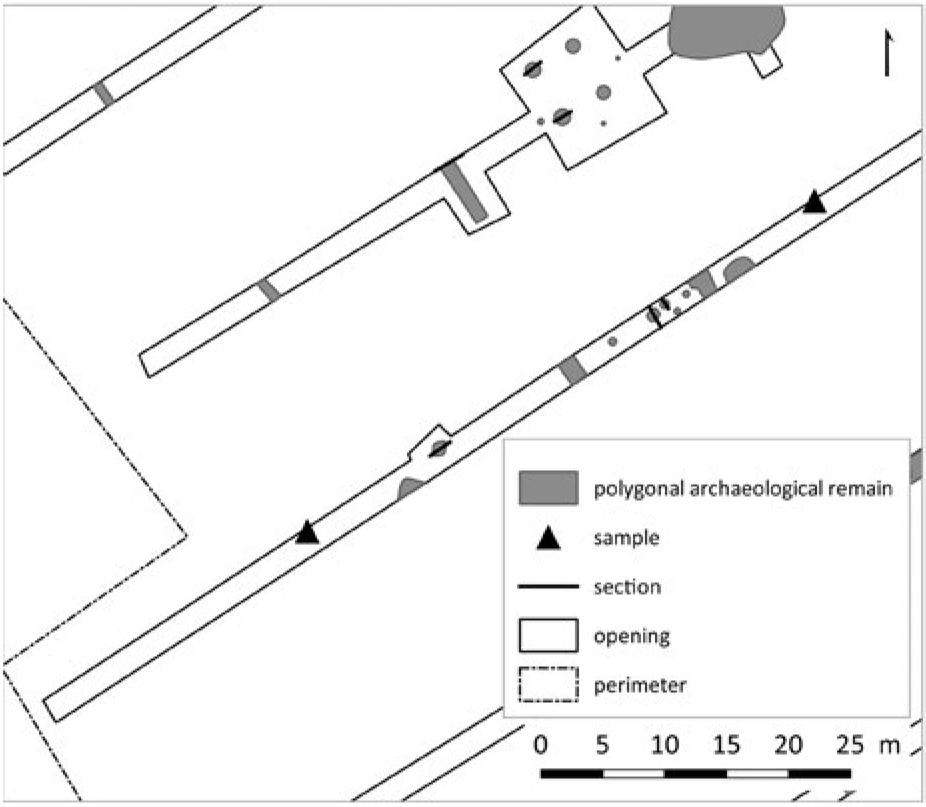

Fig. 2. Example of spatial data recorded and represented: the operation of Mer-Séris (managed by François Cherdo, Inrap).

for guiding the archaeologists in their use of GIS: most of them are used to manipulating Computer Aided Design tools and one of the biggest difficulties is to help them to understand the logic of GIS.

For the moment, only 'raw data' are recorded in the six layers. 'Raw data' means data recorded and interpreted in the field, that is, data that cannot be discussed afterwards. For each layer, a 'type' and an 'ID' corresponding to the recording number given by the archaeologist must be captured. The 'ID' is essential as it allows linking the spatial data to the rest of the archaeological archives of the operation (inventories, databases, photographs, etc). For the layer 'perimeter' other data are recorded, such as the operation number related to the managing system of the Institute activity and the operation number imputed by the state services. We chose to separate the 'perimeter' from the other types of opening to make the manipulation of the data easier for archaeologists. Indeed, it is not necessary to study the 'perimeter' at the level of operation. On the other hand, it is useful to produce a spatial layer containing the perimeters of all the operations undertaken by the Institute.

We chose to keep a data graphic representation according to the traditional representation of archaeological data: archaeological remains are represented in the GIS in the state they have been observed and drawn in the field, that is, most of the time by their outline. This representation is not necessarily suitable for spatial analyses but it is a representation that is easily understood by both archaeologists and the general public.

The rest of the data recorded and represented in the GIS is the area of freedom of archaeologists: they can create as many spatial layers as they need, use external databases or not, etc. The six layers above are what we ask to be collected systematically at the end of each operation in order to constitute a catalogue of all the spatial data of the Institute. This catalogue aims to be a data search tool for archaeologists. Linked to the Dolia catalogue and digital library of the Institute,[2] it will offer easy access to the main data produced by the Inrap. To this purpose, we set up a PostGIS-Postgre server, which gathers the layers of the operations described above. Three chronological fields are added to the initial archaeological data provided by archaeologists: *terminus post quem* (beginning), *terminus ante quem* (ending), and a 'period'. The chronological limits defining the periods respect the regional historical differences.

At this point, no attempt at harmonization of the semantic data has been made because of the variety of regional practices or phenomena and the risk of an over-standardization of archaeological data. The most important thing is the understanding of the data from one operation to another, but not necessarily the use of the same vocabulary or databases. In other words, the goal is to ensure the technical and semantic

[2] http://www.inrap.fr/Dolia/p-17038-Accueil.htm Dolia is a catalogue referencing the documentary collection bought or produced by the institute. It also provides access to part of the operation reports of the institute. Three hundred can be downloaded in full.

inter-operability of the different systems. This is the Institute's next task.

6 Conclusion

The challenge of preventive archaeology is not a myth: (preventive) archaeology is a human science, which has to combine the requirements of the discipline with those of a concern about national heritage, but this work is hindered by the official framework, as the conditions of investigation are governed by the town and country planning process. The difficulty of the task is increased by both the competitive context and the digital revolution, which generates a redefinition of boundaries and limits.

In that context, the development of the use of GIS seems to be an inevitable development of archaeological practices and a good way of merging the different goals of preventive archaeology.

Besides technical problems such as the software and data format used, and the way of archiving the data, the main issue was that of the harmonization of the data. The question obviously arises in an Institute of this kind which produces a huge amount of data every day. This is the real challenge. According to this general idea, the definition of six layers to be created represents a first attempt, which may change in the near future.

This approach involves further consideration about the definition of common parts of data recorded and represented for all (the standards required) on the one hand and on the other, the parts of data which concern the archaeologist. The exercise is not easy: it requires finding a suitable balance between the definition of standards allowing inter-operability and diversity leading to intellectual and scientific work in human sciences.

Bibliography

Demoule, J.-P. 2007. Introduction. In Demoule, J.-P. (eds.), *L'archéologie préventive dans le monde*: 7-16. Paris, La Découverte.

Demoule, J.-P., Landes, C. (eds.) 2009. *La fabrique de l'archéologie en France*. Paris, Editions La Découverte.

Joliveau, T. 1996. Gérer l'environnement avec des S.I.G. Mais qu'est-ce qu'un S.I.G. ? *Revue de Géographie de Lyon* 71(2/96): 101-10.

Saint-Gerand, T. 2005. Comprendre pour mesurer… ou mesurer pour comprendre? In Guermond, Y. (ed.), *Modélisations Géographiques*, Traité IGAT, Paris, Hermès.

Soulier, P. 2012. Produire des connaissances en archéologie. Nouveaux champs de la recherche archéologique. *Archéopages*, Hors Série Inrap 10 ans:16-20. Paris.

Rodier, X., Saligny, L. 2011. Abstraire: formaliser et modéliser l'information archéologique. In Rodier, X. (ed.), *Information spatiale et archéologie.* Collection Archéologiques: 39-55. Paris, Errance.

Rodier, X., Ciezar, P., Moreau, A. 2013. Using GIS in French rescue archaeology. The choice of Inrap: a tool for research at the scale of excavation. In Contreras, F., Farjas, M., Melero, MJ. (eds.), *Fusion of cultures. Proceedings of the 38th annual Conference on Computer applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. 2494: 217-20. Oxford, British Archaelogical Reports.

Dynamic Distributions in Macro and Micro Perspective

Espen Uleberg
(espen.uleberg@khm.uio.no),

Mieko Matsumoto
(mieko.matsumoto@khm.uio.no)

Museum of Cultural History, University of Oslo, Norway

Abstract: This paper addresses how the national MUSIT database can be used to reveal geographic relations of single finds from south-east Norway in macro and micro perspective. This is the third presentation of our project Dynamic Distributions — analysis of the relationships between archaeological finds and landscape types, including the whole geographical district of the Museum of Cultural History, University of Oslo.

EDA in a GIS provides opportunities to work with combinations of data, creating a cycle of analysis, improved datasets, and better understanding in the field of archaeology. The map-based EDA becomes a rewarding tool for research of prehistoric land use.

The Norwegian Early Neolithic is much debated and the view of Neolithic society is changing. In this paper, meticulously prepared data in the MUSIT database was combined with a holistic landscape categorization. It has shown that this way of study has a value for the archaeological discourse in Norwegian Stone Age research.

Keywords: MUSIT database, Exploratory Data Analysis (EDA), landscape categorization, Norwegian Neolithic, Funnel Beaker Complex

Introduction

Site distributions are a way to present archaeological sites in overview and combinations. The dynamic in combinations of different sets of artefacts, maps, and scale levels creates new understanding. This paper addresses how the MUSIT (MUSeum IT) database can be used to reveal geographic relations of Norwegian Stone Age sites in macro and micro perspective. This is the third presentation of our project Dynamic Distributions — analysis of the relationships between archaeological finds and landscape types.

The Norwegian university museums cooperate in the national organization MUSIT to create common database systems. The data used in this article are from the Stone Age collection at the Museum of Cultural History (KHM), University of Oslo. The KHM district covers the ten counties in east and south Norway (Figure 1). The project has extended its geographical area from three (Matsumoto and Uleberg 2015) to six (Uleberg and Matsumoto 2015), and in this paper to all ten counties. Typology and geotagging are registered in the database, and the information on the webpage (www.unimus.no) is updated on a weekly basis.

The project explores the possibilities afforded by this nearly total overview of archaeological finds in this region. Geotagging of the sites has made the dataset well suited for map-based Exploratory Data Analyses (EDA) (Andrienko and Andrienko 2006). After extracting data from the database, a variety of combinations of artefacts and landscape categories can be explored at different scale levels. This can promote new understanding, which in turn can generate new ideas for a next set of combinations. This kind of study has become feasible due to the national MUSIT database and the abundance of available digital maps.

The project has concentrated its work around large stone tools. Find circumstances indicate that finely made Neolithic axes, sickles, and daggers were grave-goods, offerings, or depots. The distribution of such artefacts in the landscape may contain a different meaning than the distribution of settlement sites. These items have been prestigious objects and reflect a certain layer of perception within the landscape — the symbolic landscape that differs from the everyday landscape presented through the settlement sites. Locations for graves and offerings have been chosen deliberately and for other reasons than the settlements (Tilley 1994).

1 The database

The database is maintained and developed for the university museums in Norway by MUSIT (Matsumoto and Uleberg, forthcoming). MUSIT is a national cooperation among the six museums. As of June 2015, more than 877,000 artefact entries from the archaeological museum collections in Oslo, Stavanger, Bergen, Trondheim, and Tromsø have been published online (www.unimus.no/arkeologi/forskning). In Oslo, this represents more than 90% of the entire archaeological collection. Furthermore, over 580,000 images from the photo database, mainly excavation documentation and artefact images, are published under a CC-licence (www.uinimus.no/foto, http://creativecommons.org). KHM uses the licence CC-BY-SA. The images can be used freely as long as they are attributed to the museum (BY) and shared with the same attributes (SA). Digital sound and video are stored in the same database, but access is limited.

1.1 Digitizing Archaeology

Digitization of the archaeological collections in Norway started in the 1990s, with transcription and SGML-tagging of artefact catalogues (Holmen and Uleberg 1996). These files were converted to the MUSIT database (Jordal *et al.* 2010), which

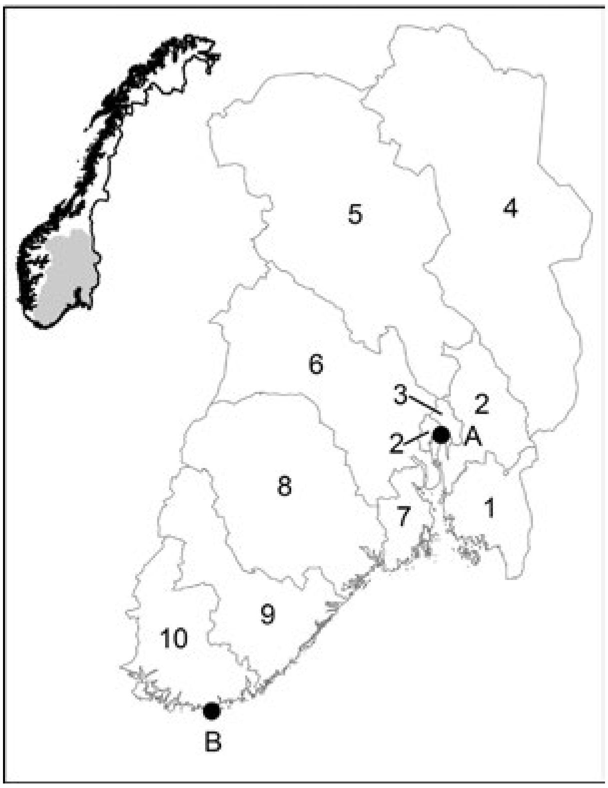

Fig. 1. The district of the Museum of Cultural History, University of Oslo with counties (1–10) and places mentioned in the text (A–B). 1. Østfold; 2. Akershus; 3. Oslo; 4. Hedmark; 5. Oppland; 6. Buskerud; 7. Vestfold; 8. Telemark; 9. Aust-Agder; 10. Vest-Agder; A. Oslo fjord; B. Hamremoen.

Tab. 1. The precision categories.

Precision levels	**Range no.**
site	1
property unit	2
creek	3
cadastral unit	4
cadastral units sharing name	5
urban area	6
rural area	7
river	8
small lake	9
lake	10
area	11
island	12
mountain	13
parish	14
muncipality	15
county	16
mountain area	17
landscape area	18
country	19

is used by all the university museums. In the same period, several local Access databases were in use. KHM started to use the MUSIT database in 2004, and in the following years, the Access databases were migrated to this database. The MUSIT application has also modules for conservation and acquisition, and has become a device of vital importance for research and collection management. The database structure builds on CIDOC-CRM (www.cidoc-crm.org/) and is event-based (Jordal *et al.* 2011). The cataloguing events make it possible to update the entries with new information, such as artefact names and description, while old versions are kept as historic data.

In 1866 the Norwegian university museums began to publish acquisitions together in annual reports (Årsberetning for foreningen til norske fortidsminnesmerkers bevaring), and later in separate publications (Østmo 1998). This tradition has now been replaced by online publishing of individual catalogues. All old catalogues with different nomenclatures are registered and published in their original form. It provides a unique possibility to study the development of artefact terminologies and catalogue tradition over time (Glørstad and Uleberg 2002). At the same time effort is needed when using the material as big data. Previously it was not possible to extract all artefacts of a certain type because they were catalogued according to different nomenclatures. The old terminology could have been linked to new terms through lists of synonyms, but an old term will not always be equivalent to new classifications. Instead, the artefacts will be reclassified according to new ideas and typological knowledge. One example is the flint sickle, which was described as a saw (*sag*) in the 19th-century catalogues. As a result of the project Dynamic Distributions, reclassifications of Stone Age axes, sickles, and daggers have been added as events. The whole process is stored in the database, and the new classification is published online.

MUSIT developed a qualitative system for geotagging archaeological sites to make it possible to add coordinates to finds with varying context information. Metadata relating to geographical accuracy and precision will often express that a location is correct within a certain radius. This accuracy can be linked to the registration method — digitized from maps on the computer screen, coordinates from GPS in the field, and so on. Recent finds, especially from modern excavations, can have precise context information, i.e. the exact position within the excavation. Information about artefacts acquired early or from private collections can be simply in which cadastral unit or parish they were found. GIS offers the possibility of looking for patterns at any scale level, although not all data can be used at all scale levels. Precision is a crucial part of the meta-data, and care must be taken that the precision level of the archaeological data matches the scale level of the map.

The verbal descriptions of geographic information needed to be translated to coordinates. The geographic borders of a parish are irregular and cannot be expressed as a point within a circle. One solution might have been to express all units as polygons, but the units are not stable, and detailed polygons would have given a false impression of accuracy. MUSIT chose instead to use representative points and qualitative accuracy levels reflecting the site information. The most accurate level is the site and possibly the exact coordinates within the site. Less precise values might be divided into one category following cadastral and other administrative units, or into another such as geographical names for landscapes, mountains, rivers, and creeks. Dynamic Distributions has ranked these values in order to compare finds from both categories (Table 1).

1.2 Database for research

The MUSIT database provides a good basis for map-based EDA. The geotagged data are published for free download and find distributions can be combined with elements from digital maps. Affiliates of the Norwegian universities have for several years had access to a wide range of different geographic, geological, and thematic maps, and the Norwegian Mapping Authority (Kartverket) is making more digital maps freely downloadable (http://data.kartverket.no).

This archaeological dataset is well suited to obtain a general overview and testing out ideas at an early stage. The information, however, is very often taken from the initial catalogue text which is often primitive or scarcely informative. Since different artefact names can be used for the same type of object, the first query results should be critically scrutinized before they are processed further.

Today, the time of analogue excavation documentation and artefact catalogues is definitely coming to an end. The Norwegian university museums have agreed on Intrasis (www.intrasis.com) as their common system for excavation documentation, and it will be possible to combine and compare results more efficiently than ever before. The artefacts are registered in the MUSIT database, and the nomenclature for archaeological periods, find categories, and artefact materials are shared by all museums. These authoritative lists make it possible to formulate meaningful queries across all collections. A national authoritative list for artefact terminology is being prepared. Different research traditions and, in part, different types of material make this a challenging process.

The availability of digital data has opened up new venues for research. There are great amounts of digital data, but not all data are curated in a way that makes them accessible to a wider audience. The MUSIT database makes the collections available to students, researchers, and the general public. The experience from Dynamic Distributions is that the museum database is an excellent tool to try out new ideas and inspire further research, but the database needs to be constantly updated with new information. Since Dynamic Distributions is based at KHM in Oslo, the database has been updated simultaneously, as the project evolves. In other cases it is a challenge to integrate information and new categorizations from important research projects.

2 Landscape categorization

The landscape that exists today is a palimpsest of past and modern activities. Since the first settlements, humans have left their marks on it. Some, such as settlement sites or agricultural plots, are modest and the result of mainly functional choices, while others can be monuments deliberately placed and constructed to demonstrate a presence in the landscape and to fill it with meaning that can be passed on through the generations (Tilley 1994).

The site distribution is the result of surveys and occasional finds within this palimpsest landscape. The aspiration is that it reflects a prehistoric reality, but it is also an outcome of modern activity. The site distribution reflects the interests of researchers, local amateur archaeologists, agricultural activity and, not least, modern rescue archaeology.

The construction of site distribution maps is a common way to study archaeological artefacts and group them into cultures or techno-complexes. The maps present archaeological finds within a geographical area, in relation to river systems or topography. Several studies have used administrative borders as limits, reflecting the topographical ordering of the museum archive where the documents are sorted by county, municipality (earlier parish), and cadastral unit.

The relationship between geographical area and archaeological types was central in the Kulturkreislehre (Steuer 2006). With New Archaeology in the 1960s, territories could be defined in relation to functional variables such as soil types and geology. One example is the correlation between Funnel Beaker groups and the extent of brown soil and oak forest in western Sweden and Norway (Hulthén and Welinder 1981). The project Dynamic Distributions has decided not to rely on single attributes, but instead to combine the find distribution with a holistic landscape categorization made by Oskar Puschmann (1998, 2005).

Puschmann’s categories are based on six landscape components: 1) major landform; 2) geological composition; 3) water and waterways; 4) vegetation; 5) agricultural land use; and 6) buildings and technical installations. A series of national or regional thematic maps and/or registers are employed. Puschmann describes three scale levels in detail. Today’s agricultural landscapes are divided into five categories for a scale level of 1:2 million. Regions and sub-regions are constructed at the scale levels 1:500 000 and 1:250 000. The six variables will be discussed in the following.

3.

3.1 Major landform and geological composition

Major landform and geological composition could be a fairly stable background for all other variables. In the long-term perspective of archaeology, however, the major landform is influenced by land/sea alterations due to interactions of eustatic and isostatic change. Around the Oslo fjord, the land has been constantly rising after the last Ice Age, and the marine limit was as high as 220 m around 10,000 BP (Sørensen 1979). On the coast of Vest-Agder and southern parts of Aust-Agder, the regression minimum was below the present sea level during the Boreal chronozone. In this area, submerged Mesolithic settlement remains and potentially graves are discovered (Nymoen and Skar 2011). Around the Oslo fjord, most of the sites from the early Stone Age can be interpreted as coastal sites even though they are situated far inland today. The change in major landform during the Neolithic period, which is presented here, was much less dramatic, but some sites were on islands in an archipelago that no longer exists. This should be considered at more detailed scale levels.

3.2 Water and waterways

The greatest change affecting the variable water and waterways is the sea level change and the consequent change from salt water and fjords to fresh water lakes and rivers. The river beds were formed as the ice sheet retracted and the land rise turned the seabed into dry land. As long as the analyses concern artefacts in the landscape on a larger scale, the river flows in this part of Norway can be seen as stable.

3.3 Vegetation

The vegetation has undergone dramatic changes. The early pioneer vegetation of birch and fir near the coast was replaced by hazel, oak, and elm in the Preboreal (10000–9000 BP) and linden followed in the early Atlantic period (8000 BP). This warm period was followed by the less warm and drier Subboreal (5000–2500), which started at the same time as the Neolithic. A shift to a colder climate occurred around 2500 BP, and has, broadly speaking, continued till today (Stenvik 2005). The vegetation is changed, but the gradation between the different vegetational zones indicates factors important for prehistoric settlement.

3.4 Agriculture

The agricultural variable clearly reflects modern preferences. The co-variation between agriculture and especially Neolithic artefacts should be carefully considered. The clayish soils around the Oslo fjord are not considered to be well suited for early agriculture, and yet there is an obvious concentration of finds in this area (Matsumoto and Uleberg 2015). Distribution analyses of thin-butted axes, and also with weighed counts related to an administrative or agricultural area, however, indicate that the find distribution is not a reflection of modern agriculture but reflects the Neolithic landscape use (Brøgger 1906; Hinsch 1955; Mikkelsen 1984).

3.5 Buildings and technical installations

The variable buildings and technical installations have clearly no direct connection to prehistoric settlement. On the other hand, archaeological surveys and excavations are often carried out in relation to new installations, and there will generally be more activity in areas with denser habitation.

3.6 Use of landscape classification

In general, it can be argued that the holistic landscape classification developed by Puschmann provides an interesting framework for grouping archaeological sites. Earlier, different aggregations of this division have been used and proved useful to analyse archaeological distributions (Matsumoto and Uleberg 2015; Solheim 2012; Uleberg and Matsumoto 2015). In this paper, we will use Early Neolithic axes as an example of how the level of sub-regions can be used to look for site distribution patterns.

The combination of archaeological finds and landscape categorization has given promising results, indicating that the underlying variables are important for prehistoric settlement or co-vary with underlying structures. The scale level of the landscape and the different accuracy levels must match. Puschmann's sub-regions can include parts of different municipalities, and consequently sites with an accuracy level of municipality or parish would be misleading if they were mapped on the sub-region scale level. The sub-regions are therefore combined with sites with cadastral-level accuracy.

4 Macro and Micro perspective

GIS combined with the vast range of digital maps and geotagged artefacts opens new opportunities, but also caveats. The geographic data have been captured with a certain purpose and to be used at a certain scale level. Decisions were made about sampling and generalizations in relation to the scale. The geographical data are correct at the scale level they were constructed for, but GIS makes it possible to present a dataset at any scale. It is therefore necessary to pay great attention to the intended scale level (Harris 2006).

The combination of find distributions and landscapes in six counties in south-eastern Norway has earlier proved that there is a high degree of continuity from the Late Mesolithic through the Neolithic, and that there was an increase in the number of finds as well as an expansion from the coast to more interior areas (Matsumoto and Uleberg 2015; Uleberg and Matsumoto 2015). In this paper, Østfold, Telemark, Aust- and Vest-Agder are included, and the analyses which will concentrate on the distribution of early agriculture; phenomenological facts are discussed in accordance with archaeological research questions of Early Neolithic in southern Norway.

4.1 Norwegian Neolithic

Norway is on the outskirts of Neolithic Europe, and in the Early Neolithic it can be seen as a northern province of the Funnel Beaker Complex further south, in west Sweden and Denmark (Glørstad 2009). The chronology and typology applied in Norway has to a large extent depended on resemblance with the far more abundant Danish material.

The Early Neolithic and Middle Neolithic A correspond to the Funnel Beaker Complex in this part of Norway, and is therefore treated as a single chronological unit. Some Funnel Beaker elements and a few indications of agriculture are found in the Oslo fjord area from around 5000 BP/3800 BC. In the following Middle Neolithic B, the most outstanding finds are the battle-axes, which points to more external contacts to the east. In the Late Neolithic the exchange networks reaches even further, and there is a definite shift to agricultural subsistence economy (Prescott 2009).

The existence of a Neolithic in the strict sense in Norway has been discussed in relation to artefacts and other indicators. Pollen analysis in Telemark has supported the idea of early extensive pastoralism. Plantago lanceolata and other apophytes suggesting an open landscape in the mountains dated to around 5000 BP have been interpreted as a result of early grazing

(Indrelid and Moe 1983; Mikkelsen 1989; Stenvik 2005). Pollen analysis has also indicated Early Neolithic grazing in the valleys in Hedmark (Amundsen 2011). Animal husbandry has not been supported by osteological evidence, and early agriculture in south-east Norway has been refuted (Prescott 1996).

The area around the Oslo fjord has the best conditions for agriculture in this part of Norway. Thin-butted, point-butted, thick-butted, and multi-facetted axes, corded ware, and even all three Norwegian megaliths are found here and make it the core area of the Funnel Beaker Complex. The distribution of Neolithic axes has traditionally been seen as indications of a Neolithic subsistence, and the Early Neolithic economy has been interpreted as an agricultural subsistence although the distribution of settlement sites shows a strong continuation from the marine Late Mesolithic (Glørstad 2005). Landscape analysis has shown that Early Neolithic sites in south-east Norway are not situated in areas best suited for this early agriculture, such as the end moraines, but rather in relation to rivers and coastal areas (Solberg 2012). It is now argued that this phase (3800–3300 BC) did not necessarily include agriculture, but those artefacts, and to some extent burial practices, were adopted (Glørstad 2009).

The settlement sites often have a combination of tanged arrows, fragments of thin-butted flint axes, flakes with the cylindrical cores from which they were produced, and occasionally corded ware (Glørstad 2004). Complete flint axes are rarely found at settlements, but stone axes occur occasionally. The flint axes are imported from Denmark, and may have been used in exchange relations. Stone axes are produced regionally in local stone. The fact that only fragments of flint axes are found at settlements implies two separate life cycles; in one cycle the axe is treated as a valuable item in a depot or deposited as a burial gift, while in the other, the axe ends up as a fully exhausted raw material.

4.2 The Funnel Beaker Complex

One of the central elements in the discussion of the Funnel Beaker Complex in Norway has been the distribution of thin-butted axes of flint and stone. Thin-butted axes are mostly single stray finds, and the distribution of finds connected to the Funnel Beaker Complex has been correlated with brown soils and oak forest, explaining why the culture did not extend south-west of the Oslo fjord (Hulthén and Welinder 1981). This correlation has also supported the assumption of a neolithization around the Oslo fjord, and even a critical evaluation has acknowledged that there might have been an agricultural subsistence in the Early Neolithic (Prescott 1996). Such a correlation was not shown when combining finds and landscapes from Akershus and Oslo at a higher scale level (Matsumoto and Uleberg 2015; Uleberg and Matsumoto 2015).

The recent discovery of an Early Neolithic enclosure, dated to 3900–3600 BC at Hamremoen in Vest-Agder, gives new perspectives on the distribution of the Funnel Beaker Complex in Norway, and signals new impulses compared to the Mesolithic society in this area (Glørstad and Sundström 2014). It is the first Neolithic enclosure to be found in Norway, around 200 km from the outskirts of the area traditionally associated with the Funnel Beaker Complex. The distribution of thin-butted axes continues along the coast, however, suggesting a continuation of Funnel Beaker influence. In the following, the landscape maps will be interpreted in light of the ongoing discussion concerning the Funnel Beaker Complex in Norway.

4.3 Visualizations

The map (Fig. 2) visualizes the distribution of thin-butted flint and stone axes in the sub-regions. The sub-regions were constructed for a scale level of 1:250,000, and transcend the administrative borders of municipalities and counties. Sea level in the Early Neolithic was up to 40 m higher than it is today. Based on the general topography, the change in sea level is negligible at this scale level. Finds with an accuracy of cadastral unit or better are included.

The distribution of thin-butted axes counted as number per county has a general fall-off curve from the distribution centre in south Scandinavia through Østfold and very few specimens further south than Telemark (Glørstad 2009). The map (Figure 2.1) shows the number of axes within each sub-region, divided into five classes. There is a concentration around the Oslo fjord, and the distribution continues along the coast of Telemark and Aust- and Vest-Agder.

The postulated correlation between brown soils and axes cannot be seen, however. On the contrary, the densest concentration of axes is in a sub-region within the clayish soil region. There is uncertainty in that small pockets of preferred soils may be present within the region. In general, this landscape type is not regarded as optimal for early agriculture but well suited for pastoralism. The find distribution could show that the Early Neolithic subsistence in fact depended more on pastoralism than on agriculture, and this could be related to the early indications of pastoralism in Telemark (Mikkelsen 1989) and Hedmark (Amundsen 2011).

The number of thin-butted axes normalized by the area of each sub-region (Figure 2.2) gives a somewhat different impression. There are three small regions to the west of the Oslo fjord that have a high score in this presentation. One of them belongs to the clayish soil area and the other two, to the region of lower valleys.

The distribution of thin-butted axes of flint shows a clear concentration in the outer part of the Oslo fjord and in the area to the east (Figure 2.3). With the same normalization (Figure 2.4) of this group, the highest density is found on the west side of the fjord.

The stone axes have the highest concentration in the same area as the flint axes (Figure 2.5). The normalization also shows for this group that there is a high density in a sub-region to the west of the Oslo fjord, but not overlapping with the flint axes (Figure 2.6).

The map (Figure 2.3–2.5) shows differences in the distribution of flint and stone axes. The flint axes were produced within limited areas with good flint resources in Sweden and Denmark, and were relatively standardized. The most typical stone axes are found in areas with many flint axes, and there is more variability further away. This might suggest less knowledge of original items, or perhaps illustrate less need to make an exact copy (Glørstad 2009). The stone axes have as wide a distribution as the flint axes. Both have a concentration around

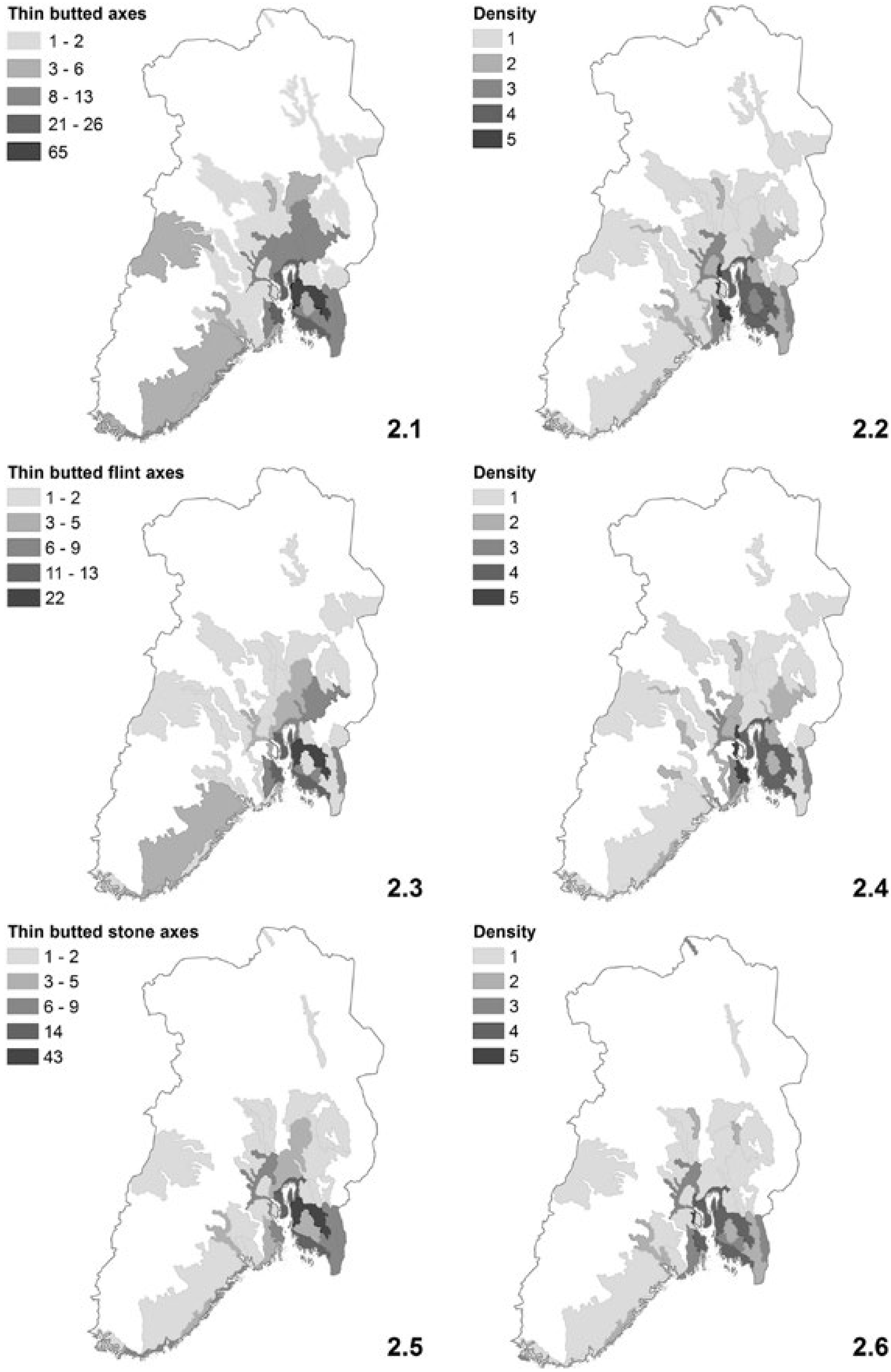

Fig. 2. Macro level distribution of thin-butted axes in sub-regions. 2.1 Number of axes per sub-region (n); 2.2 Five density levels of number of axes per sub-region normalized by area (n/A); 2.3 Flint axes n; 2.4 Flint axes n/A; 2.5 Stone axes n; 2.6 Stone axes n/A.

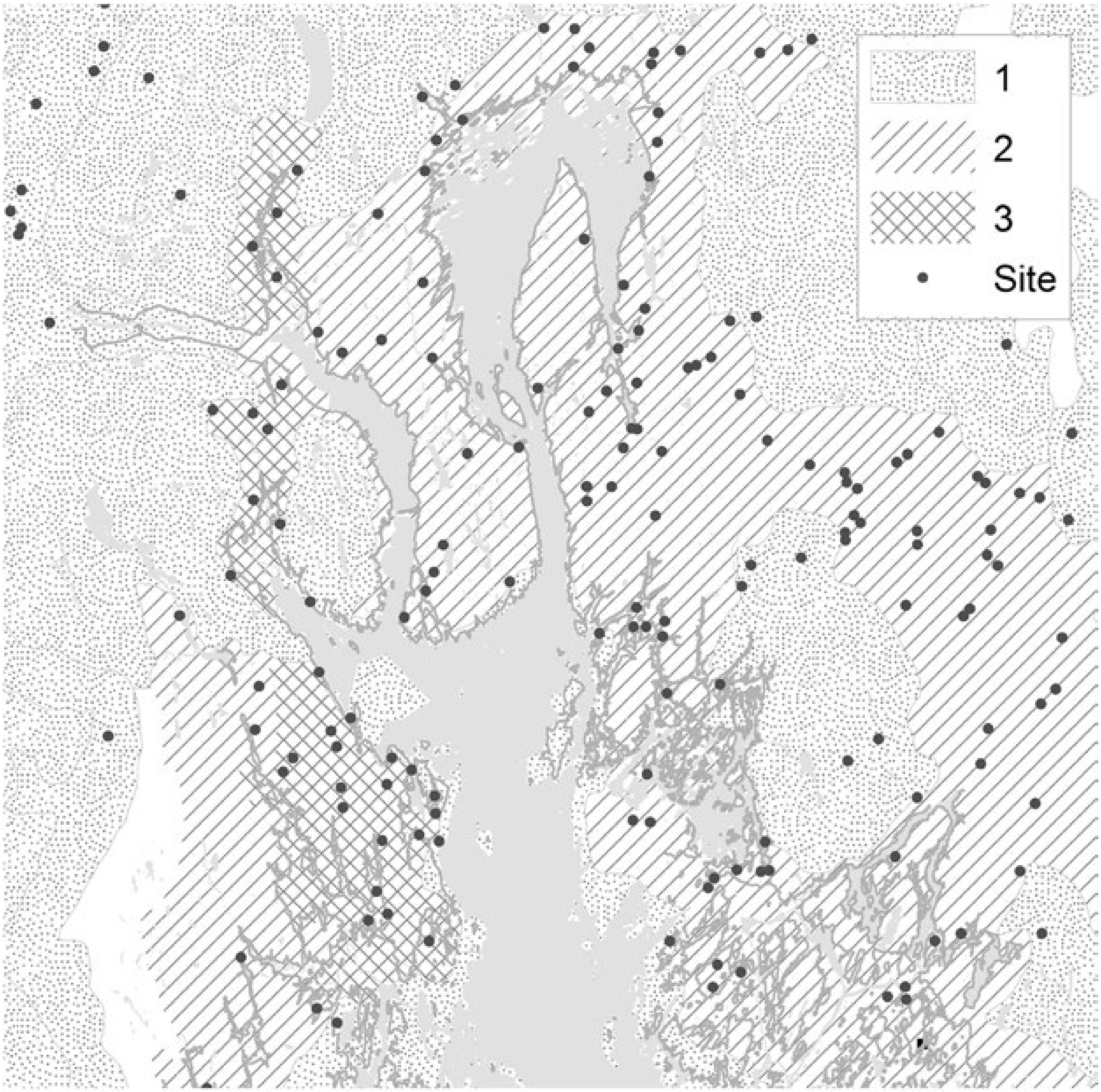

Fig. 3. Micro level distribution of thin-butted axes over sub-regions around the Oslo fjord. Three density levels of number of axes/area of sub-region. The approximate sea level at the transition from Late Mesolithic to Early Neolithic, 40 m a.s.l., is indicated.

the Oslo fjord, but the stone axes also have a concentration far from the traditional core area of the Funnel Beaker Complex.

This distribution can be consistent with the idea that stone and flint axes belonged to different exchange networks, or that different local groups have preferred different types. The flint axes have been exchanged as prestige commodities with groups further away from the central areas, but some of them have ended as raw material for small tools at settlement sites (Glørstad 2004). The distribution suggests exchange networks along the coast. There are not many axes in Telemark, Aust- and Vest-Agder, but as a landscape, the whole coast is defined as one sub-region. The presence of fragmented flint axes at the Neolithic sites along the coast also implies that this sub-region was used by groups that were in contact with the Funnel Beaker Complex around the Oslo fjord. The Early Neolithic enclosure in Vest-Agder suggests an affiliation with the Funnel Beaker Complex further south.

The map at this macro level gives an overview of the broad distribution of finds. It presents a distribution coinciding with good, but not necessarily the best, land for early agriculture.

Looking at the distribution at micro level might support this observation.

The micro level analysis concentrates on the area around the Oslo fjord, with the sub-regions with the highest find density to the west. It includes sub-regions categorized by the ratio of axes to area, and the sites are also shown as points. Waterways are included, and the altitude is an important variable at this scale due to sea level change.

According to the curve for isostatic change (Sørensen 1979), sea level was at a level of 35−40 m higher than today at the transition between the Late Mesolithic and the Early Neolithic. Sea level was higher in the inner part of the Oslo fjord than further south. An altitude of 40 m a.s.l. is indicated on the map, to illustrate the situation around 5000 BP. The areas with highest density on the west side of the fjord are today fertile agricultural areas. They are broadly speaking following a line north–south, from one fjord to the next west of the Oslo fjord. At the beginning of the Neolithic period, it was a proper fjord landscape. The terrain rises westwards, and the landscape changes to forest. There is also a concentration of finds near the Early Neolithic coast on the east side of the fjord. Here, the landscape changes more slowly, and therefore the sub-regions are wider and consequently the ratio of finds to area is much lower.

This axe distribution at micro level supports the impression from the macro level that agriculture was not the most important factor. There are no strong indications of agriculture at this stage in Norway. The microanalyses shows affiliation to the coast and a marine adaptation continued from the Late Mesolithic.

5 Concluding remarks

The Norwegian Early Neolithic is much debated and our view of Neolithic society is changing. In this paper, meticulously prepared data in the MUSIT database was combined with the holistic landscape categorization. It has shown that this kind of visualization will contribute to the archaeological discourse in Norwegian Stone Age research.

Several recently excavated settlement sites and the unique enclosure in Vest-Agder create a new basis for the understanding of this transition period. Axes had life cycles during which they could be deliberately deposited at places with meaning in the landscape, in this way showing the other landscape that complemented the landscape of daily tasks.

This article has presented two examples of single finds in combination with different kinds of digital map data. The open data in the MUSIT database affords new possibilities to try out new ideas. Map-based EDA offers an opportunity to work more inductively with the data. A certain combination can raise an awareness of insufficient or incongruent data, creating a cycle of analysis, of improved understanding, and improved datasets. The possibility of trying many different combinations makes the map a rewarding tool for improved research and better understanding.

The combination of digital landscape categories and large archaeological databases with EDA in a GIS offers the possibility of expanding on fine-tuning analysis at different scale levels.

Bibliography

Andrienko, N. and Andrienko, G. 2006. *Exploratory Analysis of Spatial and Temporal Data. A Systematic Approach*. Berlin and Heidelberg, Springer Verlag.

Amundsen, H. R. 2011. *Mot de store kulturtradisjonene: endringsprosesser fra tidligneolitikum til førromersk jernalder mellom Mjøsa og Femunden*. PhD dissertation. University of Oslo.

Brøgger, A. W. 1906. *Studier over Norges Stenalder. I.* Øxer *uden Skafthul fra yngre Stenalder fundne i det sydøstlige Norge*. Videnskabs-Selskabets Skrifter. 1. Math.-Naturv. Klasse. 1906. No.2. Christiania: Jacob Dybwad.

Glørstad, H. 2004. Svinesundmaterialet i lys av annen forskning i Oslofjordsdistriktet og i Vest-Sverige. In Glørstad, H. (ed.) *Bind 4. Oppsummering av Svinesundprosjektet*. Varia. 57: 47-58. Oslo, Universitetets kulturhistoriske museer. Fornminneseksjonen.

Glørstad, H. 2005. Tangen – en neolittisk boplass fra Kragerø kommune. *Viking*. LXVIII-2005: 25-54.

Glørstad, H. 2009. The Northern Province? The Neolithisation of Southern Norway. In Glørstad, H. and Prescott, C. (eds.), *Neolithisation as if history mattered. Processes of Neolithisation in North-Western Europe*: 135-168. Lindome, Bricoleur Press.

Glørstad, H. and Uleberg, E. 2002. 200 års flid for massenes føtter eller digitalisering av Oldsaksamlingens funn fra steinalder. In: Hofseth, E. H. (ed.) *UKM − En mangfoldig forskningsinstitusjon*. Universitetets kulturhistoriske museer Skrifter. Nr. 1: 73-82. Oslo, Universitetets kulturhistoriske museer, Universitetet i Oslo.

Glørstad, H. and Sundström, L. 2014. Hamremoen − an enclosure for the hunter-gatherers? In: Furholt, M., Hinz, M., Mischka, D., Noble, G. and Olausson, D. (eds.), *Landscapes, Histories and Societies in the Northern European Neolithic*. Frühe Monumentalität und soziale Differenzierung. Band 4: 29-47. Bonn: Verlag Dr. Rudolf Habelt.

Harris, T. M. 2006. Scale as Artifact: GIS, Ecological Fallacy, and Archaeological Analysis. In: Lock, G. and Molyneaux, B. L. *Confronting scale in archaeology*: 39-54. New York: Springer.

Hinsch, R. 1955. Traktbegerkultur − Megalitkultur. En studie av Øst-Norges eldste, neolitiske gruppe. *Universitetets Oldsaksamling* Årbok. 1951-1953: 10-177.

Holmen, J. and Uleberg, E. 1996. Getting the most out of it − SGML-encoding of archaeological texts. Paper presented at the IAAC'96, Iasi, Romania. [Online] http://www.dokpro.uio.no/engelsk/text/getting_most_out_of_it.html [Accessed: 24th june 2015].

Hulthén, B. and Welinder, S. 1981. *A Stone Age economy*. Theses and Papers in North-European Archaeology 11. Stockholm, Akademilitteratur.

Indrelid, S. and Moe, D. 1983. Februk på Hardangervidda i yngre steinalder. *Viking*. XLVI-1982: 36-71.

Jordal, E., Holmen, J., Olsen, S. A. and Ore, Ch.-E. 2010. From XML-tagged Acquisition Catalogues to an Event-based Relational Database. In Nicolucci, F. and Hermon, S. (eds.), *Beyond the Artifact. Digital Interpretation of the Past. Proceedings of CAA2004, Prato 13-17 April 2004*: 81-5. Budapest, Archaeolingua.

Jordal, E., Uleberg, E. and Hauge, B. 2011. Was It Worth It? Experiences with a CIDOC CRM-based Database. In Zhou, M., Romanowska, I., Z. Wu, P. Xu and Verhagen, P. (eds.), *CAA2011 – Revive the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 39th International Conference, Beijing, April 12-16*: 255-60. Amsterdam, Pallas Publications.

Matsumoto, M. and Uleberg, E. 2015. Scale Dependent Patterns in South-Eastern Norway. In Traviglia, A. (ed.), *Across Space and Time. Papers from the 41st Conference* *on Computer Applications and Quantitative Methods in Archaeology Perth, 25-28 March 2013*: 283-8. Amsterdam, Amsterdam University Press.

Matsumoto, M. and Uleberg, E. (forthcoming). Digitalizing Archaeology in Norway. Paper from Condition.2015. Conservation and digitalization conference, 19.-22.05.2015, Gdańsk.

Mikkelsen, E. 1984. Neolitiseringen i Norge. *Universitetets Oldsaksamling* Årbok 1982/1983: 87-128.

Mikkelsen, E. 1989. *Fra jeger til bonde. Utviklingen av jordbrukssamfunn i Telemark i steinalder og bronsealder*. Universitetets Oldsaksamlings Skrifter Ny rekke. Nr. 11. Oslo, Universitetets Oldsaksamling.

Nymoen, P. and Skar, B. 2011. The Unappreciated Cultural Landscape: indications of submerged mesolithic settlement along the Norwegian southern coast. In Benjamin. J., Bonsall, C., Pickard, C. and Fischer, A. (eds.), *Submerged Prehistory*: 38-54. Oxford and Oakville, Oxbow Books.

Prescott, C. 1996. Was there *really* a Neolithic in Norway? *Antiquity*. 70 (267): 77-87.

Prescott, C. 2009. History in prehistory – the later Neolithic/ Early Metal Age, Norway. In Glørstad, H. and Prescott, C. (eds.), *Neolithisation as if history mattered. Processes of Neolithisation in North-Western Europe*: 193-216. Lindome, Bricoleur Press.

Puschmann, O. 1998. The Norwegian landscape reference system – use of different sources as a base to describe landscape regions. *NIJOS rapport*. 12/98. Ås, Norsk Institutt for jord- og skogkartlegging.

Puschmann, O. 2005. Nasjonalt referansesystem for landskap. Beskrivelse av Norges 45 landskapsregioner. *NIJOS rapport*. 12/2005. Ås, Norsk Institutt for jord- og skogkartlegging.

Solberg, A. 2012. Ferdselsårer for ideer og materiell kultur i tidligneolitikum. Kyst og elveleier i sørøstnorske grensetrakter. In Solberg, A., Stålesen, J. A. and Prescott, C. (eds.) *Neolitikum. Nye resultater fra forskning og forvaltning*. Nicolay Arkeologisk Tidsskrift. 4: 35-6.

Solheim, S. 2012. *Lokal praksis og fremmed opphav: arbeidsdeling, sosiale relasjoner og differensiering i* østnorsk *tidligneolitikum*. Unpublished PhD thesis, University of Oslo.

Stenvik, L. 2005. Vegetasjonshistorie. In Østmo, E. and Hedeager, L. (eds.), *Norsk arkeologisk leksikon:* 412-421. Oslo, Pax Forlag.

Steuer, H. 2006. Verbreitungskarte. In Hoops, J. (ed.), *Reallexikon der Germanischen Altertumskunde*. Band 32: 142-166. Berlin and New York, Walter de Gruyter.

Sørensen, R. 1979. Late Weichselian deglaciation in the Oslofjord area, south Norway. *Boreas*. 8: 241-6.

Tilley, C. 1994. *A Phenomenology of Landscape. Places, Paths and Monuments*. Oxford Berg.

Uleberg, E. and Matsumoto, M. 2015. Visualization based on the Norwegian University Museum Database. In Costa, L., Djindjian, F., Giligny, F. and Moscati, P. (eds.), *CAA2014 − 21st Century Archaeology. Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*: 323-31. Oxford, Archaeopress.

Østmo, E 1998. Register over trykte tilvekster av norske oldsaker. Delvis på grunnlag av eldre arbeider av Helge Gjessing og Per Fett. *Universitetets Oldsaksamling* Årbok. 1997/1998: 177-90.

CHAPTER 5
New Trends in 3D Archaeology

Hand-free Interaction in the Virtual Simulation of the Agora of Segesta

Riccardo Olivito
riccardo.olivito@sns.it
Scuola Normale Superiore, Pisa, Italy

Emanuele Taccola
emanuele.taccola@unipi.it
University of Pisa, Italy

Niccolò Albertini
niccolo.albertini@sns.it
Scuola Normale Superiore, Pisa, Italy

Abstract: The aim of the paper is to illustrate an application of immersive virtual reality, concerning the archaeological investigation in the agora *of Segesta. The research, led by a team of archaeologists and researchers of the Scuola Normale Superiore and the University of Pisa, has developed a 3D simulation of the ancient* agora*, allowing experts and non-experts to virtually reproduce the excavation activity and to interact with the hypothetical reconstruction of the monuments.*

The application is configured to run-in two different virtual environments: within the CAVE-like system of the DreamsLab at the Scuola Normale Superiore, where the user can manage it in a complete hand-free way, and on wearable, such as the Oculus Rift DK2 and the Myo Armband, making the application easily portable and available-on the field, during the fieldwork activity, the final goal being to bridge the gap between the data acquisition and interpretation steps.

Keywords: Cyber-Archaeology, Immersive Virtual Environments, Hand-free Gesture Interaction

1 Introduction [R.O.]

The archaeological investigations in the *agora* of Segesta, restarted in 2001 (Ampolo and Parra 2012), have brought to light a large part of the ancient public square and of the buildings which bordered it along the north, west, and east sides (Fig. 1). The excavations have made it possible to acquire new data on the planimetric, architectural and monumental features of the *agora*, and to emphasize the role of a large *stoa* with two projecting wings, which was built in the Late-Hellenistic period (end of the 2nd century BC).

The formulation of a hypothetical reconstruction of the vertical development of the building is the result of an accurate architectural study (Abate and Cannistraci 2012). This two-storey and two-aisled complex, built on a three steps stylobate, had the role to border the *agora* and, at the same time, to set up a monumental scenography for the ancient public square. With a total height of c. 11m, the *stoa* was composed of a doric colonnade at the lower level (6.6m high), and of an ionic colonnade (4.3m ca. high) completed with *symae* and lion's head protome dripstones at the upper floor. The planimetry of the *agora* and its *stoa*, although still under investigation, is quite well-documented. The north side of the building, 82m long, was completed on the eastern and western sides with two projecting wings, having a length of 20m. As far as the internal plan of the *stoa* is concerned, an intermediate row of octagonal pilasters had the function to create two aisles (the external one c. 5.8m deep; the internal one c. 5.5m in depth) and sustain the second floor.

The most up-to-date data allow us to exclude the presence of rooms and walls along the back wall. A quite different situation is that attested in the N-W corner of the monument. Here a stair was set up, making it possible to reach the upper floor of the *stoa*. As to the eastern corner, it was completely occupied by the only room so far attested within the building, whose main entrance was marked by semi-columns and pillars, certainly emphasizing the role of this part of the *stoa*. The discovery of burnt traces along the walls of the room, probably to be related to wooden shelfs, could suggest an identification of the so-called 'Ambiente I' with an archive or a documents depository (Abate and Perna 2012; Abate and Cannistraci 2013).

Still in the eastern wing of the portico, the presence of a threshold south of the so-called Room I indicates with no doubt the presence of other rooms (at least one) in this part of the building.

Furthermore, new investigations in the Nord side of the building, along its rear wall, allowed archaeologists to discover the collapsed remains of some stone arches that had been built in order to sustain and strengthen points where the rock had been cut before the construction of the stoa.

In this very articulated architectural and archaeological setting, during the last two campaigns of excavation new digital methods and techniques of documentation have been tested, in order to improve the level and quality of the data acquisition phase and the following elaboration and analysis processes (Olivito, Taccola and Albertini 2015).

2 Methodological Issues [R.O.]

Since the 1960s archaeology has been involved in a deep theoretical debate concerning all the aspects of the research activity, relating to data interpretation and dissemination methods. In this regard, the rapid spreading of scientific tools and methods to be applied to a still traditional discipline played a fundamental role.

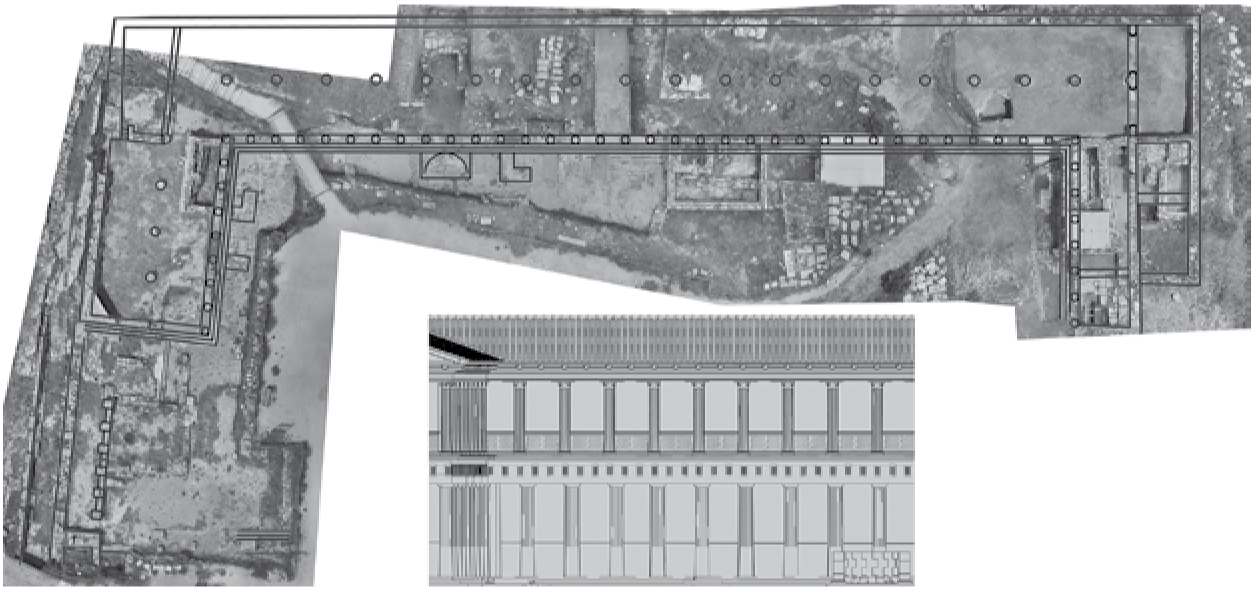

Fig. 1. Ortophoto of the agora (GSD 0.008m) with main alignments and front of the *stoa*.

Processual (or New-) archaeology debated on the importance of using scientific methods and technological tools (quantitative, taxonomic, computational, and laboratory analysis) in order to investigate issues mainly of economic, sociological, anthropological, and material culture nature (Binford and Quimby 1972). Processual-archaeologists used to consider each cultural phenomenon as unique and unrepeatable: as a result, they looked at scientific methods and technological tools as the best solution to transform Archaeology in a real Hard Science.

At the same time, the research of the exactitude of the material data, to be investigated through 'aseptic' and objective tools and methods, led to an overestimation of the role played by scientific analysis tools to the detriment of the interpretative process.

In opposition to this positivist approach, during the 1980s, Post-Processual (or Anti-Processual) Archaeology (Hodder 1986; Renfrew 1994) pointed out the variety and unpredictability of factors (of human, social, cultural, and environmental nature), which affect the historical process and cannot be considered as invariable and independent from the context in which they take place. In their opinion, the historical reconstruction is a process that, even if investigated with the methods and scientific instruments, needs to be interpreted looking at the context and the individual and psychological factors.

In this articulated theoretical context new techniques of computer-graphics and Virtual Reality have been recently integrated, stimulating a transition from two-dimensional to three-dimensional visualization methods. This led to the birth and development of the so-called Virtual Archaeology and to a strong advancement in the production of archaeological reconstructions increasingly characterized by a high-photorealism (Forte and Siliotti 1997). But 'Virtual-Archaeology was not able, substantially, to elaborate sophisticated cyber behaviors in 3D real time environment' (Forte 2010).

For this reason, during the last years scholars have introduced the new concept of 'Cyber' into the archaeological practice. As Zubrow has noticed, cyber involves the connotation of 'control' and 'being controlled' (Zubrow 2010). This connotation is central to Cyber-Archaeology, for 'the core of the process is not into the model, data or environment but in the mutual relations produced by interaction/embodiment/enaction' (Forte 2010).

Whereas Virtual-Archaeology is mainly based on static 'reconstructions', Cyber-Archaeology assigns a key role to the concept of 'simulation' and 'simulation slice' (Clark 2010), which is not a 'reconstruction', but rather only one of the possible interpretations of a certain context.

Cyber-Archaeology might thus represent an articulated and interdisciplinary solution, not only able to solve the dichotomy between Processual- and Post-processual Archaeology, but also to overcome the limits of Virtual-Archaeology.

In our opinion, Cyber-Archaeology can ensure a more thorough and dynamic investigation of the past and, at the same time, a more detailed and effective dissemination of scientific results, even to non-experts.

3 Data acquisition [E.T.]

According to the principles of the most recent virtual- and cyber-archaeological approaches, in creating the 3D models of the agora of Segesta, computer graphics and aerial and terrestrial close-range photogrammetric techniques have been employed (Olivito and Taccola 2015).

With the first method, although using measured data and consolidated studies of the elevations, the buildings have been reconstructed as scholars suppose they use to appear at end of the 2nd century BC. With the second method, objects and structures have been acquired in their current condition with reality-based procedures.

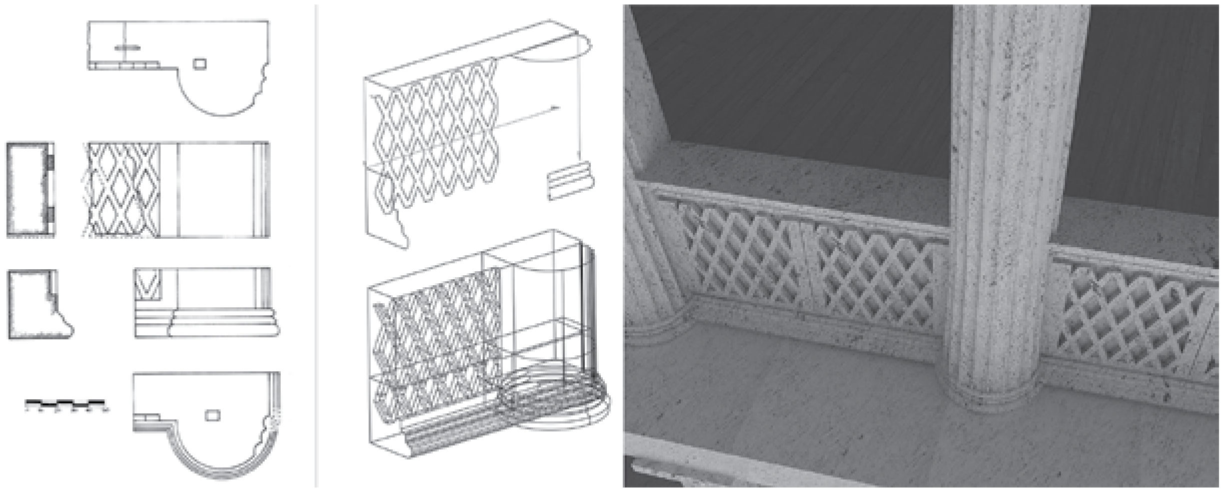

Fig. 2. Manual drawing of an architectural element turned into 3D model.

The operation of 3D reconstruction took a long time, because the drawings of architectural elements available have been so far made with traditional manual techniques on paper. Therefore as first it has been necessary to scan, then vectorize and finally turn them into 3D objects (Fig. 2).

To properly position the 3D models of these architectural elements, the measurements and ratios of proportions of the visible structures were compared with similar examples best preserved in Sicily and in the Mediterranean area: this has allowed to gather precise information on architectural volumes, from which reliable data for the 3D reconstruction of the ancient *agora* (Fig. 3) have been obtained. The software used for these operations are AutoCAD and 3ds Max.

The *agora* reconstructed has been inserted into its environment, having a DTM generated by the contour lines of the Barbaro mountain, and then rendered with photorealistic textures derived from the materials used for its edification (Taccola 2012).

In a first step, the 3D model has been made available for interaction in a virtual environment specifically created for the Cave Automatic Virtual Environment of DreamsLab and on portable and wearable devices such as the Oculus Rift DK2.

To guarantee the fluidity in real-time rendering without losing quality, the model of the agora of Segesta has been adapted in Unity 3D Game Engine using techniques of decimation of polygons but keeping the size of the textures (Albertini *et al.* 2014).

After that, the model has been integrated in a dedicated application for the CAVE-like system (Fig. 4). At this preliminary stage, the interaction is limited to navigation within the virtual environment: for this purpose a 'walk' interaction metaphor has been developed to make the movement as natural as possible, even if it has been necessary to solve the conflict between a very large virtual environment (c. 100m) and the actual size of the CAVE that is much smaller (3m).

In this case, the fruition of the model within the virtual environment requires only the use of 3D glasses and needs no particular skills, being limited to short movements back and forth and sideways, which still ensure excellent functionality.

Furthermore, the immersion allows to consider issues not easily verifiable by using only 2D tools available so far, such as possible solutions adopted in the carpentry; physical and spatial relations between the *stoa*, its internal space, and the other monuments of the public square; relations between architecture, decorations, and documentary apparatus (e.g. statues and inscriptions); the role played by natural and artificial lighting in different moments of the day.

However, the interaction limited to navigation makes the 3D model a reconstruction rather than a simulation. In fact, with this configuration the user cannot derive in real-time information and obtain metadata from the visualized elements. At this stage, the application is conceivable as a Virtual-archaeological tool.

Recently, a new strategy mainly oriented towards simulation and a Cyber-archaeological approach: for this purpose, the 3D model of the *agora* has become a basis for further analysis or for the creation of a 'Simulation Slice'.

In addition, since 2013 techniques of photogrammetric survey, both aerial and terrestrial have been introduced, in order to document in real-time the fieldwork activity and to digitally acquire the most important items found during the excavation (above all architectural elements).

The software used for these operations are Agisoft Photoscan, Geomagic Studio and KopterTool.

The aerial coverage of the *agora* (c. 3500m^2) required an UAV, a hexacopter Microkopter. It took 3 flights from an altitude of 15m for the survey of the entire area, according to a pre-set flight plan.

664 images have been processed and turned into a high-resolution 3D model, properly oriented according to the reference system used within the area of excavation by a series of Ground Control Points measured with total station. It

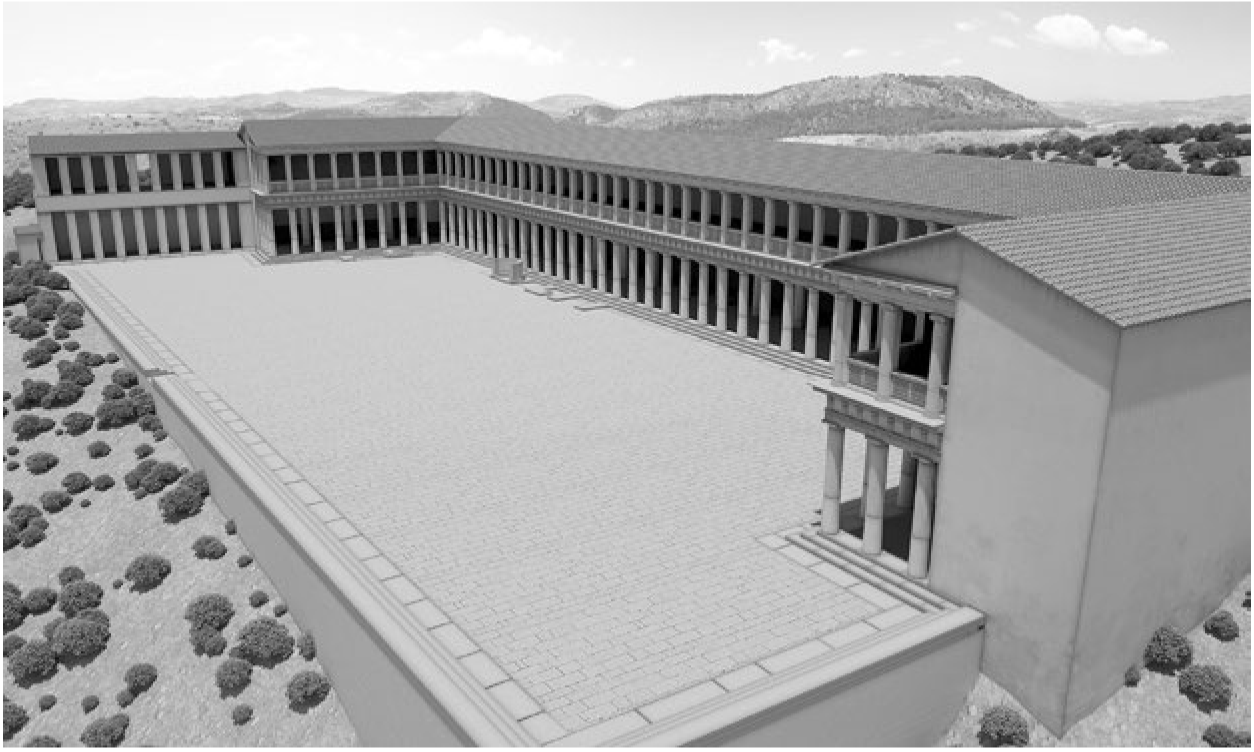

Fig. 3. 3D model of the agora of Segesta.

Fig. 4. 3D model of the agora within the CAVE.

constitutes the necessary basis for the positioning and alignment of all the surveys obtained with terrestrial procedures.

In fact, terrestrial and aerial photogrammetry have been integrated: in may 2014 and may 2015, during the two three-week campaign of excavation on the site of Segesta, 9 photogrammetric models were created, following the progressive development of field activities.

The excavation levels included the most superficial layers, up to the traces of medieval re-occupation of the area and those relating to the collapse, abandonment, use and edification of the late- Hellenistic *stoa* (Fig. 5).

In addition, two significant items found inside the excavated levels have been documented individually in 3D: a dripstone (*geison*), relative to the decorative apparatus of the second floor of the *stoa*, and an oven dating back to the Swabian era,

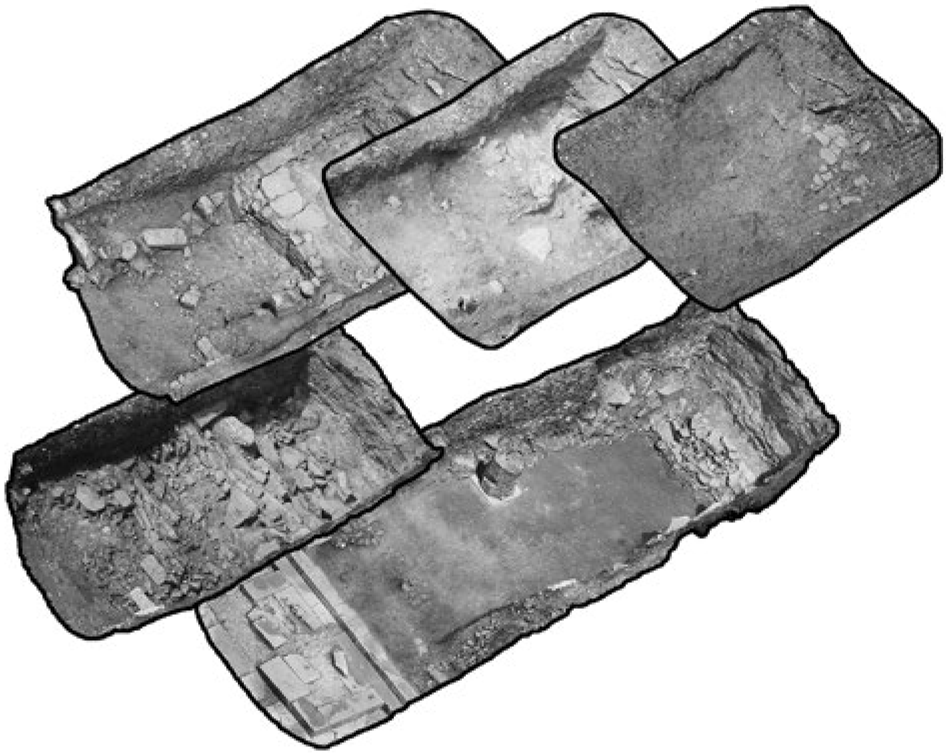

Fig. 5. The main image-based models of the stratigraphic sequence, realized during the fieldwork activity.

built over the collapse of the wall of the Hellenistic building. Even the latter have been aligned properly to the 3D survey by UAV and to the 3D models of excavation activity.

4 Immersive VR Applications [N.A.]

All these photogrammetric models have been adapted with Unity 3D Game Engine to the virtual immersive environment that already included the 3D reconstruction of the *agora*. Although it is still experimental and currently being finalized, this application, configured to visualize, interact with and interrogate the models, nevertheless presents encouraging prospects, both from the scientific, technical, and communicative point of view.

The aim of the new application is to furnish the operator a wider number of functions, with a higher quality, enhancing the level of embodiment while operating within the virtual environment. In order to reach this purpose, it has been decided to focus on the gestures available in the simulation, paying special attention to the improvement of the interaction between users and digital models. This has been made possible due to the visualization of the perfectly overlapped and aligned models of the stratigraphic layers acquired on the field, to the possibility of manage them while operating in the virtual simulation and, finally, to query and examine the relative metadata simply by using hand-gestures.

In fact, in the new application a key role is played by the use of a sensor for the tracking of hands (leap sensor) that makes the application completely hands-free (Olivito, Taccola and Albertini 2015). With a 3D printer a support for 3D glasses has been created, on which the ultrasonic sensor and the leap can be mounted at the same time. In so doing the user can use the leap sensor in a non-standard way, because it is attached on the head, and not, as usual, on a flat surface. In parallel, a 2D interface usable in a natural way, by hand movements, has been developed (Fig. 6). This makes the application friendly and easy to use. Whereas the single stratigraphic layers can be slid up and down by virtual arrows visualized on the screen of the CAVE and activated by virtually pushing the icon with the hand, the models of peculiar items (i.e. the dripstone and the oven) can be popped-up, automatically rotated, and zoomed-in for a closer view, thanks to an interactive icon which appears only together with the layers where they have been found.

At present, only one user can control the gestures, while the visualization and the activity within the virtual simulation has a multi-user nature (max 3 or 4 people). As far as the leap is concerned, it is possible to affirm that the detection of hands position and movement is very accurate and not onerous either for the device or for the user.

In the very next future, and thanks to the rapid development of wireless hand trackers, new features will be introduced. For instance, the new hand-tracking system will allow for the introduction of new and more complex gestures (e.g. the hand-controlled rotation of models, the measurement of distances, areas, volumes, objects), which will improve the quality of immersivity and embodiment within the virtual simulation.

The increase of the stratigraphic models due to further fieldwork activities, will indeed require an extension of the natural interface used for the interaction within the virtual

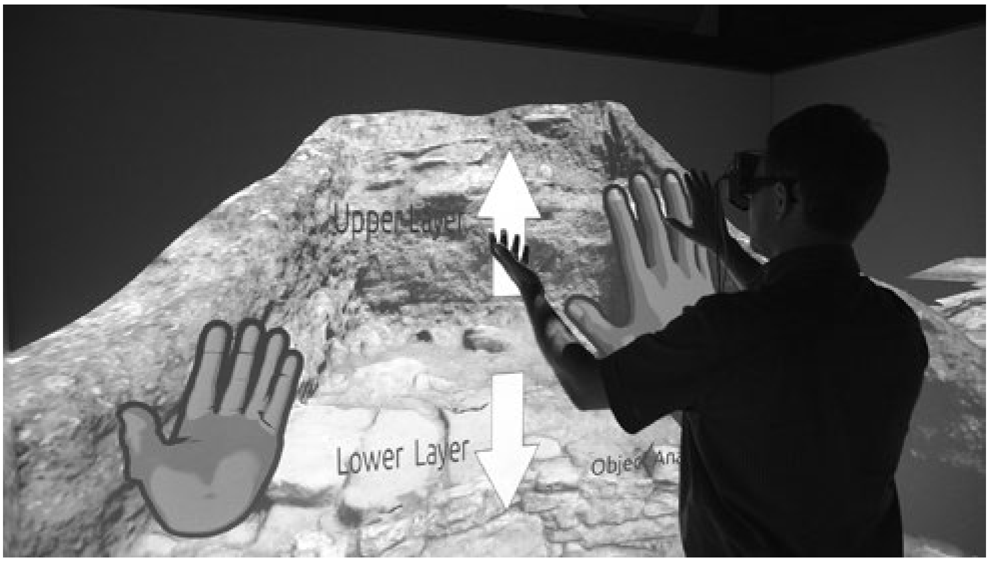

Fig. 6. The application combining 3D glasses and leap sensor within the CAVE.

environments, allowing for the quick selection of single layers and for a rapid browsing of the stratigraphic sequence.

Furthermore, the attempt to solve the problem of visualizing large amounts of data and text, such as records of single layers, architectural elements, and objects discovered during the fieldwork activity within the virtual environment is still in progress. At present, this issue has been overcome thanks to the creation of links to the metadata and text files, to be activated with a specific gesture. The links, in fact, connect to the database used for the collection and query of the excavation data, which contains layers records, text files, images, drawings, that can consequently be visualized either within the CAVE or on an external device (laptop, monitors, tablets). In so doing, different users have the opportunity to contemporarily operate into the CAVE and look the database over, extract information on single layers and objects and, finally, modify in real time previous interpretation of the archaeological datum.

In this regard, it is important to refer to two different tests realized in order to improve the level of natural interaction within the virtual environment. The aim of the new application development has been the research of its portability and usability, also while working on the field. The Oculus Rift DK2 has been the most suitable device for this purpose.

During the first test, the Oculus Rift DK2 has been linked to the leap sensor as already used in the CAVE. This attempt has raised doubts on the efficiency of the combination of these two devices: the main issues were indeed related to the gesture recognition phase, due to problems in the too much bulky visualization of hands representation, not perfectly synchronized with actual hands movements (Fig. 7).

These difficulties, which make problematic the use of these two devices in combination, have led towards a second test, in which the Oculus Rift DK2 has been linked to the Myo Armband (Fig. 8), a hardware that recognizes the gestures through a muscle sensor. The process of integration of Myo required a re-design of the interface. Whereas the leap sensor uses a 3D movement of the hands, this device has required a recalibration of the interaction on the muscle detection made by the sensor, in addition to the detection on two dimensions operated by the gyroscope.

Unity3D allowed us to manage the interface between the Oculus Rift DK2 and Myo and to integrate the gestures within the virtual world, so as to transpose the natural movements in the virtual environment. In addition to this, the gyroscope calculates the rotation of the hand, adding a rotational gesture to those already acquired by the muscle sensor. Thus, it is potentially possible to increase the number of gesture acquired, deciding which task to fulfil depending on the combination of rotation of the arm and muscle gesture performed.

In so doing, with the acquisitions of the gesture it is possible to control the main tasks (e.g. slide-up and slide-down between the layers), whereas the movement of the arm performs a sort of virtual cursor for other types of tasks that require a spatial reference (e.g. indicating an object).

5 Conclusions [R.O., E.T.]

In studying the *agora* of Segesta it is now possible to rely on a 3D model that allows for a more articulated and interactive idea of the ancient square and its buildings at the end of the 2nd century BCE. As a result, it is possible to shed new light on issues of great importance such as physical and spatial relations between objects and monumental context; internal and external visibility; relations between open and closed spaces; lighting inside the building. It is possible to affirm that the 3D simulation and the new virtual application will allow for a deeper knowledge of the public square of Segesta and for a better dissemination of the data, both in the scientific community and in the non-experts audience.

Indeed, although still in phase of development, the application allows scholars and even non-experts to interact with the digital models in a more accurate and useful way, to query the metadata collected and stored during the fieldwork activity,

Fig. 7. The application combining the Oculus Rift DK2 and the leap sensor.

Fig. 8. The application combining the Oculus Rift DK2 and the Myo Armband.

and, due to the availability of an easy-to-use set of hand-free gestures, to adopt external devices for the consultation of the database while operating in the CAVE.

By working in an autonomous or collaborative way, it will then possible to have a virtual simulation of the field activity. With the further development of the research, the quality and quantity of models and data that can be visualized will be improved. In parallel, although aware of the limits of wearable devices such as the Oculus Rift Developer Kit 2 (and even more of the first release Oculus Rift Developer Kit 1), the aim is to extend the application to this kind of devices, with the intention to increasingly reduce the still existing gap between data collection/elaboration and data interpretation, even while operating on the field.

As to the combination of the Oculus Rift and the Myo Armband, at present the number of gestures is limited to slide, selection, and rotation. Despite this, and differently from the leap sensor, the Myo allows for a visualization of the scene without other graphic intrusions (hands representations, interfaces, menu, etc.). In so doing, the realization of the gestures, even if not extremely natural, is doubtless more comfortable and efficient. As a result, in our opinion this combination can assure better results and is worth being further developed, the final aim being its use during the archaeological campaign.

Bibliography

Abate, A., Cannistraci, O. S. 2012. La stoa tardoellenistica dell'agora di Segesta: alcune note preliminari sull'elevato architettonico del lato Ovest. In C. Ampolo (ed.), *Agora greca e Agorai di Sicilia*: 305-19. Pisa, Edizioni della Normale.

Abate, A., Cannistraci, O. S. 2013. Segesta. Agora. Analisi architettonica dell'ingresso monumentale all'ambiente I della stoa Nord. *Annali Scuola Normale Superiore,* s. 5, 5/2: 29-48.

Albertini N., Barone V., Brogni A., Legnaioli S., Licari D., Taccola E. 2014. The *agora* of Segesta in immersive virtual environments. In: *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the sixth international conference, Athens, 22-25 October 2013*: 299-304.

Ampolo, C., Parra, M. C. 2012. L'agora di Segesta: uno sguardo d'assieme tra iscrizioni e monumenti. In C. Ampolo (ed.), *Agora greca e Agorai di Sicilia*: 271-86. Pisa, Edizioni della Normale.

Binford, L. R., Quimby, G. I. 1972. *An archaeological perspective*. Studies in archeology. New York, Seminar Press.

Cannistraci, O. S., Perna, M. 2013. Agora. Settore NordEst (SAS 4; 2011). Relazioni preliminari degli scavi a Segesta (Calatafimi-Segesta, TP; 2011). *Annali Scuola Normale Superiore,* s.5, 4/2: 12-6.

Clark, J. T. 2010. The fallacy of reconstruction. In M. Forte (ed.), *Cyber-Archaeology*. British Archaeological Reports International Series 2177: 63-73.

Forte, M. 2010. Introduction to Cyber-Archaeology. In M. Forte (ed.), *Cyber-Archaeology*. British Archaeological Reports International Series 2177: 9-13.

Forte, M., Siliotti, A. 1997. *Virtual archaeology: re-creating ancient worlds*. New York, H. N. Abrams.

Hodder, I. 1986. *Reading the past: current approaches to interpretation in archaeology*. Cambridge, New York, Cambridge University Press.

Olivito R., Taccola E. 2015. 3D modelling in the agora of Segesta: techniques and data interpretation. *Archeologia e Calcolatori* 25: 61-74.

Olivito, R., Taccola, E., Albertini, N. 2015. A hand-free solution for the interaction in an immersive virtual environment: the case of the agora of Segesta. In International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Archives), XL-5/W4: 31-36. Available at: http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-5-W4/31/2015/isprsarchives-XL-5-W4-31-2015.pdf. [Accessed: 18 February 2015].

Renfrew, C. 1994. Towards a cognitive archaeology. In C. Renfrew, E. B. W. Zubrow (eds.), *The ancient mind: elements of cognitive archaeology. New directions in archaeology*: 3-12. Cambridge, New York, Cambridge University Press.

Taccola, E. 2012. Ricostruzioni 3D per l'agora di Segesta. In C. Ampolo (ed.), *Agora greca e Agorai di Sicilia*: 175-88. Pisa, Edizioni della Normale.

Zubrow, E. B. W. 2010. From Archaeology to I-archaeology: Cyberarchaeology, paradigms, and the end of twentieth century. In M. Forte (ed.), *Cyber-Archaeology*, British Archaeological Reports International Series 2177: 1-7.

Master-Hand Attributions of Classical Greek Sculptors by 3D-Analysis at Olympia - Some Preliminary Remarks

A. Patay-Horváth
Eötvös Loránd University,
Archaeological Institute of the Hungarian Academy of Sciences, Budapest

Abstract: The sculptural decoration of the temple of Zeus at Olympia (built ca. 475-455 BC) is generally considered to be one of the most important and most magnificent works of ancient Greek art. The preserved fragments have been thoroughly studied since their discovery in the 1880's, but they still pose some important questions. Perhaps the most difficult and the most distressing problem regards the identity of the master(s) of these works. Despite the high artistic quality and their excellent workmanship, nobody really knows, who the sculptor (or the sculptors) of these pieces actually was (were) and where he (they) came from. A conventional art historical method (master-hand attribution developped by G. Morelli) is therefore combined with the possibilities provided by the most recent 3D technologies in order to investigate the problem. The paper gives an outline of the project and its principles and discusses basic methodological problems connected with it.

Keywords: Shape analysis, Methodology

1 The subject and the problem

The sculptural decoration of the temple of Zeus at Olympia consists of two pediments and twelve metopes. Given the large size of the building itself, the sculptures were all well over life-size and were made of white Parian marble in the first half of the 5th century B.C. A large number of surviving fragments is conserved in the Archaeological Museum of Olympia and in the Musée du Louvre in Paris. Most of them are quite well preserved and are depicted in practically every handbook on Greek art or on ancient art in general, because nowadays they are generally considered to be one of the most important and most magnificent works of ancient Greek art. (Figure 1) They have been thoroughly studied since their discovery in the 1880s, but they still pose some important questions, as indicated by the growing number of monographs and scholarly articles related to them (e.g. Treu 1897; Ashmole-Yalouris 1967; Barringer 2005; Patay-Horváth 2008; Patay-Horváth 2011; Kyrieleis 2013).

Perhaps the most difficult and distressing problem concerns the identity of the master(s) of these works. Despite the high artistic quality and their excellent workmanship, nobody really knows, who the sculptor (or the sculptors) of these pieces actually was (were) and where he (they) came from. In order to answer this question, i.e. to determine the place of origin of the so-called 'Olympia master(s)' a project has been started recently, which tries to combine the possibilities offered by the latest 3D scanning technologies with a traditional art historical method. This 3D-analysis is expected to enable the identification of individual master sculptors and workshops in general and to reveal something about the origins of the 'Olympia-master(s)' in particular. The method developed may easily be applied or adapted to many other similar problems of classical archaeology and history of art in general.

2 Previous research

Classical archaeologists realized very early that the only available ancient literary source (Pausanias' 'Description of Greece', Book 5, Chapter 10, 7) is most likely to be unreliable and have tried since more than a century to identify the 'Olympia master' with a local, an Athenian, a Spartan, North-Peloponnesian, Parian or other sculptor, but practically everybody arrived at different solutions (Herrmann 1987; Dörig 1997; Holloway 2000; Kyrieleis 2006). All the traditional methods have already been tried to solve the problem, but none has proved to yield convincing results (Fig. 2). Even the basic question, whether there was one single master or several different ones, remained controversial.

This is certainly due to the subjectivity of the stylistic judgements and to the relative rarity of original sculpture dating from the given period (the so-called severe style). But on the other hand, archaeologists were almost exclusively relying on photographs when they were looking for stylistic parallels. This method worked well in establishing master-hands in two-dimensional art (in the case of ancient Greek art: vase-painting), but is not sufficient in three-dimensional art, i.e. sculpture, because three-dimensional objects can only partially be displayed by photographs. The images unavoidably conceal some parts of the object and even those, which are shown, are usually distorted. Moreover photographs taken with different equipment, under different lighting conditions and from different viewpoints can hardly be used to compare fine stylistic traits. Simple pieces of sculpture, e.g. archaic Greek standing male and female statues could effectively be studied by this method, but as the complexity of sculpture increases, photographs are no more sufficient. The failure to detect master-hands in the case of classical sculpture is therefore not surprising.

Plaster casts were occasionally also employed in studying ancient sculpture. These have the advantage of representing the real structure of a three-dimensional work of art, but they are quite expensive and therefore no institute or researcher can afford to have all the relevant pieces in this form at his disposal. Though they enable us to compare pieces which are normally stored in different collections, far away from each other, they are not scalable, making comparisons between

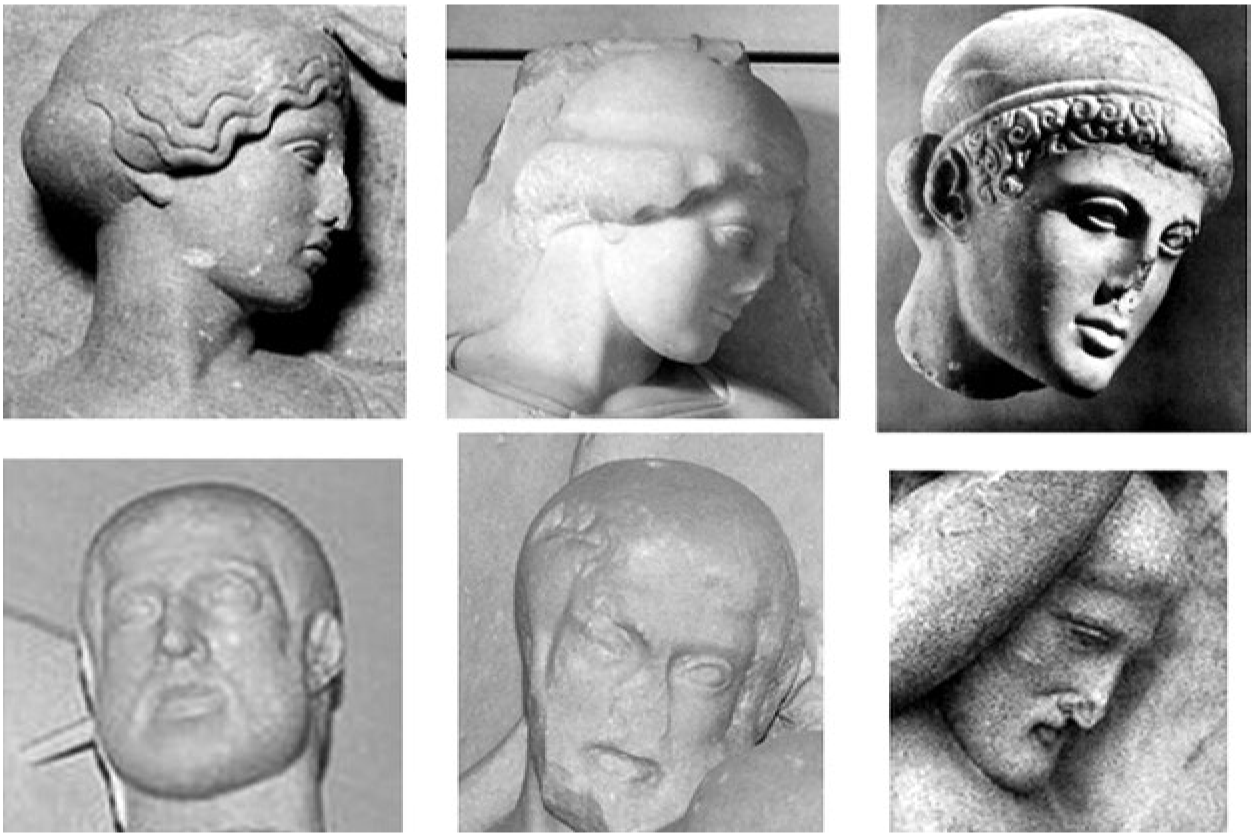

Fig. 1. Heads of Athena (above) and Heracles (below) from the metopes of the temple of Zeus at Olympia.

them for the human eye difficult. Their handling is not easy either, especially if they are of great dimensions, as in the case of the sculptures from the temple of Zeus. Moreover, it is quite difficult to take measurements from them, and therefore it is only natural, that this was normally not practiced so far.

3 Methodology

In order to reach the main objective, namely the identification of the so-called 'Olympia master', I intend to avoid the inherent difficulties of the hitherto used tools (photographs, plaster casts) by analysing 3D models. The aim is not only to solve an old and important question of art history, but at the same time, to elaborate a tool-kit, which can be applied to any other set of sculptural masterpieces and will enable identification of master-hands in general.

3.1 Basic principles

3D models can be used for this purpose basically because they are not concealing or distorting any part of the sculpture as photographs do, and in spite of the plaster casts, it is easy to scale and to manipulate them. So they combine the advantages of the two traditional media and eliminate at the same time the disadvantages of both. In addition, it is e.g. easy to take measurements of any given part of the statues or to create profile drawings from them. Fine details of anatomy and drapery or delicate forms can also be extracted and compared to each other, to detect individual master hands, as it is usually and successfully practiced in the case of two-dimensional art.

3.2 The Morelli method

The method of detecting master-hands in different works of art by observing idiosyncrasies in the rendering of small details has been developed by Giovanni Morelli during the 19th century and is commonly referred to as master-hand attribution (Vakkari 2001). Morelli used it first to distinguish the works of famous renaissance painters, but the method itself was successfully applied to many other periods. Sir J. D. Beazley first used this method to identify Attic black-figure and red-figure vase-painters (Fig. 3), afterwards he applied this method to Etruscan vase-painting too. His attributions are nowadays generally accepted and they revolutionized our understanding of ancient art (Beazley 1947, 1956, 1963, 1971). Many other scholars followed this path and although the names of the Greek vase-painters are irrecoverably lost, one can reconstruct the history and development of Corinthian, Etrusco-Corinthian, Laconian and South-Italian vase-painting by identifying hundreds or thousands of individual oeuvres (Stibbe 1972; Amyx 1988; Trendall 1967, 1982; Szilágyi 1998).

The Morellian method was not unanimously accepted by everybody in the 19th century and its application in ancient art provoked some controversy even recently (Whitley 1997; Oakley 1998). It is true, that the distinctions between closely related workshops or individual masters is not always clear-cut and some attributions are reconsidered from time to time, but actually no one questions the basic principle and no better method has been proposed to tackle the problem. The method seems, according to our present knowledge, to be useful und

Fig. 2. Head of Apollo from the West pediment of the temple of Zeus (left) and the 'Blond boy' from the Acropolis at Athens (right). The obvious and strong similarity gave rise to different hypotheses concerning the origin of the Olympia-master.

Fig. 3. Two heads by the same painter (Kleophrades Painter), identified and named by J. D. Beazley. The similarities in the rendering of anatomical details (lips, nose, eyes, ears) are obvious enough.

trustworthy in general and proved to be applicable in every case, where a sufficiently large number of detailed figural representations are available for analysis.

Since the human eye cannot automatically and reliably extract characteristic features from 3D objects and photographs cannot faithfully reproduce three-dimensional details (Fig. 4), the use of the Morellian attribution method in the analysis of three-dimensional art was rather limited so far. On the other hand, there have already been some attempts to apply the Morelli-method to three-dimensional art, where the necessary prerequisites (sufficiently large number of detailed, well-preserved figural representations) are assured (Langlotz 1927; Frel 1969; Walter-Karydi 1987). Personal impressions and subjectivity (naturally inherent in connoisseurship) played a much greater role in these cases than in the analysis of two-dimensional art and due to the limitations of traditional photographic documentation, it was impossible to demonstrate the attributions as convincingly as in the case of vase-painting. The obvious biological and technological constraints may, however, be overcome by using virtual 3D models produced by 3D scanning.

3.3 A recent attempt for using 3D data

Comparing digital 3D models (or particular parts of them) with each other represents a possibility to detect master-hands in

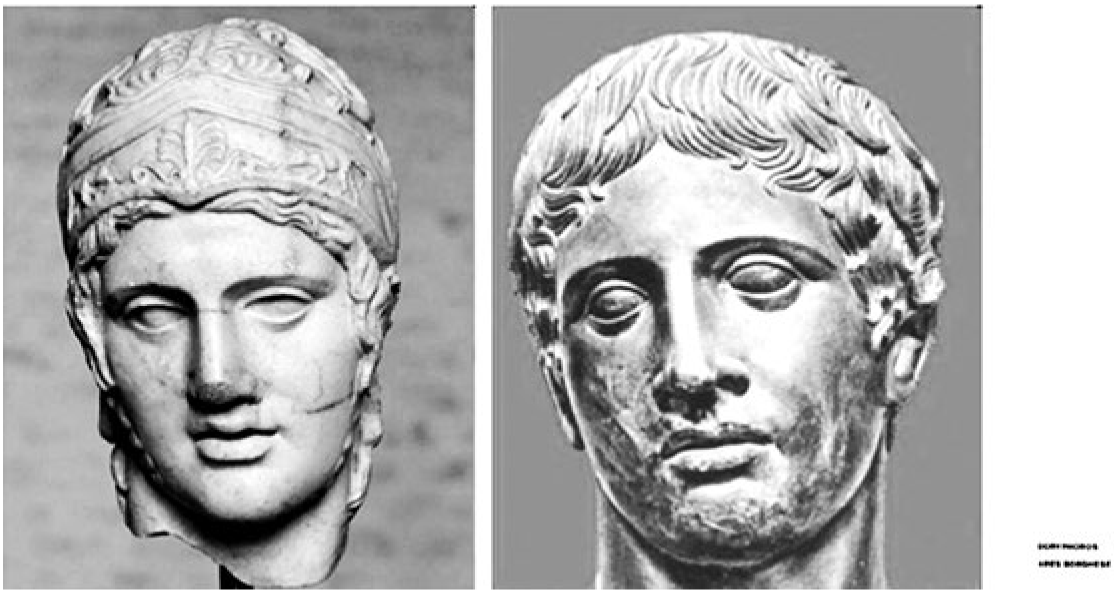

Fig. 4. Two ancient heads (left: 'Ares Borghese'; right: 'Doryphoros') and their profiles compared. The striking similarities of the profiles are not readily discernible for the human eye, neither in the photographs, nor in reality.

ancient sculpture and in some special cases even this simple method may yield significant results, as shown recently by such an investigation into the question of the 'Ephesian amazons'. In this case we have Roman copies of several famous fifth-century pieces, which were attributed by ancient literary tradition (Plinius, *Nat*. *Hist*. 34.53) to three important classical Greek sculptors, Pheidias, Polykleitos and Kresilas and modern scholarship produced an endless debate concerning the correct attribution of the three different Amazon-types to the three famous sculptors (Boardman 1985; Bol 1998; Strocka 2004; Berger 2004). Stylistic arguments were put forward in favour of all possibilities, but objective proof was lacking. The problem and the state of the art were apparently very similar to the question of the 'Olympia-master' and it is therefore remarkable that a recent project making use of the digital 3D models of the statues could significantly contribute to solving this problem.

The 3D models reasonably demonstrated that one of the Amazon types ('Sosikles') has facial characteristics, which are basically identical to those of some famous pieces of sculpture (the 'Doryphoros' and the 'Diadoumenos'), attributed with certainty to Polykleitos (Sengoku *et al*. 2015).

The more or less exact matching of two or more pieces of sculpture is, however, more likely to be the exception rather than the rule. For in the case of the Ephesian amazons, we are dealing with ancient marble copies, which are based on Greek bronze originals and the bronzes themselves were cast with a technology enabling the multiple use of the same model. So provided that the Roman copies reproduce the lost originals faithfully (a reasonable assumption, since the usage of plaster casts is attested for making such copies; cf. Landwehr 1985), it is possible to detect exactly the same three-dimensional features resulting from the same model used by the Greek artist for creating different statues. But if we are studying original marble works of art created during the 5th century BC, which are not directly depending on reusable models, it is unlikely to find exactly the same form more than once. Comparing digital models mechanically to each other will therefore not yield exact matches even if the models are scaled to approximately the same size.

Even if it is evident that not all the preserved copies are equally precise, in the case of ancient copies the multitude of the available pieces is a real advantage, since it is possible to compare several pieces which are more or less identical in their pose and dimensions. With classical originals, on the contrary, several problems arise from the fragmentary state of preservation and the uniqueness of each piece, which makes comparisons between individual figures or features more difficult. The method of comparing must therefore be more flexible and cannot exclusively rely on mechanical and quantitative methods.

3.4 The new approach: the Morelli method in 3D

The basic idea is to start from two commonly accepted and fully justified assumptions of the Morelli method:

1. That unconscious idiosyncrasies in the rendering of frequently occurring anatomical and other details do exist.

2. That the trained human eye is capable of detecting these traits in 2D, i.e. one can distinguish the individual characteristics of different artistic personalities.

Assuming in addition on the basis of the available evidence (cf. Fig. 4 and 5) that similar idiosyncrasies exist not only in two-dimensional but also in three-dimensional art, even if they cannot always be identified by ordinary human observers, one can conclude that the detection of master-hands in three-dimensional art simply requires the extraction of reliable and thus (in contrast e.g. with normal photographs) really comparable 2D images from the existing 3D data.

This task is perfectly feasible on the present technological level, and in this way, i.e. by comparing 2D images (either by

Fig. 5. Head of the Amazon Sosikles (left) and 3D comparison of the face with that of the Doryphoros (right). The similarity strongly suggests that the same model was used for both the male and the female head.

trained human observers or by some special software) it will be possible to detect the idiosyncrasies in any pieces of sculpture made by the same individual.

This inherent possibility of the 3D models has practically not been realized yet. The usage of 3D scanning in recording and visualization of three-dimensional works of art is becoming widespread, but the resulting models were (apart from the recent attempt described above) not used for analytical purposes in the study of the history of art. In the case of paintings, however, there are already some promising projects and applications, showing the feasibility of this idea. The fine geometry of paint layers can be captured and used as a digital fingerprint to identify the painter or to detect forgeries. (Breuckmann 2011) Observations of technical characteristics are used in the case of ancient jewellery to identify master-hands or workshops as well (Dági 2006).

The 3D analysis proposed here will not, however, concentrate on such technological features, which might equally be detected without 3D models, but on the stylistic idiosyncrasies (proportions, special renderings of individual anatomical or other features), which will become recognizable through the systematic extraction of certain 2D patterns.

4 Implementation

The high precision of the latest scanning equipment will be used for taking exact measurements on different pieces of sculpture in such quantity, that they might be evaluated statistically and can perhaps provide evidence for detecting special features, which are characteristic of a single master or workshop.

Most importantly, different profile drawings or slices will be produced from the comparable parts of the figures (in most cases the heads) and these 2D images will be compared like vase-paintings to each other by human observers or by some software packages (in order to express the degrees of similarity in an exact way). Profile drawings were only made sporadically so far (mainly for practical reasons), but can easily be produced from 3D models and as Figure 4 clearly shows, they are likely to reveal many details, which would be hard to detect otherwise.

This methodology will be tested and elaborated first on contemporary pieces of sculpture, where the sculptor is known with absolute certainty and then applied to ancient works of art in three consecutive stages.

4.1 Delphi

The well-preserved frieze of the Siphnian treasury at Delphi (dating c. 530-525 BC.) will be scanned and analysed, because in this case there is a sculptor's signature preserved on the frieze (Fig. 6), stating that some parts or figures were made by the same artist (Viviers 2002). This would provide a second test, because it can be reasonably assumed, that the pieces were produced (or at least designed) by the same individual. As the frieze is quite well-preserved, there are many possibilities for making comparisons concerning proportions, special features in anatomy and other details. Most probably they will turn out to be decisive in identifying the master (just like in vase-painting, where this is already established and commonly accepted).

4.2 Olympia

During the past seven years, I have investigated the problem of the arrangement of the central figures of the east pediment of the temple of Zeus and produced virtual 3D models by scanning the fragments and finally a digital reconstruction of the statue group as well (Patay-Horváth 2011). These models will be complemented by scanning the remaining pieces belonging to the sculptural decoration of the temple in Olympia and in the Louvre as well.

Using the results achieved by the analysis of the Siphnian frieze in Delphi, the first step in the analysis of the sculptures from Olympia is to determine, whether the statues and metopes were

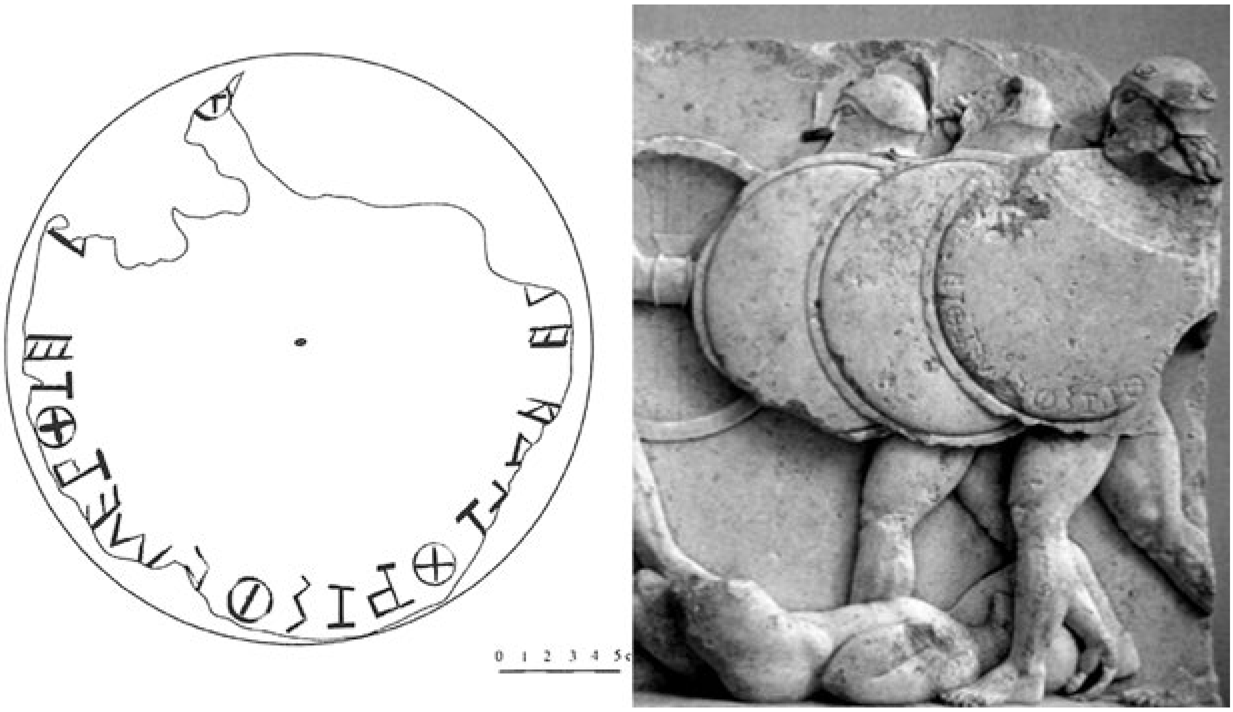

Fig. 6. Artist's signature inscribed on the rim of a shield from the north side of the frieze of the Siphnian treasury at Delphi: '... and on the rear, was made by xxx'. (The artist's name is missing or was deliberately deleted.)

made or designed by a single man/workshop or by two or more different ones. As already mentioned, there is no scholarly consensus not even on this basic question.

4.3 Severe style

The last step involves the scanning and analysis of nearly contemporary Greek sculptures (from large size marble works to small-scale terracotta and bronze figurines) with known proveniences. The analysis of their stylistic details and the comparison of these results with those obtained at the sculptures of the temple of Zeus could point to the localisation of the 'Olympia master' sculptor.

5 Conclusion

Pausanias, a Greek traveler during the 2nd century AD has described the temple of Zeus at Olympia in detail and recorded the opinion of his local guides concerning the master sculptors of the pediments as follows:

'The sculptures in the front pediment are by Paeonius, who came from Mende in Thrace; those in the back pediment are by Alcamenes, a contemporary of Pheidias, ranking next after him for skill as a sculptor.' ('Description of Greece', Book 5, Chapter 10, 7; English Translation by W.H.S. Jones, Cambridge (MA), 1918).

These ancient attributions are usually and most plausibly considered as erroneous (Moustaka 2004), but modern scholarship was equally unable to suggest better ones. Even if the names of the sculptors will most probably remain unknown, the methodology outlined above will at least enable us to determine their places of origin. In addition, the method can be applied afterwards to other similar problems and will contribute to our understanding of sculpture in general.

Acknowledgements

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Bibliography

Amyx, D. A. 1988. *Corinthian vase-painting of the archaic period* I-III. Berkeley, University of California Press.

Ashmole, B., Yalouris, N. 1967. *Olympia. The Sculptures of the Temple of Zeus*. London, Phaidon.

Barringer, J. M. 2005. The Temple of Zeus at Olympia, Heroes and Athletes. *Hesperia* 74: 211-41.

Beazley, J. D. 1947. *Etruscan vase-painting.* Oxford, Oxford University Press.

Beazley, J. D. 1956. *Attic black-figure vase-painters.* Oxford, Oxford University Press.

Beazley, J. D. 1963. *Attic red-figure vase-painters*. Oxford, Oxford University Press.

Beazley, J. D. 1971. *Paralipomena*. Oxford, Oxford University Press.

Berger, E. 2004. Polykleitos I. In Vollkommer, R. (ed.), *Künstlerlexikon der Antike*: 712-23. München-Leipzig, Nikol.

Boardman, J. 1985. *Greek Sculpture. The Classical Period.* London, Thames and Hudson.

Fig. 7. Statue of Nike, signed by Paeonius in Olympia (left) and figure K of the east pediment of the temple of Zeus (right).

Bol, R. 1998. *Amazones volneratae*. Mainz, Philipp von Zabern.

Breuckmann, B. 2011. 3-Dimensional Digital Fingerprint of Paintings. *Proceedings of the 19th European Signal Processing Conference* (EUSIPCO 2011): 1249-53. http://www.eurasip.org/Proceedings/Eusipco/Eusipco2011/papers/1569422705.pdf [Accessed: 3 june 2014]

Dági, M. 2006. Training the Eye: Technical Details as Clues in the Attribution of Ancient Jewellery. *Bulletin du Musée Hongrois des Beaux-Arts* 105: 41-72.

Dörig, J. 1997. *The Olympia Master and His Collaborators*. Leiden, Brill.

Frel, J. 1969. *Les sculptures attiques anonymes, 430 – 300*. Praha, University Karlova.

Herrmann, H.-V. (ed.) 1987. *Die Olympia Skulpturen.* Darmstadt, Wissenschaftliche Buchgesellschaft.

Holloway, R. R. 2000. The Master of Olympia: the Documentary Evidence. http://www.brown.edu/Departments/Joukowsky_Institute/publications/papers/olympia/olympia.html [Accessed: 29 may 2014]

Kyrieleis, H. 2006. Paros und Olympia. Zu den Skulpturen des Zeustempels in Olympia. Γενεθλιον. *Αναμνηστικός* τόμος για την συμπλήρωση είκοσι χρόνων λειτουργίας του *Μουσείου* κυκλαδικής τέχνης: 183-201. Athens, Goulandris Museum of Cycladic Art.

Kyrieleis, H. (2013) Pelops, Herakles, Theseus. Zur Interpretation der Skulpturen des Zeustempels von Olympia. *Jahrbuch des Deutschen Archäologischen Instituts* 127/128: 51-124.

Langlotz, E. 1927. *Frühgriechische Bildhauerschulen*. Nürnberg, Weidmann.

Landwehr, C. 1985. *Die antiken Gipsabgüsse aus Baiae*. Berlin, Gebr. Mann.

Moustaka, A. 2004. Paionios II, In Vollkommer, R. (ed.), *Künstlerlexikon der Antike*: 611-2. München-Leipzig, Nikol.

Oakley, J. H. 1998. Why study a Greek vase-painter? A response to Whitley's 'Beazley as theorist'. *Antiquity* 72: 209-13.

Patay-Horváth, A. 2008. Zur Rekonstruktion und Interpretation des Ostgiebels des Zeustempels von Olympia. *Mitteilungen des Deutschen Archäologischen Instituts, Athenische Abteilung* 122: 161-206.

Patay-Horváth, A. 2011. *Virtual 3D Reconstruction of the East Pediment of the Temple of Zeus at Olympia*. Budapest, ELTE / MTA.

Sengoku-Haga K. *et al*. 2015. Polykleitos' Works 'From One Model': New Evidence Obtained From the 3D Digital Form Comparisons, In Patay-Horváth, A. (ed.), *New*

Approaches to the Temple of Zeus at Olympia: 201-222. Newcastle, Cambridge Scholars.
Stibbe, C. M. 1972. *Lakonische Vasenmaler des sechsten Jahrhunderts v.Chr.* Amsterdam, North-Holland Publishing.
Strocka, V. M. 2004. Pheidias, In: Vollkommer, R. (ed.) *Künstlerlexikon der Antike*: 646-72. München-Leipzig, Nikol.
Szilágyi, J. GY. 1998. *Ceramica etrusco-corinzia figurata* 1-II. Firenze, Olschi.
Trendall, A. D. 1967. *The red-figured vases of Lucania, Campania and Sicily*. Oxford, Oxford University Press.
Trendall, A. D. 1982. *The red-figured vases of Apulia I-II*. Oxford, Oxford University Press.
Treu, G. 1897. *Olympia III. Bildwerke aus Stein und Thon*. Berlin, Ascher.
Vakkari, J. 2001. Giovanni Morelli's 'Scientific' Method of Attribution and its Reinterpretations from the 1960's until the 1990's. *Konsthistorisk Tidskrift* 70/ 1-2: 46-54.
Viviers, D. 2002. Le bouclier signé du trésor de Siphnos à Delphes. 'Régions stylistiques' et ateliers itinérants, ou la sculpture archaïque face aux lois du marché. In *Identités et cultures dans le monde méditerranéen antique. Études réunies par Christel Müller et Francis Prost en l'honneur de Francis Croissant*: 53-85. Paris, Sorbonne.
Walter-Karydi, E. 1987. *Die* Äginetische *Bildhauerschule. Werke und schriftliche Quellen*. Mainz, Philipp von Zabern.
Whitley, J. 1997. Beazley as theorist. *Antiquity* 71: 40-7.

Using 3D Models to Analyse Stratigraphic and Sedimentological Contexts in Archaeo-Palaeo-Anthropological Pleistocene Sites (Gran Dolina Site, Sierra De Atapuerca)

I. Campaña(1)

A. Benito-Calvo(1)

A. Pérez-González(1)

A. I. Ortega(1)

J.M. Bermúdez de Castro(1)

E. Carbonell(2,3)

[1] Centro Nacional de Investigación sobre la Evolución Humana (CENIEH), Burgos, España.
[2] IPHES, Institut Català de Paleoecología Humana i Evolució Social, Tarragona. España.
[3] Universitat Rovira i Virgili (URV), Campus Catalunya, Tarragona, España.

Abstract: Gran Dolina is a cavity that belongs to the second level of the Sierra de Atapuerca multi-level karst system and shows an Early and Middle Pleistocene sedimentary infilling 25 m thick, divided in eleven lithostratigraphic units. High densities of remains have been found in Gran Dolina, including hominid bones, fauna and lithic tools.

The use of 3D models in stratigraphy and sedimentology is a new topic that allows new analysis and studies, increasing the knowledge of archaeological sites. In Gran Dolina site, the application of 3D laser scanning and photogrammetry techniques have allowed performing 3D models, including RGB textures. The models were georeferenced to the excavation local coordinate system. From these 3D models, we identified and mapped the continuity and geometry of the sedimentary levels, reconstructing the site's original stratigraphy. The 3D geometry of the levels was used to measure the clasts' textures and the post-depositional dips of the layers. The latter helped us to infer input strikes as well as their variations in each level, and to recognize ancient sedimentary entrances.

Keywords: Laser scanner, Photogrammetry, Stratigraphic geometries, Gran Dolina site, Atapuerca, Early and Middle Pleistocene.

Introduction

Gran Dolina is a key site to understand Early and Middle Pleistocene human evolution in Europe (Rodríguez *et al*. 2011). The archaeo-paleontological remains of Gran Dolina have provided many works about Early and Middle Pleistocene that have enriched the knowledge about human linage in Europe (Bermúdez de Castro *et al*. 2012; Bermúdez de Castro *et al*. 2015; Carbonell *et al*. 1999; Rodríguez-Gómez *et al*. 2013). Gran Dolina is a cavity belonging to the intermediate level of the Sierra de Atapuerca multi-level karst system (Ortega *et al*. 2013), which shows an Early and Middle Pleistocene 25 m thick sedimentary infilling, divided in eleven lithostratigraphic units and nineteen sedimentary facies (Pérez-González *et al*. 2001; Campaña *et al*. 2015). Although most of these units are archaeologically fertile and have provided a huge number of fossils and stone tools, TD6 and TD10 units are renowned for its richness and importance. A new hominid was defined, *Homo antecessor* (Carbonell *et al*. 1995; Bermúdez de Castro *et al*. 1997), with the remains found in TD6, while TD10 has provided two high density layers of archaeological and palaeontological remains (Ollé *et al*. 2013), related to the presence of *Homo heidelbergensis*.

The Sierra de Atapuerca is situated in Burgos (Spain), at the north of the Iberian Peninsula. It consists of a carbonated Mesozoic inlier represented by a gentle anticlinal ridge (Fig. 1, Benito-Calvo and Pérez-González 2015), that belongs to the most north-western outcrop of the Iberian Chain. It is situated in the NE Neogene Duero Basin. Here, a multi-level endokarst system is formed, composed by three sub-horizontal levels and 4.7 km of explored passages (Martín-Merino *et al*. 1981; Ortega *et al*. 2013). The opening of the caves to the outside during the Early Pleistocene due to regional fluvial incision and slope retreatment (Benito-Calvo *et al*. 2015), resulted in allochthonous sediment inputs and the accumulation of archaeo-paleoanthropological remains. Finally, a railway trench built during 19th century cut the intermediate level and exposed several karstic infills such as the ones related to Gran Dolina, Galeria Complex and Sima del Elefante sites.

The use of 3D models in stratigraphy and sedimentology is a new topic that allows new analysis and studies, increasing the knowledge of archaeological sites (Westoby *et al.* 2012; Pavelka *et al.* 2014; Neubauer 2007). In this work we analyse the geometry and texture of the stratigraphic layers using 3D models and orthophotos acquired by photogrammetry.

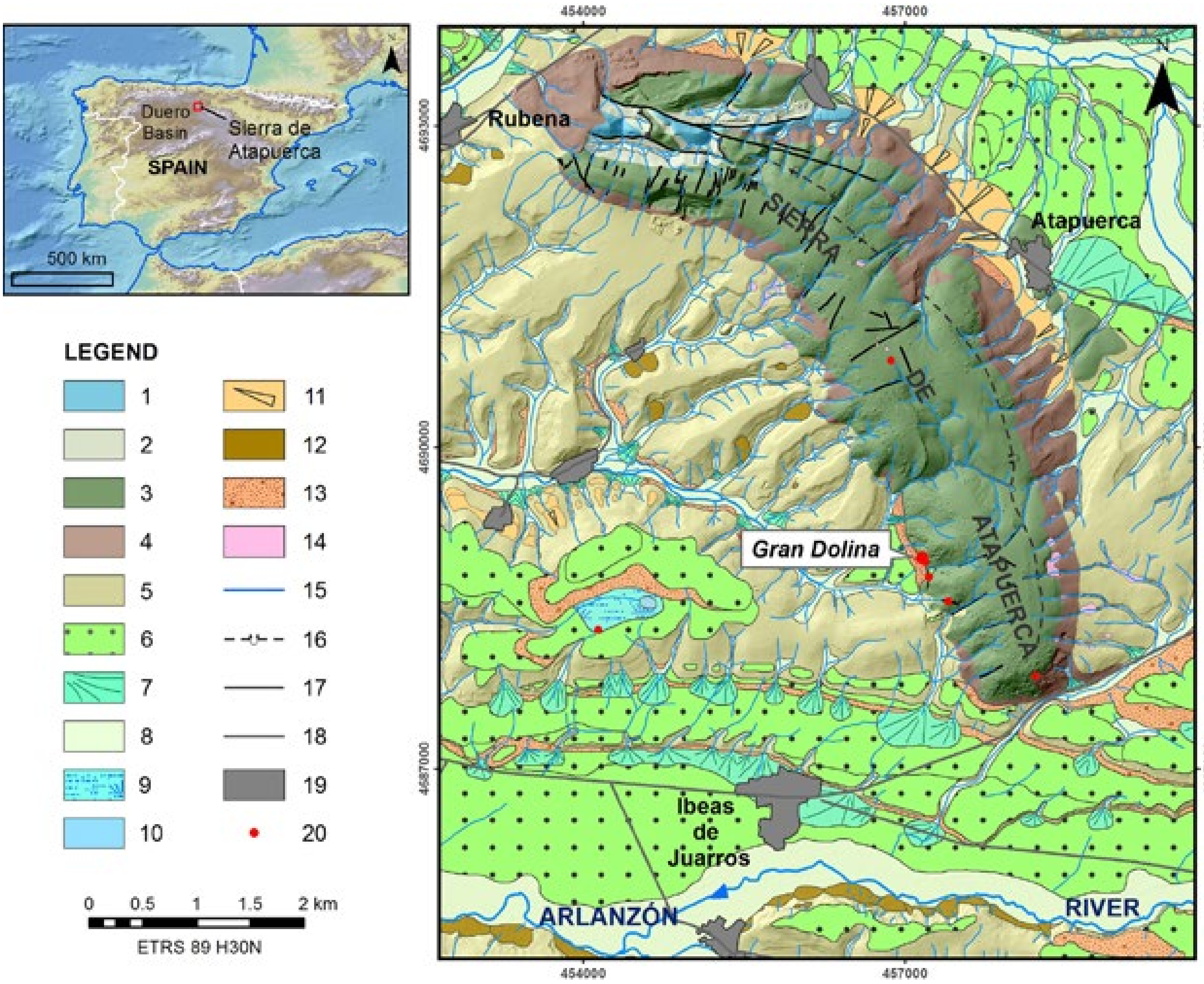

Fig. 1. General location and geological map of the Sierra de Atapuerca (simplified from Benito-Calvo and Pérez-González 2015). Legend: 1, Jurassic; 2, Early Cretaceous; 3, Late Cretaceous; 4, Oligocene; 5, Miocene; 6, Fluvial terraces; 7, Cones; 8, Floodplains and valley floors; 9, Semi-endorheic areas; 10, Seasonal pools; 11, Glacis; 12, Landslides; 13, Colluvium; 14, Dolina floors; 15, Drainage network; 16, Inferred overturned anticline; 17, Faults; 18, Roads, 19, Populations; 20, Archaeological sites.

1 Methodology

3D models of Gran Dolina site were performed using photogrammetry and laser scanner technologies. The three excavation surfaces (TD1, TD4 and TD10) were photographed with a Nikon D3X camera at different distances and angles. Then, the images were selected to avoid recurrent data and wrong images, and they were processed by Agisoft Photoscan 1.0.4 software. 3D models were improved and georeferenced using control points extracted from scanner cloud points.

We used two different laser scanners, Leica Scanstation C10 and Faro Focus X330, in the three surfaces. Leica Scanstation C10 is a time-of-flight laser scanner which point clouds are processed by the Cyclone 7.4 software. Faro Focus X330 is phase-shift scanner that uses Scene 5.4.2 software in its post-process. For both laser scanners, cloud points were acquired from different places in each surface and middle resolution configuration (~1 cm at 10 m) was used. Later, cloud points were cleaned and registered. The archaeological local coordinate system was introduced by targets.

Stratigraphic sections and measurements were carried out in ArcGIS 10.2, using orthophotos previously processed in Agisoft Photoscan. Sedimentary facies have been defined in previous work (Campaña *et al*. 2015).

2 Results and discussion

The use of laser scanners and photogrammetry technologies allowed us to perform measurements and analyses that would other way be very difficult or tedious achieve (Larsson *et al.* 2015; Bennett *et al.* 2013). Post-depositional dips, strikes, and clast textures were measured in the 3D models and orthophotos in order to estimate sedimentary input strikes.

2.1 3D models

Three 3D models were performed using photogrammetric techniques (Fig. 2, 3 and 4).

The use of laser scanners has allowed comparing the accuracy of the models. TD1 and TD4 photogrammetric models have an

Fig. 2. TD1 model by photogrammetry. 41 images used.

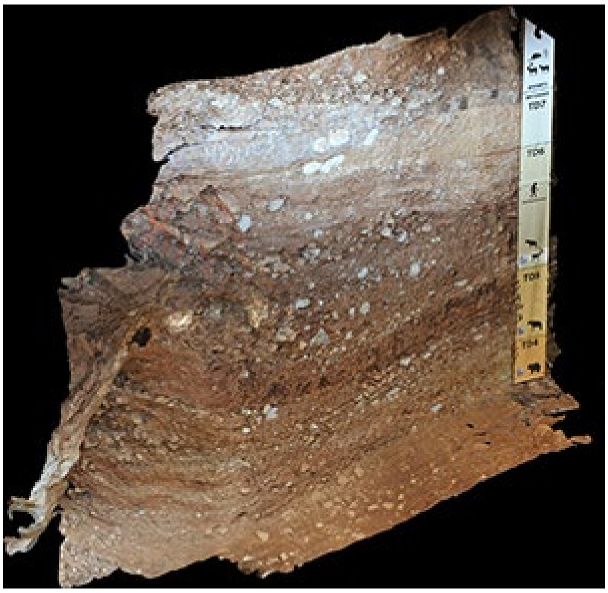

Fig. 3. TD7-TD4 model by photogrammetry. 44 images used.

excellent fit, but TD10 model shows some difficulties. First, the boundary of the model shows an imprecise definition. Second, photogrammetry in the excavation area does not provide a realistic RGB texture. The first task could be corrected including more photos of the boundaries. The second difficulty was due to the irregular surface of TD10 in the excavation area, which is not present in the vertical sections of TD10 model. Anyway, the sections of TD10 are accurate and allow measurements.

2.2 Orthophotos

The stratigraphy and sedimentology of the Gran Dolina site were done using field observations and orthophotos. The dips of

Fig. 4. TD10 model by photogrammetry. 39 images used.

the units were calculated using the orthophotos in GIS software (Fig. 5, 6 and 7). For more details about the stratigraphy and sedimentary facies we refer to Campaña *et al*. 2015.

The dips of the layers in TD10 are similar in the east and the south section, indicating that the sediment input strike is towards the corner (see below). Post-depositional deformation is not found.

The TD7 to TD4 section shows a change of sin-depositional dip beside others post-depositional dips. TD5 and the lower layers of TD6 have a dip of 10°N. These layers are mainly grain-supported gravels with clayed silts and matrix-supported boulders. Gravels with lateral silts are interpreted as channel flow and floodplain facies (Campaña *et al*. 2015), which had surely a horizontal deposition. Therefore the actual dip of 10°N of this facies could be explained by post-depositional accommodation of the sediments. The TD5 deformation occurs in the north of the section and migrates progressively towards the south in TD6 layers.

TD6.2 and TD7 have other post-depositional dips (Fig. 6) and their origin is surely different to the previous layers. The south section is composed by mud and silt layers. These layers are more compacted than the ones with more limestone clasts. Their compaction could have caused the post-depositional deformation of TD6.2 and TD7.

TD1 sediments are fluvial laminated sands and silts, which are tilted and deformed toward the center of the cavity. Considering these characteristics and a putative horizontal deposition of these facies, the current tilting observed in these layers, could be explained as post-depositional processes. The dips decrease in the upper layers, which suggests sin-depositional deformation caused by the accommodation of the sediments and the silting. Moreover, the dips increase towards the west, where the centre of cavity is found, indicates more accommodation or elimination of the sediment towards the centre of the cavity and post-depositional folds.

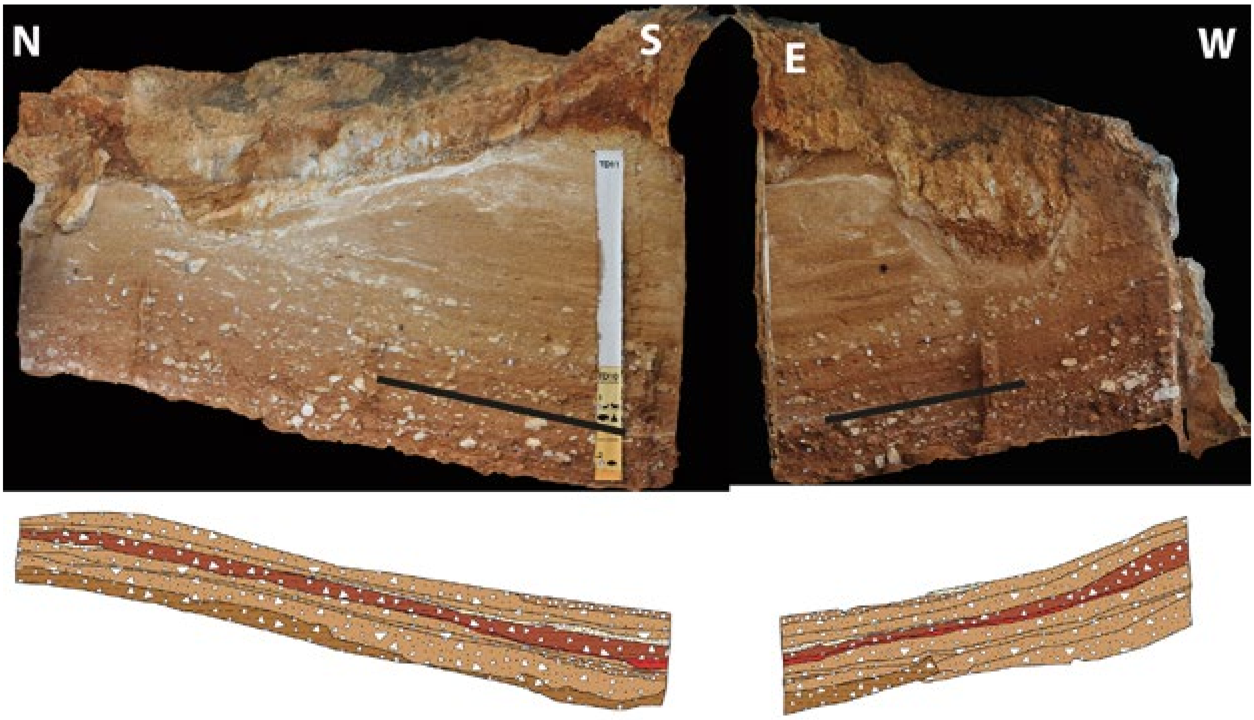

Fig. 5. East and south section of TD10. East section dip: 11° S. South section dip: 11° E.

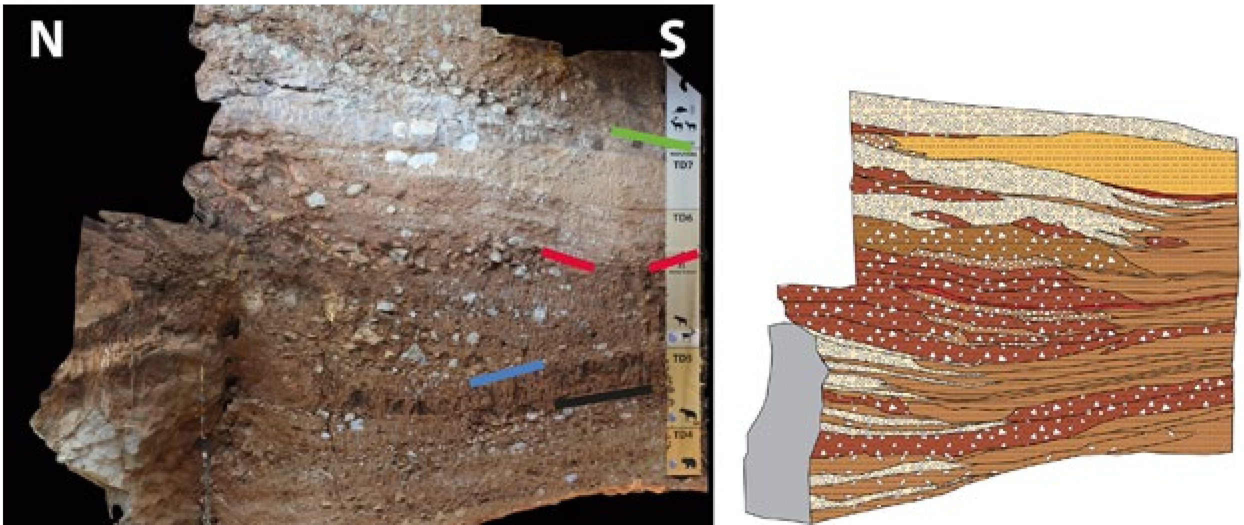

Fig. 6. TD7 to TD4 section. Silty layers have post-depositional deformation. TD7 dip: 11° S. TD6.2 dip: 15°. N-S TD6 base dip: 10°. N TD5 dip: 10° N.

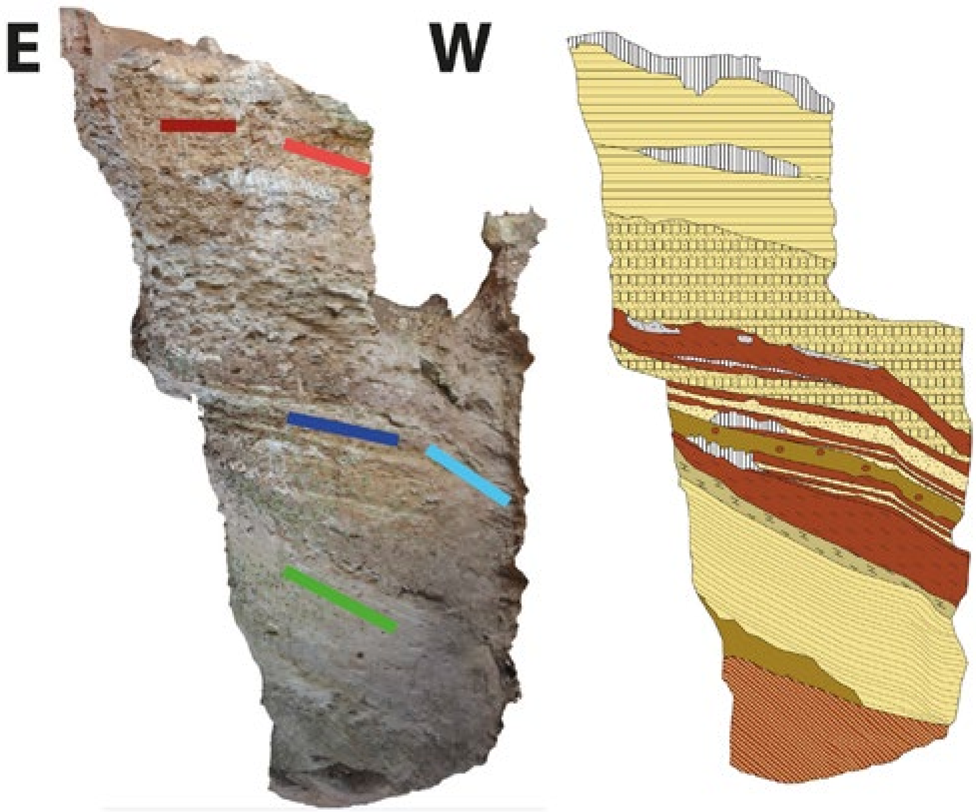

Fig. 7. TD1 section. Lower layers have a dip of 30° W. Middle layers have a dip of 12° W, and to the west increased to 33° W. Upper layers have a dip of 0°, and to the west increased to 15° W.

2.3 Clast texture

Campaña *et al*. (2015) defined six debris flow sedimentary facies in Gran Dolina site, where the clast percentage for each facies is estimated by field observations. The combined use of orthophotos and GIS software has allowed us to quantify the clast percentage of the sections (Table 1). In this work, the clast percentage of the four debris flow sedimentary facies (B, C, D and F) was calculated (Fig. 8, 9 and 10).

Tab. 1. Clast percentage for each debris flow facies analysed.

	%Clast
Debris flow Facies B	10-20
Debris flow Facies C	35-45
Debris flow Facies D	20-30
Debris flow Facies F	10-30

The results support the debris flow facies classification showing similar values to the field observation (Table 1) (Campaña *et al*. 2015). Variations in the clasts percentage could be due to changes in the sediment source, energy flow or cave entrance. High percentage of clasts, as debris flow facies C, suggests a high energy flow that dragged all the available sediments through a large entry. Low percentage of clasts, as debris flow facies B, indicates more fine sediment in the source, lower energy flow and therefore, there was no need of a large entry.

2.4 Sediment input strike

Sediment input strikes were mathematically calculated using the apparent dips and the strikes of both TD10 sections (Tab. 2). The dips were measured in the orthophotos using the layer geometries observed in the two sections. The resulted sediment input strikes have been projected in the 3D model.

Tab. 2. Strikes and dips calculated using TD10 sections.

Layer	Strike	Dip (E)
TD10-TD11	N45°E	12°
TD10.1.2	N39°E	15°
TD10.1.3	N39°E	14°
TD10.1.4	N40°E	15°
TD10.1.6	N38°E	16°
TD10.1 'Manta 1'	N33°E	15°
TD10.2.2	N35°E	18°
TD10.2.5	N45°E	20°

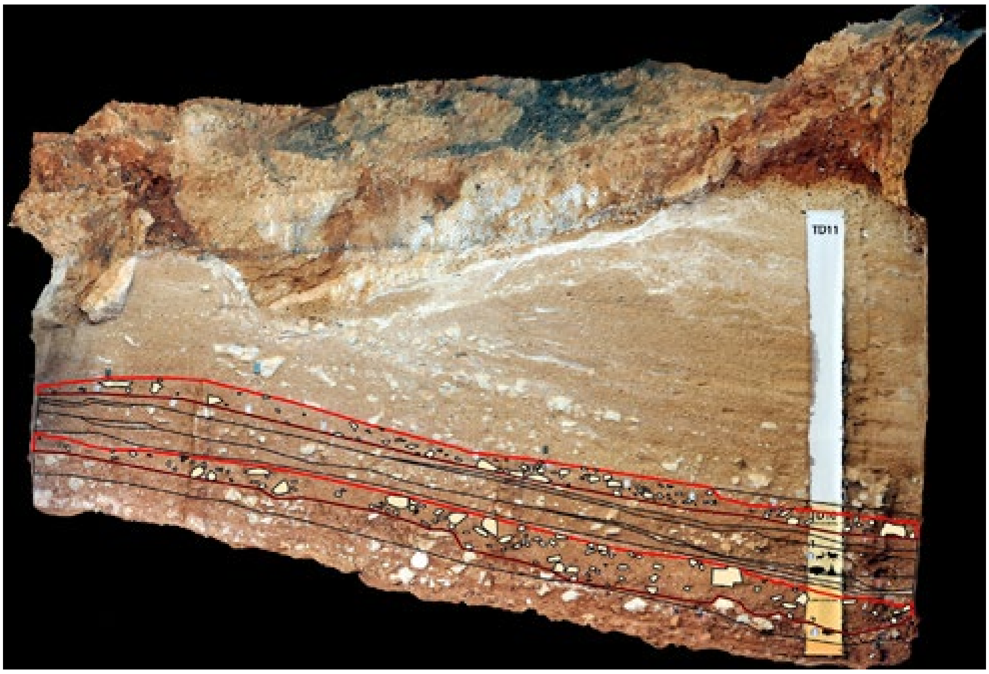

Fig. 8. NE section of TD10 with the stratigraphic limits. Red lines indicate the layers where clast texture was measured. The identified clasts are marked.

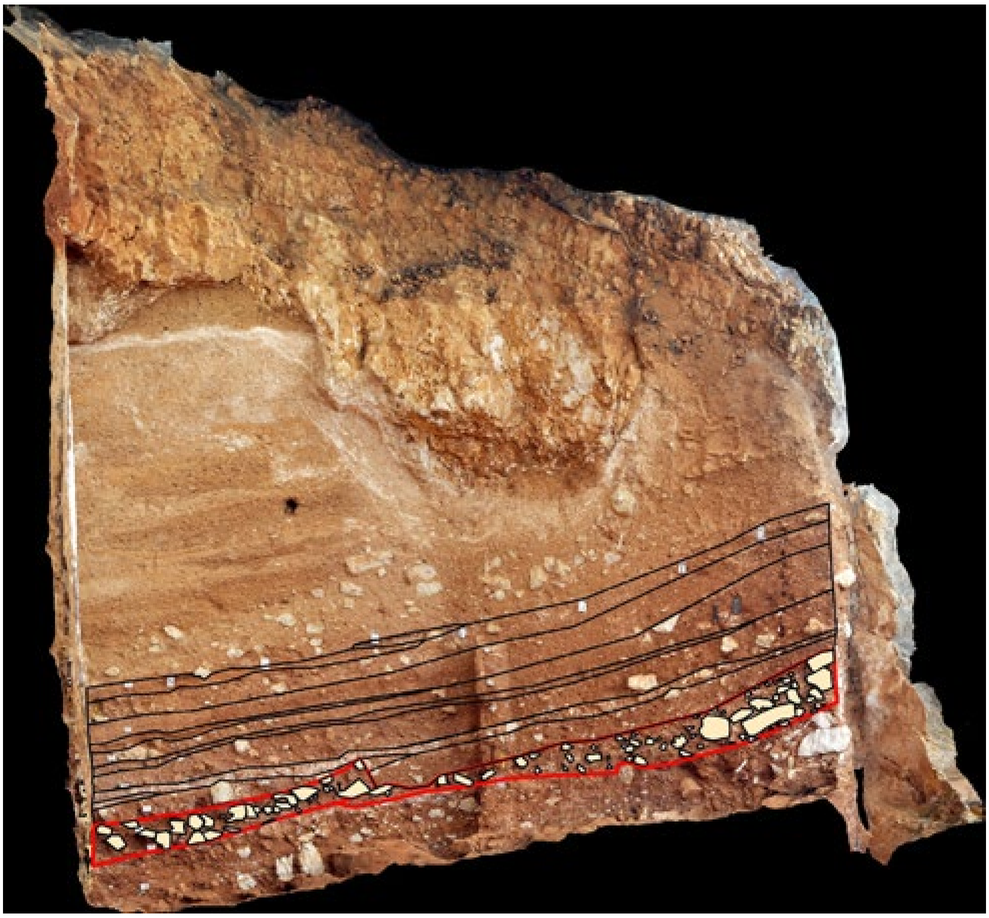

Fig. 9. SE section of TD10 with the stratigraphic limits. Red lines indicate the layers where clast texture was measured. The identified clasts are marked.

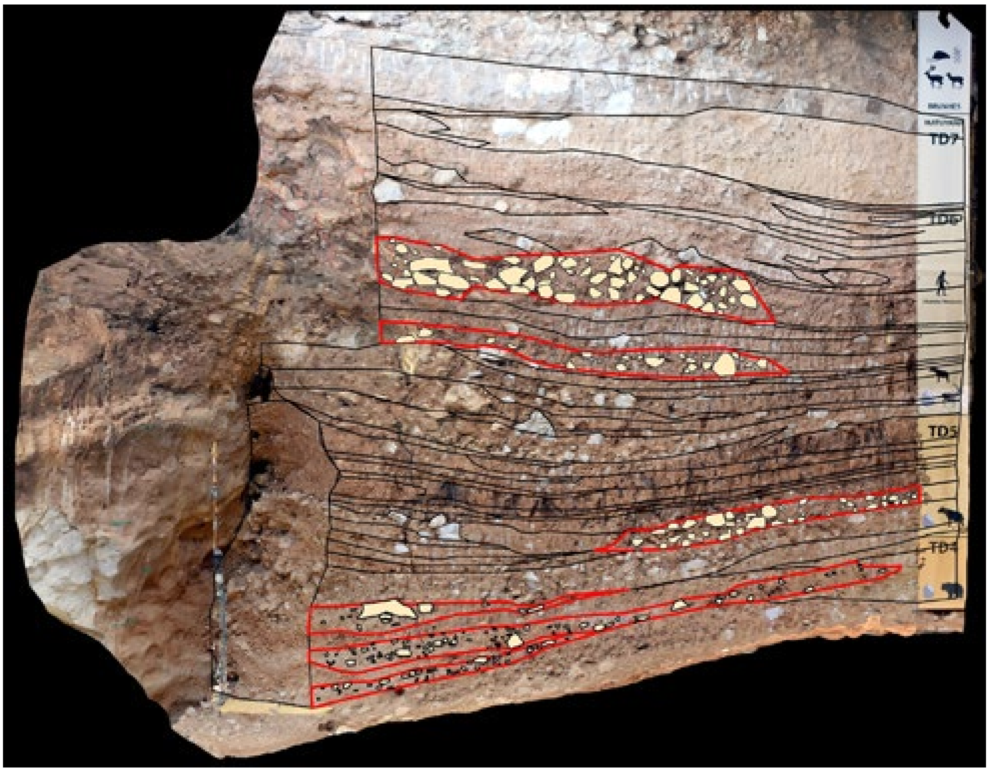

Fig. 10. TD7-TD4 section with the stratigraphic limits. Red lines indicate the layers where clast texture was measured. The identified clasts are marked.

The strike ranges from 33° to 45° with respect to the Y axis, while the dip values are situated between 12-20° towards the East. Not trend is observed in the strike (Fig. 11), providing a range between N45°E and N33°E which indicates the entry of the sedimentary inputs. Small variations may have been caused by the accommodation to the local paleo-relief. Besides, the debris flow clast percentage previously calculated suggests a large entry, which would have enabled the access and settlement of hominids in the cave (Ollé *et al*. 2013).

TD10 dips show differences, varying from 20º from TD10.2, to 15° for TD10.1. A decrease of the dip towards the upper layers is observed (Fig. 11). This can be related with the progressive filling of the cave and its main entry, which could explain the progressive decrease of the use of the cavity by the Middle Pleistocene hominins (Ollé *et al*. 2013). During the human occupation, the palaeo-relief was a gentle slope towards the east, with an irregular surface of disorganized clasts.

3 Conclusions

The application of 3D laser scanning and photogrammetry techniques have allowed us to carry out 3D models, including RGB textures. From these 3D models, we have identified and mapped the continuity and geometry of the sedimentary levels, reconstructing the stratigraphy of Gran Dolina.

Particle size analysis of large clasts cannot be analysed by laboratory methods, because a large size and the amount of sample would be needed. Orthophotos and GIS software allow an approximation to quantify clast percentage in the sedimentary units. The clast percentage supports the classification of sedimentary facies proposed in Campaña *et al.* (2015) and allow inferring the energy flow and entrance.

TD1 has a sin-depositional deformation and at least two post-depositional deformations. The sin-depositional deformation is indicated by the progressive decrease of the deformation dip towards the upper layers and is related to accommodation and filling. Post-depositional deformations are represented by two different dips in the middle layers. These deformations could be due to a loss of sediment volume in the centre of the conduct of Gran Dolina, either by accommodation or elimination of the sediments.

In TD7 to TD4 section, the dips indicated that two main post-depositional deformation processes have happened. First, processes affected TD5 and the base of TD6, inclining 10 grades the layers. Second, processes affected TD6.2, TD6.1 and TD7. Both folds could be explained by the accommodation of the finer deposits (silt and clay layers) and the first deformation is surely produced before the TD6.3.1 inputs. This could indicate a stable period without sediments inputs. The increase of clasts percentage in this section (facies B, D and C) suggests that an increase of the energy flow and size of the entry occurred during the final of Early Pleistocene. This enlargement of the entry could make the human presence in TD6.2 and TD6.1 possible.

TD10 sediment input strikes have been obtained using 3D stratigraphic boundaries of both sections. The strikes are very similar between them, indicating that the main entrance was

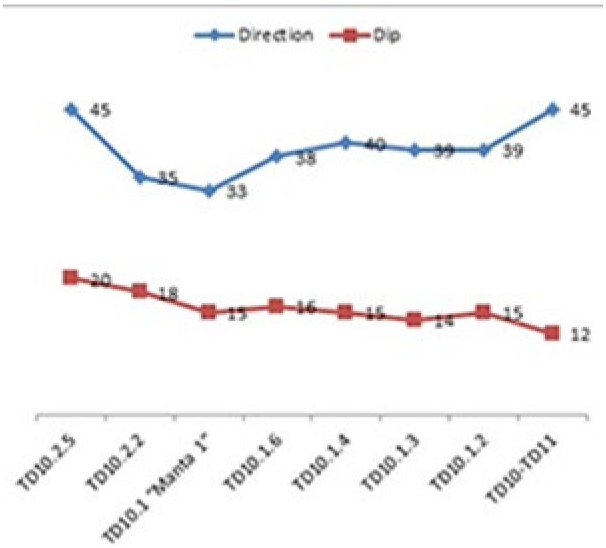

Fig. 11. Dips and directions of the sediment inputs of TD10 layers.

the same during this period. The little variations could be due to the accommodation of the sediment input to the paleo-relief. The dips show a decrease from TD10.2 to the boundary of TD10-TD11 (Fig. 11, Tab. 2) that was caused by the silting up of the west entrance. This progressive narrowing of the entrance could be related to the decrease of human presence in Gran Dolina.

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Bibliography

Bennett, M. R., P. Falkingham, S. A. Morse, K. Bates, Crompton. R.H. 2013. Preserving the Impossible: Conservation of Soft-Sediment Hominin Footprint Sites and Strategies for Three-Dimensional Digital Data Capture. PLoS (Public Library of Science) ONE 8, 4: e60755.

Bermúdez de Castro, J. M., Arsuaga, J. L., Carbonell, E., Rosas, A., Martínez, I., Mosquera, M. 1997. A Hominid from the Lower Pleistocene of Atapuerca, Spain: Possible Ancestor to Neandertals and Modern Humans. *Science* 276 (5317): 1392–5.

Bermúdez de Castro, J. M., Carretero, J. M., García-González, R., Rodríguez-García, L., Martinón-Torres, M., Rosell, J., Blasco, R., Martín-Francés, L., Modesto, M., Carbonell, E. 2012. Early Pleistocene Human Humeri from the Gran Dolina-TD6 Site (sierra de Atapuerca, Spain). *American Journal of Physical Anthropology* 147 (4): 604-17.

Bermúdez de Castro, J. M., Martinón-Torres, M., Martín-Francés, L., Modesto-Mata, M. Martínez-de-Pinillos, M., García, C., Carbonell, E. 2015. Homo Antecessor: The State of the Art Eighteen Years Later.' *Quaternary International* 0. doi:10.1016/j.quaint.2015.03.049.

Benito-Calvo, A., Pérez-González, A., 2015. Geomorphology of the Sierra de Atapuerca and the Middle Arlanzón Valley (Burgos, Spain). *Journal of Maps* 11: 535–44. doi:10.1080/17445647.2014.909339.

Benito-Calvo, A., Ortega, A.I., Pérez-González, A., Campaña, I., Bermúdez De Castro, J.M., Carbonell, E., 2015. Palaeogeographical reconstruction of the Pleistocene sites in the Sierra the Atapuerca (Burgos, Spain). *Quaternary international*. In press.

Campaña, I., Benito-Calvo, A. Pérez-González, A., Ortega, A. I., Bermúdez de Castro, J. M., Carbonell, E. 2015. Pleistocene Sedimentary Facies of the Gran Dolina Archaeo-Paleoanthropological Site (Sierra de Atapuerca, Burgos, Spain). *Quaternary International.* In press.

Carbonell, E., Bermúdez De Castro, J. M., Arsuaga, J. L., Diez, J. C., Rosas, A., Cuenca-Bescós, G., Sala, R., Mosquera, M., Rodríguez, X. P. 1995. Lower Pleistocene Hominids and Artifacts from Atapuerca-TD6 (Spain). *Science* 269 (5225): 826–30.

Carbonell, E., García-Antón, M. D., Mallol, C., Mosquera, M., Ollé, A., Rodríguez, X. P., Sahnouni, M., Sala, R., Vergès, J. M. 1999. The TD6 Level Lithic Industry from Gran Dolina, Atapuerca (Burgos, Spain): Production and Use. *Journal of Human Evolution* 37 (3-4): 653–93.

Larsson, L., Trinks, I., Söderberg, B., Gabler, M., Dell'Unto, N., Neubauer, W., Ahlström, T. 2015. Interdisciplinary Archaeological Prospection, Excavation and 3D Documentation Exemplified through the Investigation of a Burial at the Iron Age Settlement Site of Uppåkra in Sweden. *Archaeological Prospection 22(3)*: 143-56.

Martín-Merino, M. A., Domingo, S., Antón, T. 1981. Estudio de Las Cavidades de La Zona BU-IV A (Sierra de Atapuerca). *Kaite* 2: 41–76.

Neubauer, W. 2007. 'Laser Scanning and Archaeology: Standard Tool for 3D Documentation of Excavations.' *GIM International* 21 (10): 14–7.

Ollé, A., Mosquera, M., Rodríguez, X.P., de Lombera-Hermida, A., García-Antón, M. D., García-Medrano, P., Peña, L. 2013. The Early and Middle Pleistocene Technological Record from Sierra de Atapuerca (Burgos, Spain). *Quaternary International* 295: 138–67.

Ortega, A. I., A. Benito-Calvo, A. Pérez-González, M. A. Martín Merino, R. Pérez-Martínez, J. M. Parés, A. Aramburu, J. L. Arsuaga, J. M. Bermúdez de Castro, and E. Carbonell. 2013. 'Evolution of Multilevel Caves in the Sierra de Atapuerca (Burgos, Spain) and Its Relation to Human Occupation.' *Geomorphology* 196: 122–33. doi:10.1016/j.geomorph.2012.05.031.

Pavelka, K., Reznicek, J., Matouskova, E., Faltynova, M. 2014. Using of Close Range Photogrammetry in Image Based Modelling Form for Archaeology. In *35th Asian Conference on Remote Sensing 2014, ACRS 2014: Sensing for Reintegration of Societies*: 1353-8.

Pérez-González, A., Parés, J. M., Carbonell, E., Aleixandre, T., Ortega, A. I., Benito, A., Martin Merino, M. A. 2001. Géologie de La Sierra de Atapuerca et Stratigraphie Des Remplissages Karstiques de Galeria et Dolina (Burgos, Espagne). *L'Anthropologie* 105 (1): 27–43.

Rodríguez-Gómez, G., Rodríguez, J., Martín-González, J. T., Goikoetxea, I., Mateos, A. 2013. Modeling Trophic Resource Availability for the First Human Settlers of Europe: The Case of Atapuerca TD6. *Journal of Human Evolution* 64 (6): 645–57. doi:10.1016/j.jhevol.2013.02.007.

Rodríguez, J., Burjachs, F., Cuenca-Bescós, G., García, M., Van der Made, J., Pérez González, A., Blain, H. A., Expósito, I., López-García, J. M., García Antón, M., Allué, E., Cáceres, I., Huguet, R., Mosquera, M., Ollé, A., Rosell, J., Parés, J. M., Rodríguez, X. P., Díez, C., Rofes, J., Sala, R., Saladié, P., Vallverdú, J., Bennasar, M. L., Blasco, R., Bermúdez de Castro, J. M., Carbonell, E. 2011. One Million Years of Cultural Evolution in a Stable Environment at Atapuerca (Burgos, Spain). *Quaternary Science Reviews* 30 (11-12): 1396-1412.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., Reynolds, J.M. 2012. 'Structure-from-Motion' Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications. *Geomorphology* 179 (0): 300–14.

Establishing Parameter Values for the Stone Erosion Process

Igor Barros Barbosa(1)

Kidane Fanta Gebremariam(2)

Panagiotis Perakis(1)

Christian Schellewald(1)

Theoharis Theoharis(1)

[1] Department of Computer and Information Science, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[2] Department of Chemistry, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract: The computer simulation of the naturally occurring stone erosion process is very attractive because it could enable us to predict the future state of important cultural heritage monuments based on different environment scenarios and thus allow us to take appropriate action in good time. This paper describes the design and construction of two automatic erosion chambers that allows simulations of the Salt and Freeze-and-Thaw effects respectively at lower cost, based on a control system using off-the-shelf components. It also details the parameters that are being measured after each erosion cycle (3D scan, electron microscopy, micro computed tomography, 3D microscopy, XRD and petrography), which will eventually lead to a publicly available database for erosion benchmarking. In the current phase we are only concentrating on Pentelic marble and two types of Grytdal soapstone. This work forms part of the PRESIOUS EU project (www.presious.eu).

Keywords: Cultural Heritage, Accelerated Erosion Chambers, Erosion Benchmarking.

Introduction

The purpose of our study is to contribute to the simulation of the fundamental and most common degradation mechanisms that impact objects that are built out of stone. Our ultimate aim is to model and simulate the physico-chemical processes that lead to the degradation of the stone-material of Cultural Heritage (CH) objects over time. Towards this aim we are on a course to implement a prototype for the mesh alteration that currently acts on the surface geometry and allows therefore imitations of manifestations of stone degradation phenomena like surface recession and crust formation.

We first revisit the definitions of the terms that are often used when the deterioration of stone is described. In general we distinguish the terms erosion and weathering based on the involved material movement. Erosion involves the exposure of stones to external forces and transport processes that originate from water or wind flow and gravity. Note that this also includes forces and transport processes due to ice, snow or waves. In contrast weathering denotes the processes that are weakening or loosening stone particles internally. Beside the disintegration of stone into smaller pieces, weathering also involves the dissolution of material into water due to the effects of atmosphere and hydrosphere. However the terms erosion, weathering, decay, degradation and deterioration are used differently and interchangeably within different disciplines (Doehne and Price 2010). For more strict definitions refer to the ICOMOS-ISCS 'Illustrated Glossary on Stone Deterioration Patterns' (Verges-Belmin 2008).

The three main weathering processes which often work simultaneously to decompose rocks are *physical/mechanical*, *chemical* and *biological* in nature. One of the main causes of stone decay is the interaction between water and the porous structure. Water absorption can induce weathering on stone materials in several ways:

1. By chemical reaction with industrial pollutants mainly the atmospheric gases of carbon dioxide CO_2, sulphur dioxide SO_2 and nitrogen dioxide NO_2, that decay the stone material by changing its chemical composition.

2. By a physical mechanism through mechanical stresses due to freeze/thaw and wet/dry cycles, that disintegrate stones into smaller particles, which then can be removed by gravity, wind, water or ice.

3. By acting as a transport medium for salts in dissolution and recrystallization processes within the pore space.

4. By providing an essential substrate for biological growth of living organisms such as bacteria, fungi, algae and lichens.

Stone decay appears in many different forms. Stone may gradually and slowly weather away, leaving a solid surface behind. At other times sheets or flakes break off from the stone at once. Sometimes the surface starts to show blisters or a stone just loses its integrity and crumbles away. Some of the stones can appear perfectly intact for a long time while already losing cohesion underneath.

The two different chemical weathering scenarios that are usually distinguished are the weathering within a natural environment and the weathering within a polluted environment. The first (unpolluted) scenario considers (beside the air) only the gas carbon dioxide (CO_2), while the second scenario contains also the industrial gases sulphur and nitrogen dioxide (SO_2 and NO_2). The chemical weathering results in two main effects; the gain or loss of material. The first one is mostly visible as crust building upon surfaces, while the second one relates in most cases to surface recession. The crust formation is usually due to the deposition of chemical material in polluted environments, while the loss of material results mainly due to reactions of water with the stone-material and pollution gases. The chemical products in this process are subsequently washed away. Temperature and humidity play crucial roles in these processes.

The two different mechanical weathering scenarios that are usually distinguished are the weathering caused by soluble salts and the weathering caused by wet/dry and freeze/thaw cycles. Along with air pollution, soluble salts represent one of the most important causes of stone decay. Salts cause damage to stone in several ways. The most important is the growth of salt crystals within the pores, fissures and cracks of a stone, which can generate stresses that are sufficient to overcome the stone's tensile strength and turn the stone to fragmented pieces. Another important decay mechanism under the general term 'differential stress' includes the effects of wet/dry cycling, clay swelling, differential hygric stress, differential thermal stress, and stress from differential expansion rates of material in pores (such as salts or organic material) versus in the stone.

In connection with stone deterioration, the following are crucial research questions to be properly addressed (Doehne and Price 2010):

Why are certain types of stone much more vulnerable than other types to weathering? Why are certain salts much more damaging than others? Is damage caused mostly by relatively rare environmental events (rapid cooling, drying, or condensation) or cumulative everyday stresses (humidity cycling)? Can general agreement be achieved regarding the fundamental mechanisms of salt weathering? Can the dynamics of differential stress as it relates to environmental conditions be properly modelled? Can the stone damage process and weathering forms be accurately modelled using existing knowledge? How does the hydration of salts progress, and how are crystallization pressures sustained in situ? And, above all, how can this knowledge be helpful concerning the conservation treatments of Cultural Heritage objects?

The small amount of recession rates observed at cultural heritage sites, the complexity of the deterioration mechanisms, the unavailability of chemical data that characterize the monumental building materials on site, and the uncontrolled environmental conditions, make it necessary to setup accelerated erosion chambers for conducting specific purpose experiments, under controlled conditions using chemically characterized stone samples.

1 Related Work

Although there is much work that has be done concerning in situ studies of the physico-chemical processes of stone erosion and their significance to the conservation treatments of Cultural Heritage objects, the construction of accelerated erosion chambers and the conduction of specific purpose experiments, under controlled laboratory conditions is a rather under-studied issue - see the excellent survey of E. Doehne and C. Price concerning the current research on stone decay and conservation (Doehne and Price 2010), and the state-of-the-art report of C. Schellewald *et al*. concerning the simulation of stone deterioration processes (Schellewald *et al*. 2013).

Gauri, Yerrapragada, Bandyopadhyay *et al*. in a series of works (Yerrapragada *et al*. 1994; Yerrapragada *et al*. 1996; Gauri and Bandyopadhyay 1999) described the erosion on carbonate stones, and especially marble, under polluted and unpolluted, dry or wet environments. Given that the mechanisms of surface recession and crust creation are too complex, the authors set up chemical erosion chambers to study the effects of CO_2, SO_2 and NO_2 in dry or wet controlled conditions. They also made outdoor experiments measuring the amount of material that runs off during rain showers and related this to the exposed sample surface allowing them to estimate the recession under rainfall. The chemical processes were modelled by the unreacted-core model, which led to the calculation of the crust deposition rate in dry environments or the surface recession rate by acid rain.

G. W. Scherer examined several important weathering processes like the thermal expansion of calcite, freeze/thaw cycles, salt crystallization along with the swelling of clay inclusions (Scherer 2006). He reviewed these weathering mechanisms and outlined which aspects remain to be solved. He concluded that salt damage is one of the most serious, but least understood, causes of stone deterioration and that the essential mechanisms that cause stresses in stone are known, but that details are not clear.

D. G. Price noted that chemical weathering usually includes the solution of stone material, the degree of which depends on the amount of water passing over the surface, the solubility of the material, and the pH value of the water (Price 1995). Considering all possible reactions of stone materials with all possibly present chemicals becomes quickly very complex. However, for some stones the chemical degradation or weathering mechanisms of particular material components are relatively well known.

The effects of ozone and NO_x on the deterioration of calcareous stone was investigated by S. W. Massey. He investigated the effects of these gases on the deterioration of different stones in chamber reactions and field works in urban and rural environments (Massey 1999).

The corrosive effects of gaseous SO_2, NO_x, O_3, HNO_3, particulate matter, and acid rainfall are the topic of C. Varotsos *et al.*, concerned with the enhanced deterioration of the cultural heritage monuments (Varotsos, Tzanis, Cracknell 2009).

A. Moropoulou *et al*. presented in (Moropoulou *et al*. 1998) weathering phenomena on Pentelic marbles at the Demeter Sanctuary in Elefsis, Greece. A systematic mineralogical, petrographical and chemical examination of weathered stones and crusts was performed, both in situ and in the lab, on samples taken from different parts of the monument in relation to the surface characteristics as well as to the exposure to rain,

Fig. 1. Two geometric meshes of the Elefsis-column. This data was acquired in March 2013 and in October 2014. The patches that correspond to the upper box are shown in more detail in figure 2.

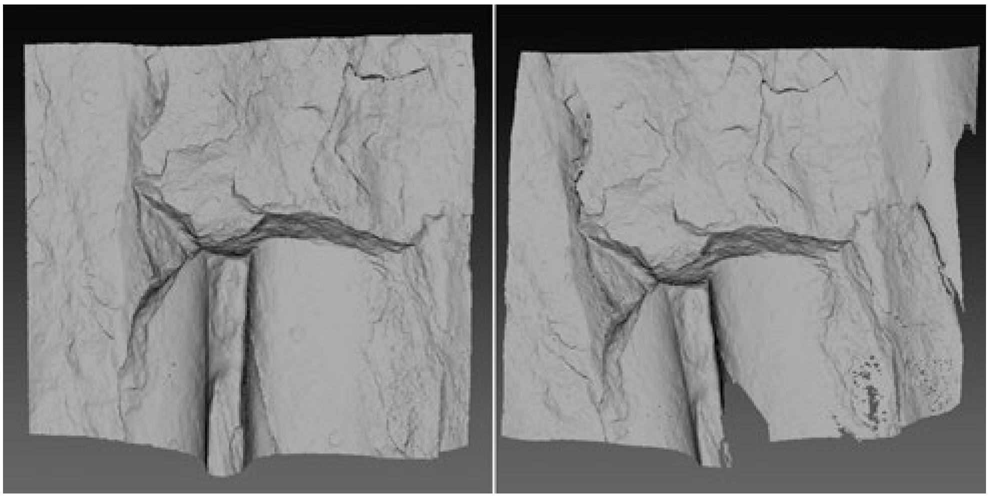

Fig. 2. Two Elefsis-column patches of approximately the same area of the column that was scanned at different times. Note that the shown area was scanned with high resolution.

sea-salt spray and wet and dry deposition of airborne pollutants and dust.

P. Storemyr in a series of works (Storemyr 1997; Storemyr, Wendler, Zehnder 2001; Storemyr 2004) presented weathering phenomena at the Nidaros cathedral in Trondheim, Norway. He noted that stones from eight quarries are used in the monument and he presented and compared the behavior in weathering and conservation of the respective stone types (soapstone and greenschist). Storemyr discussed the geology, petrography and salt content of soapstone deposits. According to Storemyr the 'Grytdal' stone seems also to contribute to the formation of black gypsum crusts as the observed crusts cannot be attributed to air pollutants (SO_2 and particulate matter) alone.

2 Accelerated Erosion Experiments

2.1 Evaluation Data from the Cultural Heritage Sites

For the investigation of the erosion mechanisms that contribute to the degradation of stones, we collected 3D geometric data from the two Cultural Heritage sites, the Demeter Sanctuary in Elefsis, Greece, and the Nidaros Cathedral in Trondheim, Norway. Figure 1 shows a lower resolution mesh of consecutive geometric scans that took place at Elefsis in March 2013 and October 2014. The areas of the Elefsis-column, that are marked with boxes, indicate the patches we selected for illustration of measurements and investigations (compare Fig. 2).

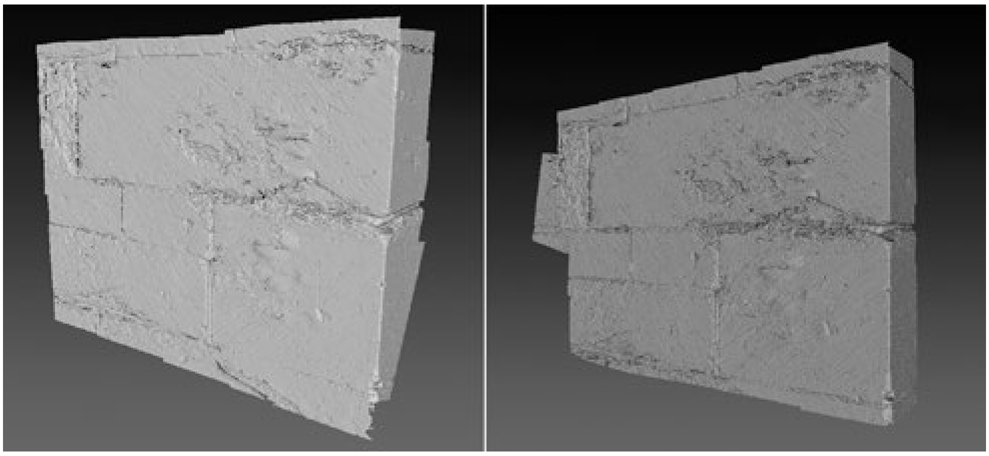

Fig. 3. Two geometric meshes of the Nidaros Cathedral. This data was acquired in April 2013 and in September 2014. The patches that show the X mason mark in more detail are shown in figure 4.

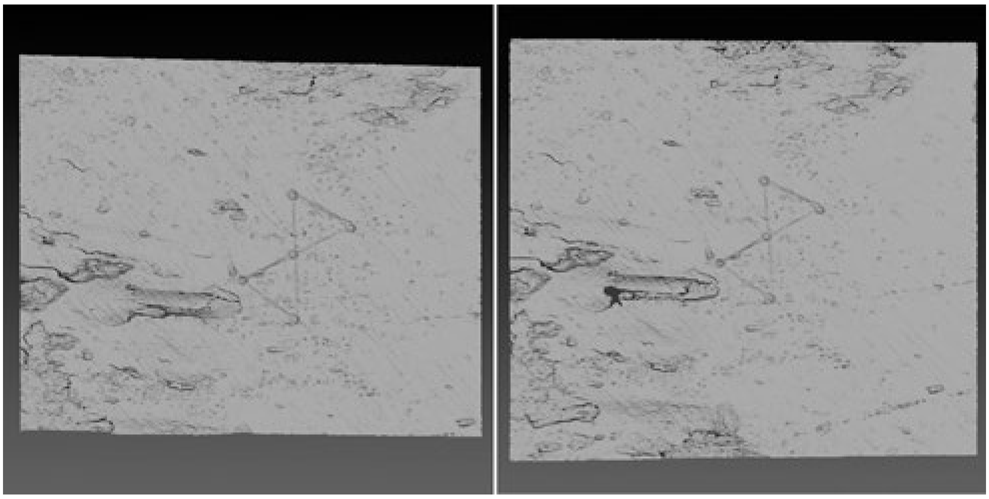

Fig. 4. Patches of two geometric measurement rounds showing the X mason mark that are present on the east wall of the Lectorium of the Nidaros Cathedral.

At the Nidaros Cathedral several smaller areas were selected for scanning. These include two wall parts from the Lectorium (Lectorium East, with Mason Marks, and Lectorium North) and two scans from the inside of the North West and South West Tower of the Cathedral. In Figure 3 we illustrate the geometric scan of the east wall of the Lectorium that contains two mason marks. A close-up view of the areas with the mason marks is depicted in figure 4.

The unavailability of chemical data and the small amount of recession observed at the Cultural Heritage sites themselves (Fig. 5), made it necessary to complement these measurements with data obtained from accelerated erosion experiments that study erosion parameters in isolation. Considered weathering experiments include effects that originate from polluted environments and from naturally occurring climatic conditions. The experiments that we finally decided to perform, include the Salt effect (using sodium sulfate Na_2SO_4), the Freeze-and-Thaw effect, that simulate mechanical effects and two chemical experiments simulating polluted industrial environments, rich in SO_2 and NO_2 (using aqueous solutions of sulfuric acid H_2SO_4(aq) and combined sulfuric and nitric acid H_2SO_4+HNO_3(aq)).

In addition to the Salt and Freeze-and-Thaw weathering experiments, the acid weathering experiments were carried out to study the effects of polluting gases such as SO_2 and NO_2 in solution forms. Cyclic soaking experiments in acidic solutions of sulfuric and nitric acids, with alternating wetting and drying stages, were used to simulate the accelerated weathering. Physicochemical changes at macroscopic and microscopic levels were monitored through characterizations using multiple analytical techniques.

The experiments simulating polluted environments were performed at the Department of Chemistry at NTNU. The

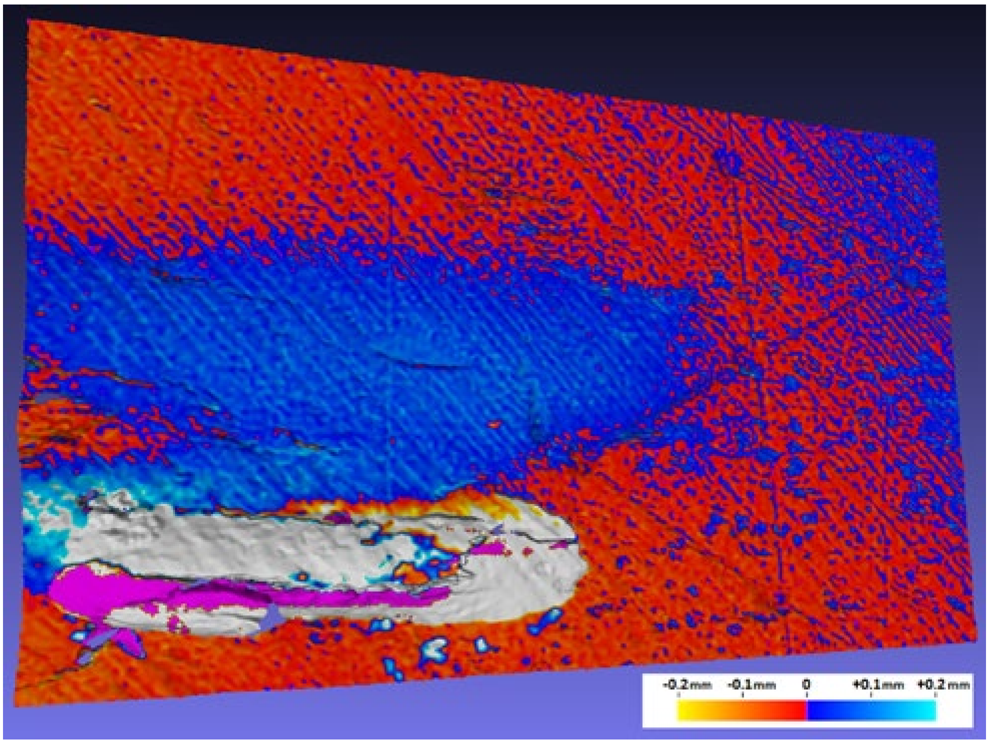

Fig. 5. Distance map of the two X mason mark patches between the two Round 01 and Round 02 3D geometry acquisitions. The meshes are at first registered, and then distances are mapped as textures onto the Round 01 mesh.

experiments concerning the Salt and the Freeze-and-Thaw effects were performed at the Department of Computer and Information Science at NTNU. In the following sections we describe the constructed accelerated erosion chambers and the performed experiments for the Salt and Freeze-and-Thaw effects.

2.2 Stone Slabs and their Labeling

In this section the stone samples and the experiments carried out in our accelerated erosion chambers are briefly described. The samples are stone slabs similar to the stones used at the two Cultural Heritage sites; the Demeter Sanctuary in Elefsis, Greece, and the Nidaros Cathedral in Trondheim, Norway. Pentelic marble was used at the Demeter Sanctuary (Moropoulou *et al*. 1998) and Grytdal soapstone was used in the Nidaros Cathedral (Storemyr 1997). The stone slabs were named according to their origin (Elefsis, Nidaros); furthermore the soapstone slabs labelled with reference to the stone quality (Good, Bad) and finally according to their size (Large, Small) (see Fig. 6). Details concerning the labelling of the specific stone samples used in each of the erosion experiments are listed in Table 1.

Pentelic Marble: dense metamorphic rock; homogeneous; almost entirely made of calcite (96% $CaCO_3$); with low porosity (3.64 *vol*%) (Moropoulou *et al*. 1998).

Grytdal Soapstone: dense metamorphic rock; non homogeneous; made mostly of chlorite (20% - 60%) and talc (5% - 20%); with low porosity (3.60 *vol*%) (Storemyr 1997).

2.3 Salt and Freeze-and-Thaw Chambers

In order to investigate the Salt effect, using Na_2SO_4 decahydrate, and the Freeze-and-Thaw effect we designed two erosion chambers. Figure 7 shows the Salt Chamber and the Freeze-and-Thaw Chamber which we constructed for our accelerated erosion experiments. They are controlled by Arduino microcontrollers (Arduino LLC 2015) and continuous measurements are taken over USB connections. Typical curves that originate from 24 hour measurements from both chambers are shown in figure 12.

One cycle within the Salt Chamber takes 6 hours and consists of submerging the stones in the salt solution for 3 hours and drying them for 3 hours in a constant light airflow created by small fans attached to the chamber. Note that 3 hours is the amount of time taken for the chambers to enter into a steady state of humidity variation. Figure 8 shows the Salt Chamber in both states. The left image shows the stones lifted up. The white crust indicates that the stones already dried for a while. On the right image, the stones are submerged within the salt solution. The temperature and humidity of the chamber is continuously monitored over the lifetime of the experiments. Diagrammatic representation of the Salt Chamber is depicted in figure 9.

The Freeze-and-Thaw Chamber is constructed out of a small refrigerator and a water purification system that are both controlled by an Arduino microcontroller. Diagrammatic representation of the Freeze-and-Thaw Chamber is depicted in Figure 11. One cycle within the Freeze-and-Thaw Chamber takes 8 hours. This includes 3 hours of freezing and 5 hours of

TAB. 1. LABELLING AND MATERIAL OF STONE SAMPLES

Stone Samples			
Stone		**Material**	**Experiment**
EL1	Elefsis Large 01	Pentelic Marble	*Freeze – Thaw*
EL2	Elefsis Large 01	Pentelic Marble	Salt
NBL1	Nidaros Bad Large 01	Grytdal Soapstone	*Freeze – Thaw*
NBL2	Nidaros Bad Large 02	Grytdal Soapstone	Salt
NGL1	Nidaros Good Large 01	Grytdal Soapstone	*Freeze – Thaw*
NGL2	Nidaros Good Large 02	Grytdal Soapstone	Salt

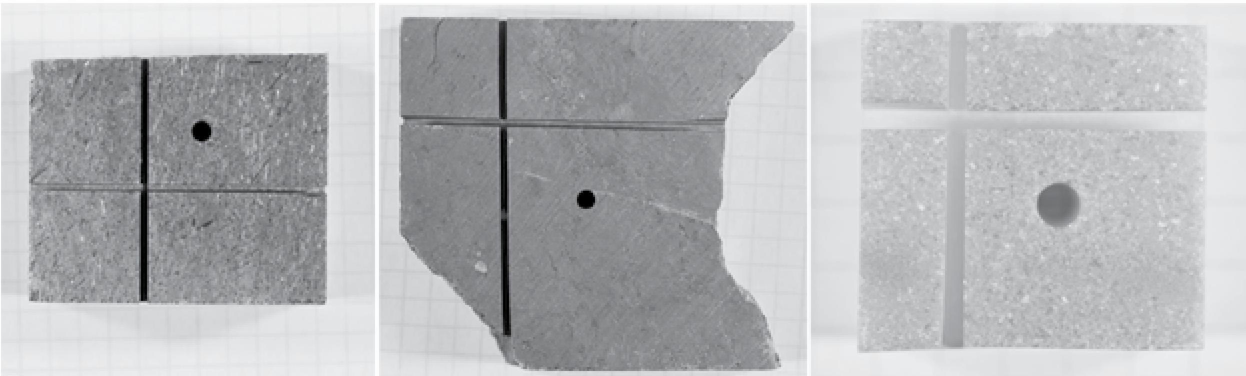

FIG. 6. PHOTOS OF SOME STONE SLABS USED IN THE ACCELERATED EROSION EXPERIMENTS.

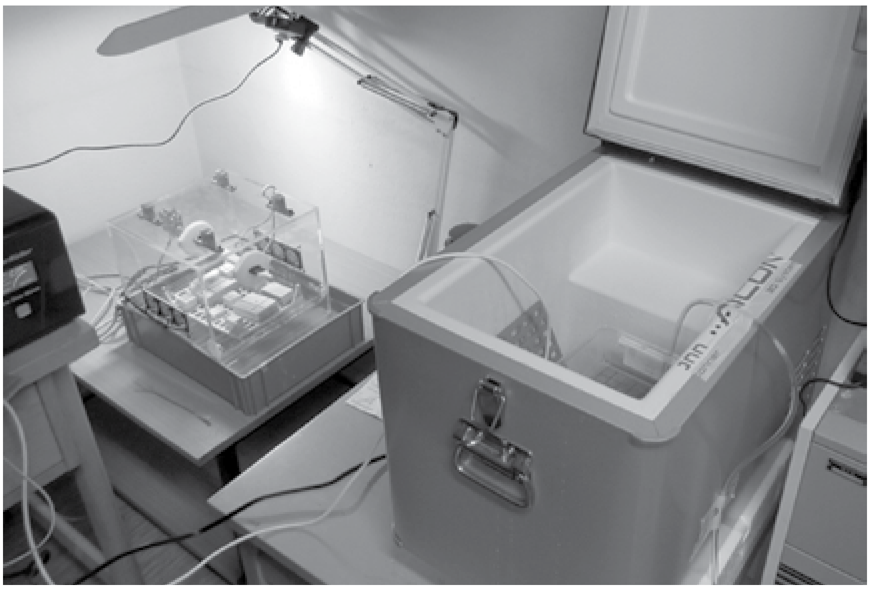

FIG. 7. THE TWO EROSION CHAMBERS (SALT AND FREEZE-AND-THAW) BESIDE EACH OTHER AT THE BEGINNING OF THE SECOND ACCELERATED EROSION ROUND. THEY ARE LOCATED IN A DEDICATED ROOM FOR OUR EXPERIMENTS WITHIN THE CELLAR OF THE DEPARTMENT OF COMPUTER AND INFORMATION SCIENCE BUILDING AT NTNU.

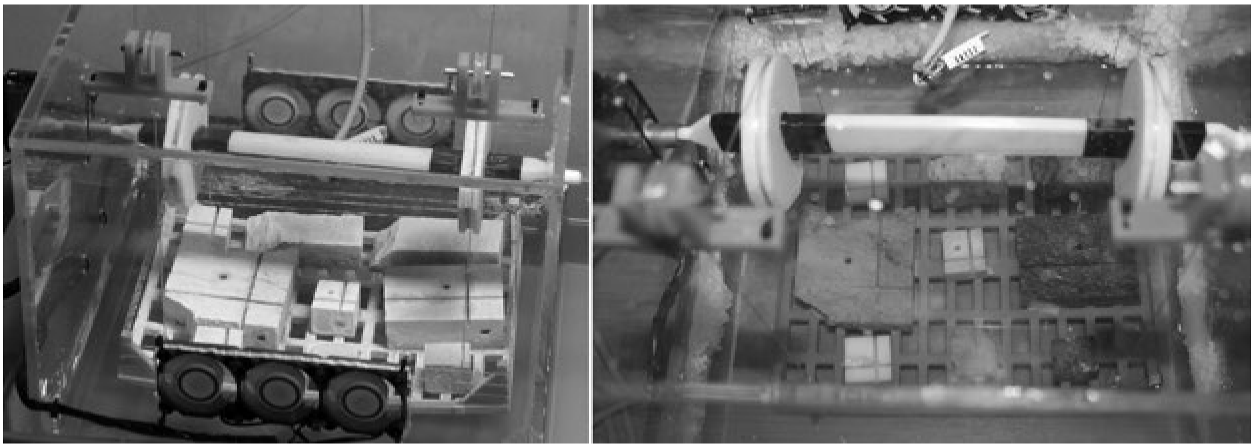

Fig. 8. The Salt Chamber shown at two different cycles and states. Dry and wet phases change every three hours during the accelerated erosion cycles.

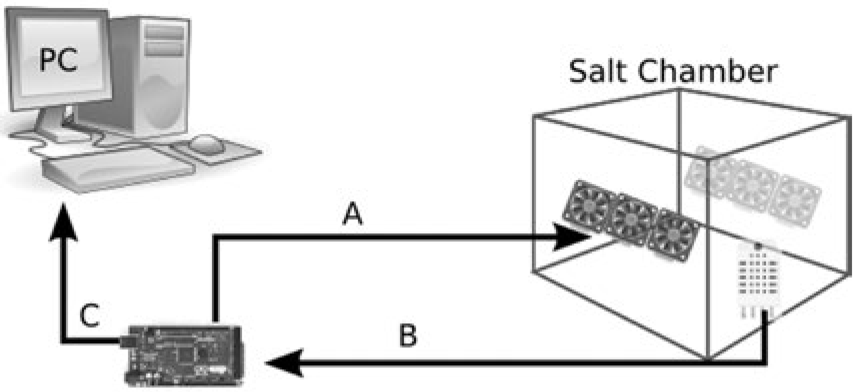

Fig. 9. Depiction of Salt Chamber control diagram: (A) Control stone submersion and fan activation; (B) Humidity and temperature reading; and (C) Data logging.

warming up. The length of the warm cycle was selected so that the chamber reaches a temperature of about $5^{o}C$. The freezing cycle guarantees a long state where the temperature is below $-5^{o}C$. Within the last 30 minutes of the warming phase, purified water drops onto the stones. For this chamber we used a separate Arduino for continuously measuring the temperature.

2.4 Experimental Setup

The first round of accelerated Salt effect erosion started on 19th September 2014 and was stopped on 21st October 2014, while the first round of the accelerated Freeze-and-Thaw erosion started on the 10th of November 2014 and ended on the 4th of December 2014. The second round for both effects started on the 4th of March 2015. We stopped the Salt Chamber on the 20th of March 2015 for characterization of the samples taking into account the noted fast progress of the salt effect. The second round of the Freeze-and-Thaw Chamber ended on the 28th of March 2015. Erosion cycles take place between measurement cycles (see Section 2.5). Details concerning the erosion rounds of our physical chamber experiments are listed in Table 2 and Table 3.

2.5 Measurement modalities

Several measurement techniques are used to characterize the changes that occur on the stone samples during the accelerated erosion cycles. The measurements consist of mass measurements, 3D Geometric Scans, Quantitative Evaluation of Minerals by SCANning electron microscopy (QEMSCAN), Scanning Electron Microscopy with X-ray microanalysis (SEM-EDS), 3D microscopy, micro Computed Tomography (micro-CT), X-Ray Diffraction (XRD) and Petrography. The data sets currently collected from these measurements along with some examples of the data for illustration purposes are summarized below.

3D Geometry Scans The 3D scans of the stone slabs in high resolution surface meshes of the 3D geometry of the stones, were performed by Aicon – our industrial partner in the PRESIOUS project – using a Breuckmann Scanner (AICON 3D systems 2015). An example of the resulting mesh data is depicted in Figure 13.

Tab. 2. Salt Chamber: Summary of the duration of the first two rounds of accelerated erosion.

Experiment	**Salt Chamber (Round 01)**
Start	2014-09-19 19:45
End	2014-10-21 15:52
Duration	31.83 Days (2750815 *sec*)
One cycle	21615 *sec* (submerge: 10810 *s* - drying: 10805 *s*)
Number of cycles	127.5 (128.0 taking the last drying into account)
Experiment	Salt Chamber (Round 02)
Start	2015-03-04 13:03
End	2015-03-20 13:19
Duration	16.01 Days (1383360 *sec*)
One cycle	21615 *sec* (submerge: 10810 *s* - drying: 10805 *s*)
Number of cycles	64.0

Tab. 3. Freeze-and-Thaw Chamber: Summary of the duration of the first two rounds of accelerated erosion.

Experiment	**Freeze-and-Thaw Chamber (Round 01)**
Start	2014-11-10 14:58
End	2014-12-04 15:02
Duration	24.003 Days (2073853 *sec*)
One cycle	28800 *sec* (warming up: 18000 *s* (incl. 1800 *s* rain) - freezer on: 10800 *s*)
Number of cycles	72
Experiment	Freeze-and-Thaw Chamber (Round 02)
Start	2015-03-04 14:25
End	2015-03-28 14:29
Duration	24.003 Days (2073853 *sec*)
One cycle	28800 *sec* (warming up: 18000 *s* (incl. 1800 *s* rain) - freezer on: 10800 *s*)
Number of cycles	72

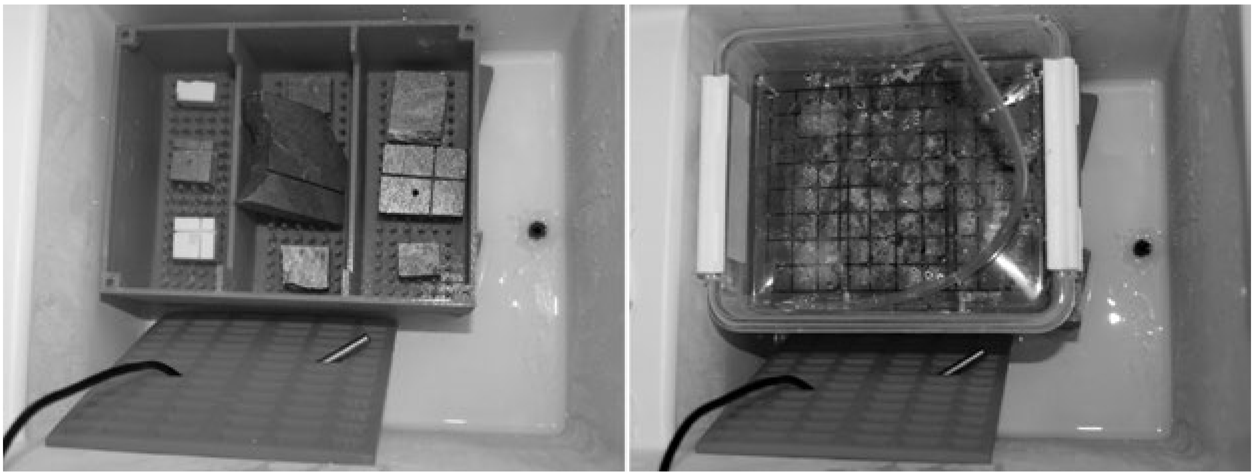

Fig. 10. The inner structure of the Freeze-Thaw Chamber. Before a freezing cycle starts, purified water drops for 30 minutes onto the stones, simulating rain.

micro-CT Micro computed tomography is a technique similar to the well-known CT scans performed in medicine. It provides x-ray images in 3D for small scale objects at a high resolution. It provides density information about the inner structure of the stone material and could be helpful when nalysing the 3D pore structure and volume changes of the stones. Figure 16 shows a slice from the micro-CT data acquired for the 'Nidaros Bad Large 2' stone slab.

3D Microscopy: to allow for additional measurements on the surface of the eroded stone slabs, 3D microscopy was employed and provides textural and 3D structure of the measured stone surfaces. Illustrations for this type of measurement are given in figure 17 where the data of three different stone surfaces is shown. A limitation of this data is that only the depth field of the surface can be measured and that any concavities that might be present are not acquired.

Petrography Petrography is a method used since the mid 1800's for describing the mineral content and the textural relationships within rocks. A thin transparent slab slice of the stone is observed with a light microscope under plane polarized light

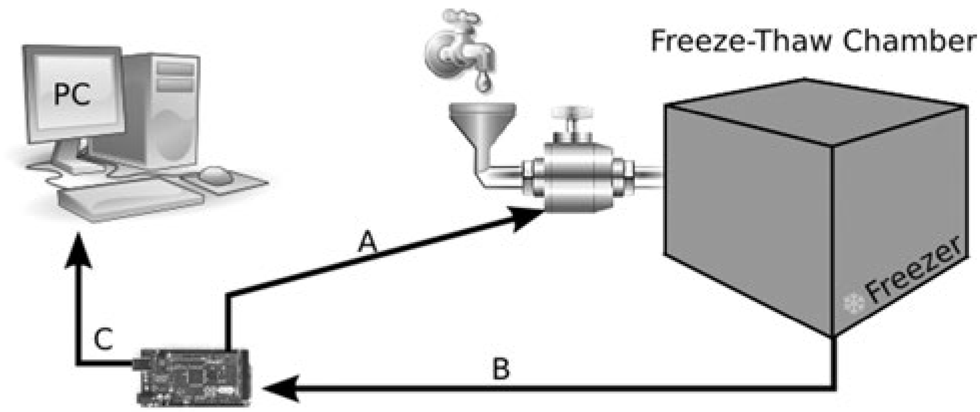

Fig. 11. Depiction of Freeze-and-Thaw Chamber control diagram: (A) Control valve for injection of purified water; (B) Temperature Readings; and (C) Data logging.

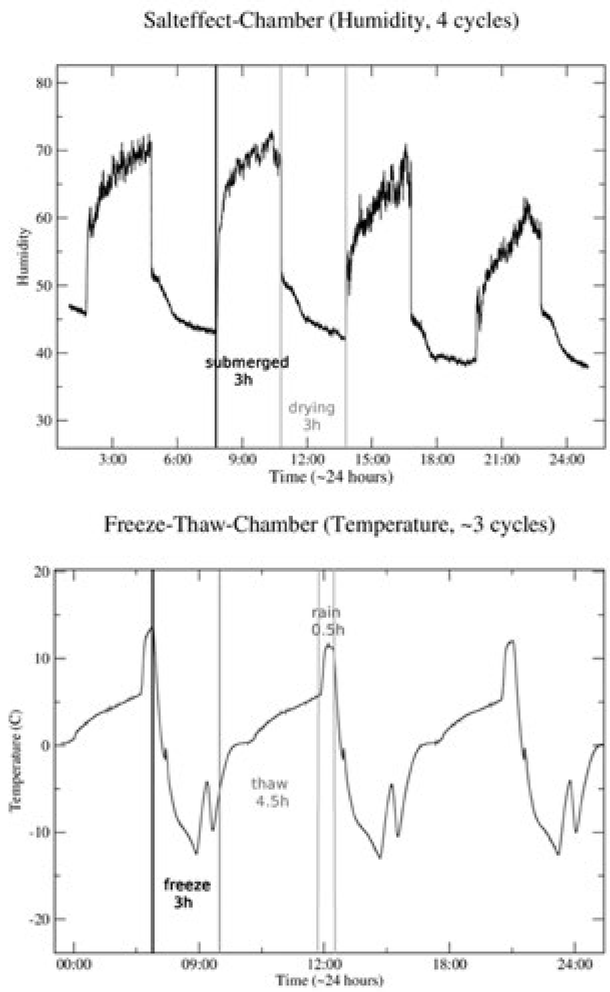

Fig. 12. Typical measurements gathered during the accelerated erosion experiments in the Salt and Freeze-and-Thaw Chambers.

of different orientations. Fluorescence microscopy was also used to characterize mineral contents, the porosity, fissures and cracking structures. An example for the obtained data of the Nidaros Good stone type is shown in figure 18.

3 Results

3.1 Estimation of the extent of erosion between Erosion Cycles

Mass measurements: after removal of the samples from the Salt Chamber, the stone samples were rinsed thoroughly with deionized water, dried for 24 hours at $105^{o}C$ and cooled to room temperature in a desiccator before mass measurements. The same procedure, except rinsing with deionized water, was followed for the stone samples from the Freeze-and-Thaw Chamber.

Mass measurements confirm our observation that stones from Nidaros (i.e. NBL1 and NBL2) suffer more erosion than the other stones and also that the Salt effects are more dramatic than the Freeze-Thaw effects (see Table 4).

Estimating erosion using micro-CT scans One way of estimating the mean erosion δ is to assume that the erosion takes place equally on all faces of the slab and that the slab can be approximated as a cube with edge length h (*"Cubic Volume Approximation"*). Then $\delta = 1/2\ \Delta h$.

Thus, for estimating Δh we use the volumes V_1 and V_2 of the slab before and after erosion respectively. Then Δh is computed from the slab volumes $\Delta h = \sqrt[3]{V_2} - \sqrt[3]{V_1} = h_2 - h_1$, where h_1 and h_2 represent the cube edge lengths before and after the erosion cycle respectively. The volumes V_1 and V_2 were computed using non-void voxel counting on the micro-CT scans of the slabs.

Estimating erosion using micro-CT scans and surface scans A second way of estimating δ is to use the surface areas S_1 and S_2 of the mesh before and after erosion respectively (*"Surface Area Approximation"*). Assuming that the surface area doesn't change too much we can use the differential equation

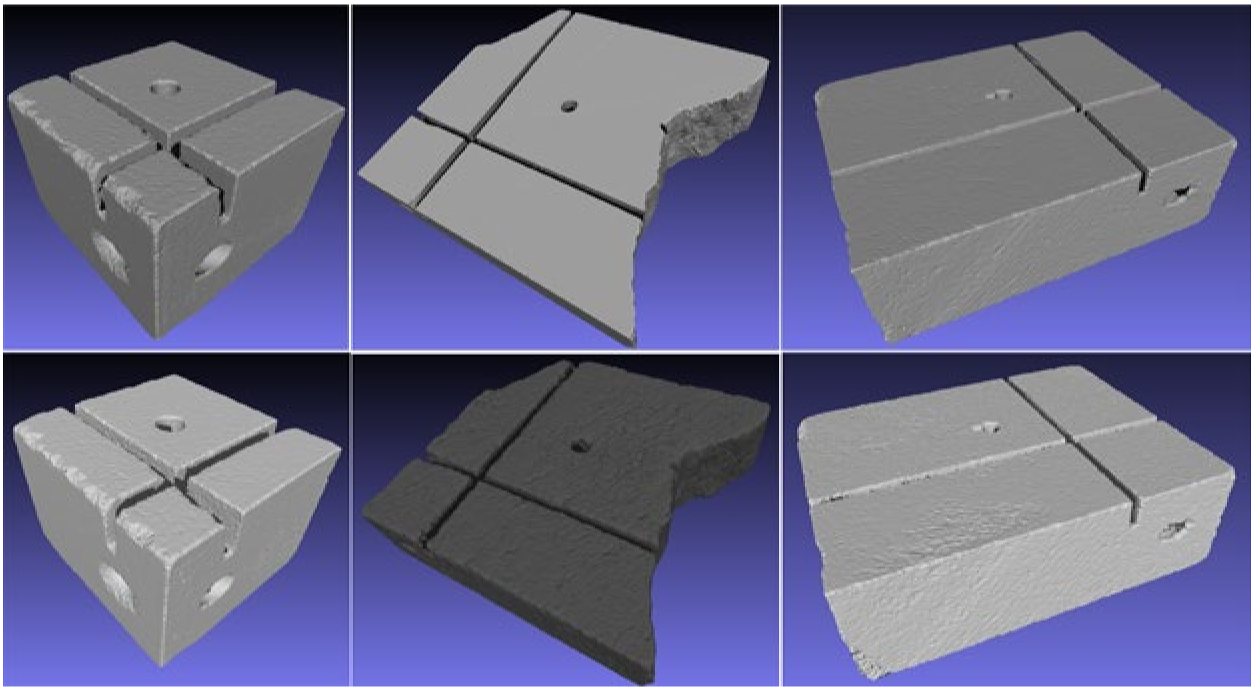

Fig. 13. Depiction of the 3D scans of some stone slabs: Top row: Round 01 (2014-06-02), Bottom row: Round 02 (2015-01-12). Notice the roughness of the surface of the R02 scans due to the erosion. QEMSCAN Quantitative Evaluation of Minerals by SCANning electron microscopy is a technique that uses a Scanning Electron Microscope (SEM) combined with X-ray spectroscopy and a database to obtain accurate mineral maps for a measured stone surface, performed by Robertson CGG (Robertson CGG 2015). The results of the QEMSCAN of the stone slabs from the Freeze-and-Thaw experiment is shown in Figure 14. The used colour codes and analysing of the mineral map is shown in Figure 15.

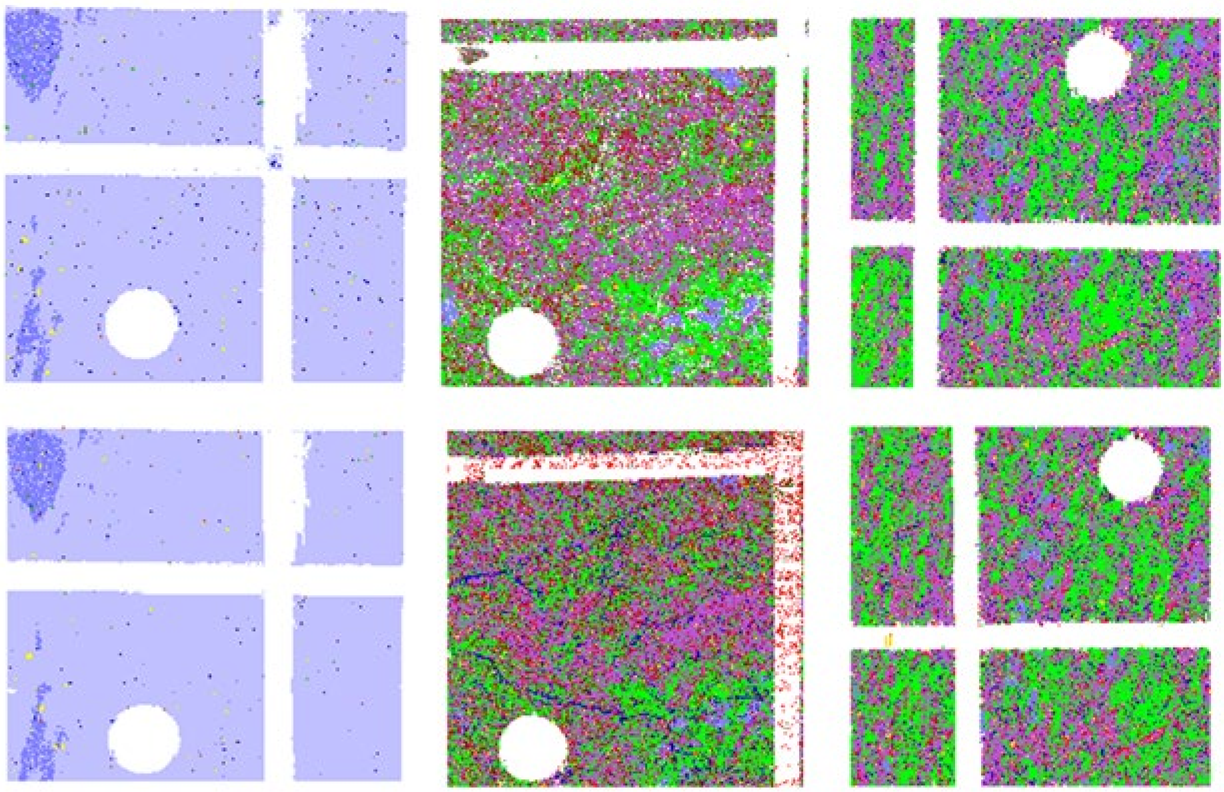

Fig. 14. Depiction of the mineral maps from the QEMSCAN of some stone slabs: Top row: Round 01 (2014-06-02), Bottom row: Round 02 (2015-01-12).

Minerals	Color	RGB-dec		
Quartz		255	255	0
K-Feldspar		221	160	221
Plagioclase Feldspar		255	105	180
Biotite		128	0	0
Illite		0	192	0
Chlorite		0	255	0
Smectite		51	102	0
Kaolinite		192	64	0
Glauconite		128	128	0
Calcite		192	192	255
Dolomite		128	128	255
Ankerite		255	192	128
Siderite		255	128	0
Gypsum/Anhydrite		178	34	34
Pyrite		255	215	0
Heavy Minerals		255	0	0
Altered Mafics		186	85	211
Pores		0	0	192
Others		128	128	128
No measurement		255	255	255

Fig. 15. Colour codes of minerals that appear in the QEMSCAN mineral maps of Figure 14.

$\Delta V = S\Delta h$, and $\delta = \Delta h = \Delta V/S$, where $\Delta V = V_2 - V_1$ and $S = S_{avg} = (S_1 + S_2)/2$.

The surface areas S were computed using the summation of the triangles area of the scanned mesh. Since the micro-CT data did in some cases not cover the whole volume of the slabs (in particular the larger stone slabs did not fit into the measurement space) during the first round (R01) measurements, V_1 could not be directly computed from them, so finally it was computed from the first round mass m_1 using the second round density ρ_2, which was considered constant between the two cycles.

Note that the above two ways of estimating δ are based on different measurements (3D scans and micro-CT). We have estimated δ using both methods and since the results for the various slabs are quite close to each other, the validity of our approximation is confirmed (see Tab. 5).

Estimating erosion on every vertex of the stone mesh A key problem in measuring erosion based on scans made across time is the difficulty in registering these scans. Due to the absence of an external reference frame, a typical registration algorithm, such as Iterative Closest Point (ICP) (Besl & McKay 1992), will align the scans so as to minimize the RMS error between them, which is not an ideal solution in case of erosion, since it diminishes the common erosion that has to be measured (see Figure 19 (a)). Here is how we handled this problem in the case of the erosion chamber slabs.

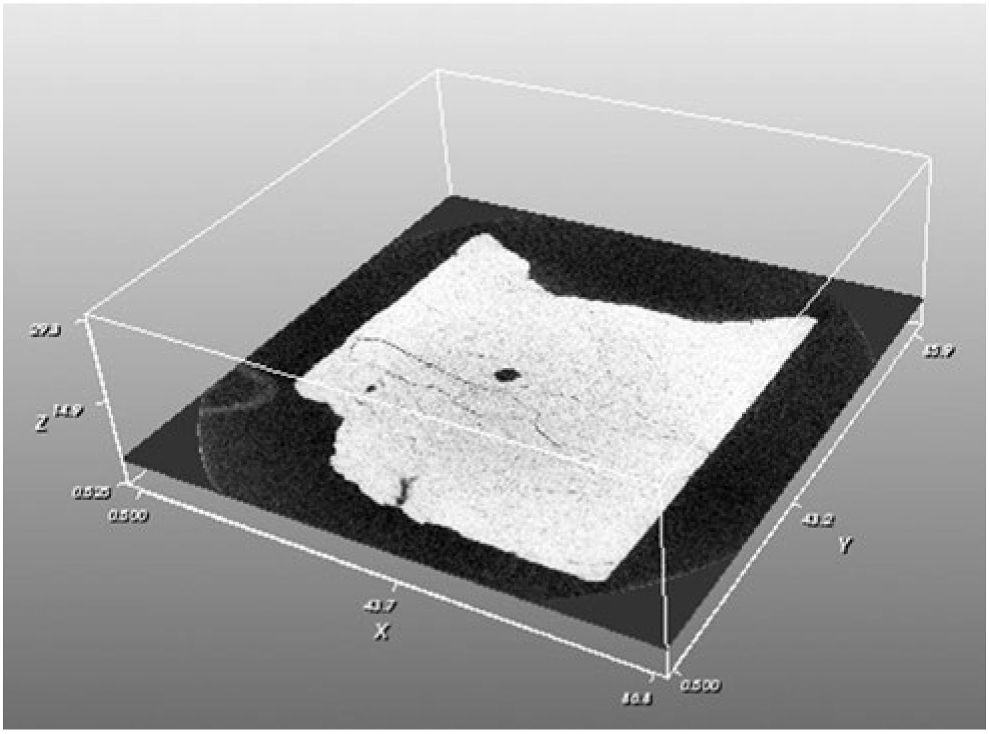

Fig. 16. Depiction of a slice from the micro-CT data of 'Nidaros Bad Large 2' stone slab.

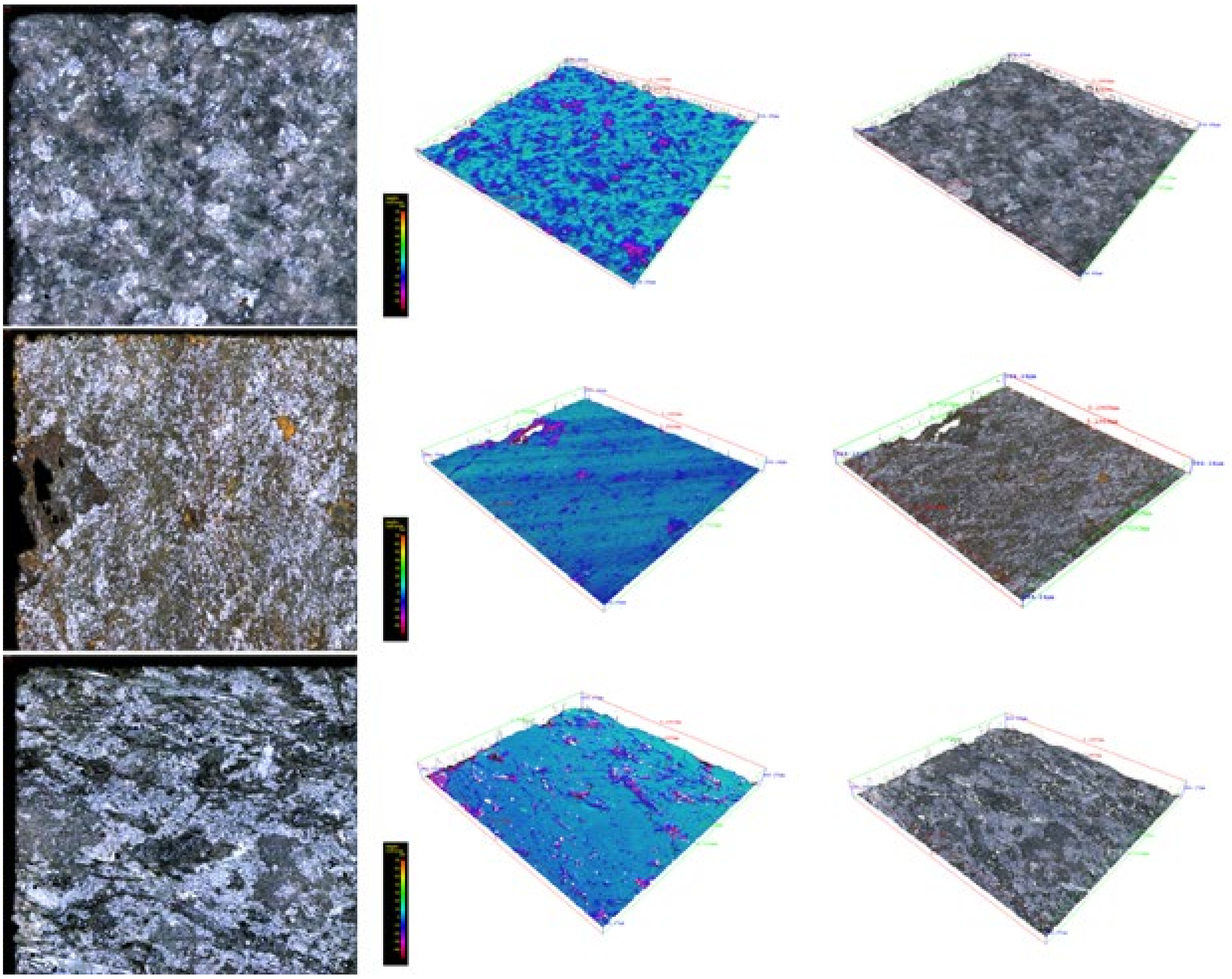

Fig. 17. 3D Microscopy images provide surface geometry data along with textural information of the scanned area. Examples from the three stone types are shown: Top row: Elefsis Large 01, Middle row: Nidaros Bad Large 01 Bottom row: Nidaros Good Large 01.

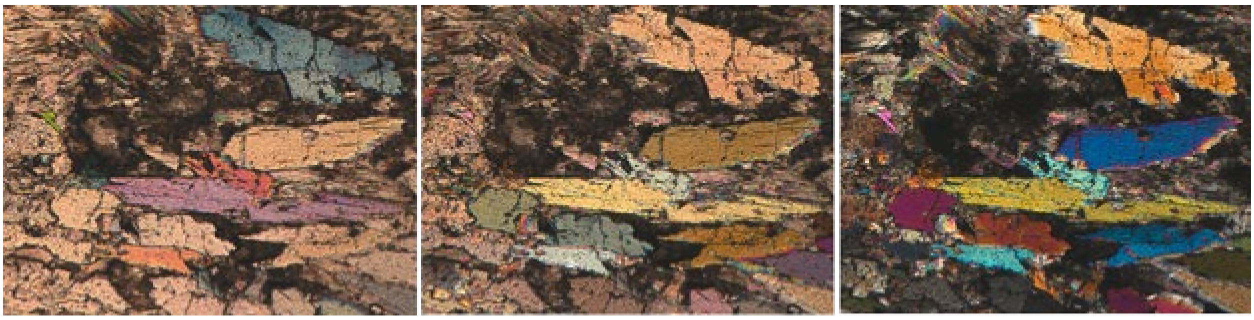

Fig. 18. A thin stone slice (Nidaros Good) is illuminated with polarized light (crossed polar in this case) that shines through it with different orientations. Depending on the orientation of the polarized light, distinctive crystals of the stone become apparent in different colour shadings.

TAB. 4. MEASUREMENTS OF THE MASS LOSS FOR THE DIFFERENT STONE SLABS. M_1 INITIAL MASS, M_2 MASS AFTER 1ST EROSION CYCLE.

Mass Loss Δm (*gr*)					
Stone		m_1 *(gr)*	m_2 *(gr)*	**Δm (gr)**	*Δm/m* (%)
EL1	*Freeze – Thaw*	29.1283	29.0847	-0.0436	-0.15
EL2	Salt	25.0409	24.8459	-0.1950	-0.78
NBL1	*Freeze – Thaw*	169.2780	168.8975	-0.3805	-0.22
NBL2	Salt	195.8884	188.9025	-6.9859	-3.57
NGL1	*Freeze – Thaw*	101.7920	101.7464	-0.0456	-0.04
NGL2	Salt	161.2788	160.5487	-0.7301	-0.45

TAB. 5. COMPUTATION OF THE MEAN EROSION FOR THE DIFFERENT STONE SLABS: (A) CUBIC VOLUME APPROXIMATION; AND (B) SURFACE AREA APPROXIMATION. (*) VOLUME V_1 COMPUTED FROM MASS M_1 USING DENSITY ρ_2 CONSIDERED CONSTANT.

Mean Erosion δ (*mm*)							
Stone		V_1 (cm^3)	V_2 (cm^3)	ΔV (cm^3)	S (cm^2)	$\delta^{(a)}$ (*mm*)	$\delta^{(b)}$ (*mm*)
EL1	*Freeze – Thaw*	10.8250	10.7281	-0.0969	31.3598	-0.0331	-0.0309
EL2	Salt	9.3050	9.1773	-0.1277	28.3975	-0.0483	-0.0450
NBL1	*Freeze – Thaw*	(*) 61.9314	61.7922	-0.1392	120.5537	-0.0148	-0.0115
NBL2	Salt	70.3382	68.6979	-1.6403	126.5692	-0.1617	-0.1296
NGL1	*Freeze – Thaw*	(*) 35.4548	35.4389	-0.0159	72.1983	-0.0025	-0.0022
NGL2	Salt	(*) 55.5347	55.2833	-0.2514	102.9147	-0.0288	-0.0244

We first register the top surface of the slabs using ICP and assume that this registration is sufficient in terms of the X and Y dimensions that define the top surface. The question is by how much to displace the slab in Z in order to accurately describe the erosion effect, see Figure 19 (b). Let us call this necessary displacement ΔZ. This should be equal to the computed mean erosion δ.

3.2 Physico-chemical aspects of the erosion

The physico-chemical aspects of the erosion involves geometrical information and physicochemical data on the surface of the object being eroded. A crucial first step for this procedure is the registration of the acquired geometric mesh data with the QEMSCAN mineral map texture data (Figures 20 and 21).

The general registration transformation matches landmark points annotated on the geometry image of the scanned 3D mesh, and the corresponding landmark points annotated on the QEMSCAN texture, which are considered as the invariant reference points under the correspondence transformation. These points are localized using the hole and the cross which are engraved onto the slabs for this purpose.

Estimating Mineral Composition using the QEMSCAN data: one way of estimating the mineral composition of each stone is by computing the occurrences of each mineral on the QEMSCAN textures.

This gives the relative surface coverage for each mineral which is actually related to the volume composition of each stone % v/v (see Table 6).

4 Concluding remarks

Although the interpretation of the results from the accelerated weathering experiments on the marble and soapstone at macroscopic and microscopic levels is still in progress, we can infer that the investigation conducted has given an insight into the changes occurring during erosion/weathering of these stones.

Low-cost, small scale, automated weathering chambers for studying accelerated Salt and Freeze-and-Thaw effects on stones were successfully designed, constructed and used. The weathered stone samples were exhaustively characterized by employing a wide range of analytical techniques and

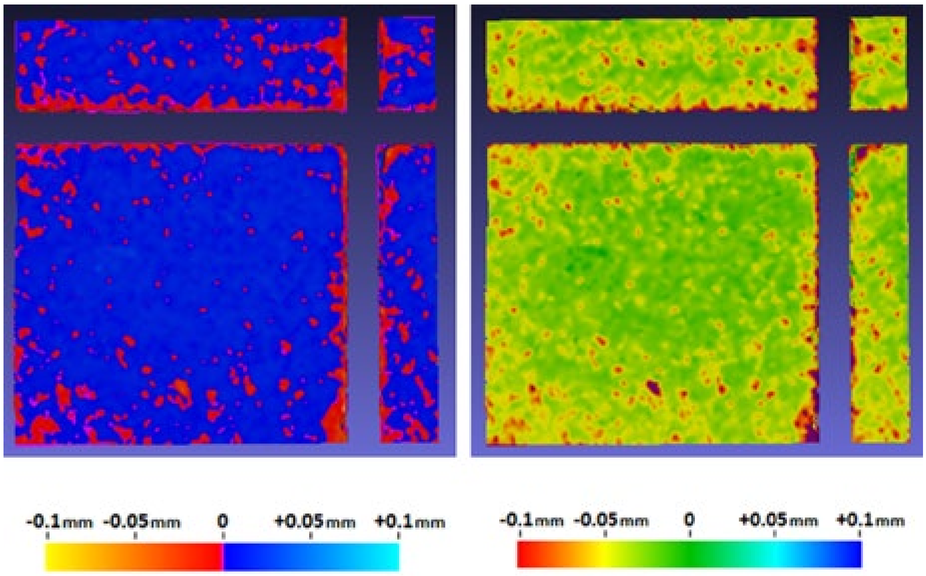

Fig.19. Differential Map of initial to eroded mesh for the frontal surface of the stone slab Elefsis Large 3 (EL3): (a) Slabs registered using ICP (blue indicates positive distances and red indicates negative distances); and (b) Slabs displaced in Z using estimated erosion value (red indicates most eroded areas and blue least eroded areas). Colours are mapped in the interval of [-0.1mm — +0.1mm]. Consider two point sets $M = \{M_1, M_2, \ldots, M_P\}$, that represents the initial surface of a stone, and $T = \{T_1, T_2, \ldots, T_Q\}$ that represents the weathered surface of the same stone, where M_i, T_j R^3. The distance $D_E(M_i) = \min_j(|M_i - T_j|)$ can be used as a local erosion measure which expresses at each vertex of the initial model M the distance of the closest vertex of the eroded model T, and is a scalar mapping of the erosion measure at each vertex of the initial stone model M, to which the eroded model T is registered. $|M_i - T_j|$ is the Euclidean distance of a point of M from a point of T. Figure 19 depicts the distance maps (i.e. the $D_E(M_i)$) between round 01 and 02 meshes of Elefsis Large 3, and consequently the computed erosion measure textured on the initial mesh.

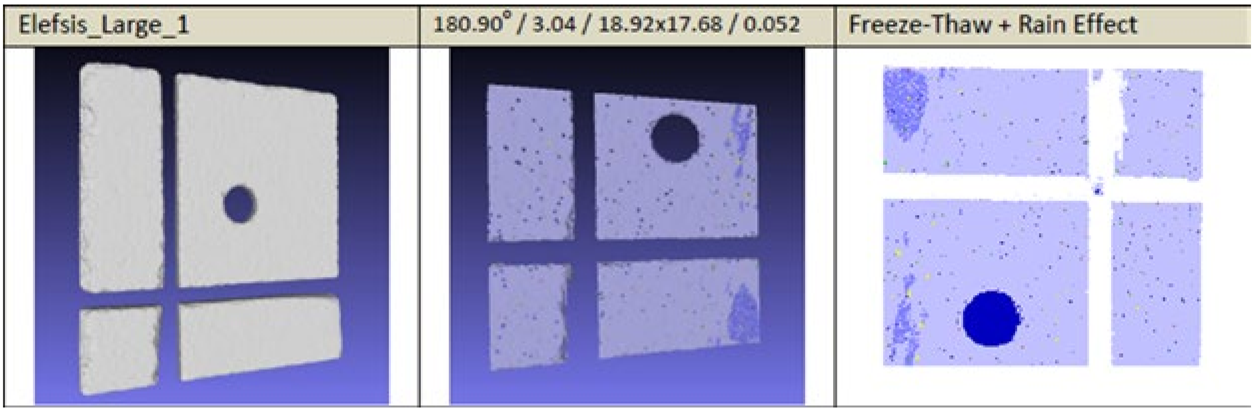

Fig. 20. Depiction of geometry and QEMSCAN registration results for the Elefsis Large 1 (EL1) marble slab.

approaches that have provided valuable information on the weathering processes and mechanisms.

Acknowledgments

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Bibliography

AICON 3D systems 2015. http://aicon3d.com/start.html

Arduino LLC 2015 http://www.arduino.cc/

Besl, P. J. and McKay, N. D. 1992. A method for registration of 3-D shapes, *IEEE Transactions on Pattern Analysis and Machine Intelligence* 14, 2: 239–56.

Doehne, E. and Price, C. A. 2010. Stone conservation: An overview of current research, Technical Report, Getty Conservation Institute, Los Angeles, US.

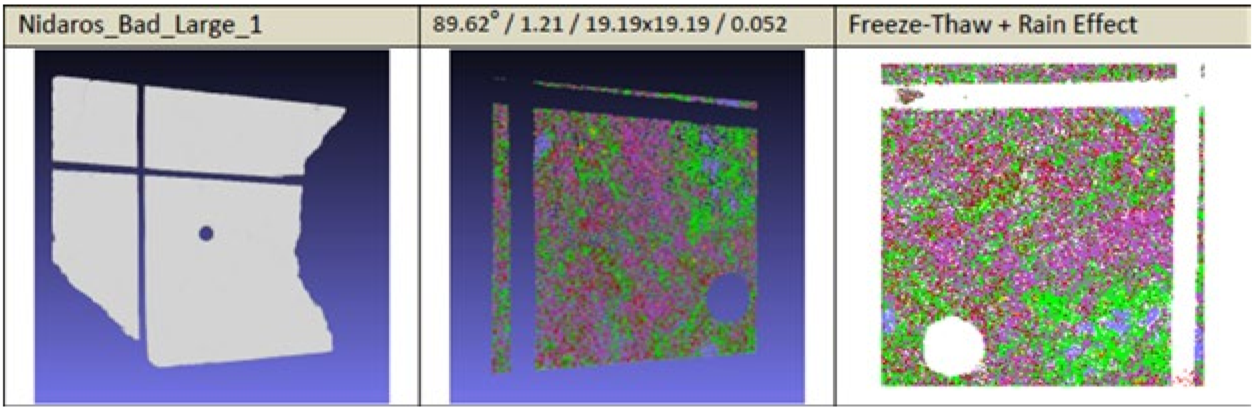


FIG. 21. DEPICTION OF GEOMETRY AND QEMSCAN REGISTRATION RESULTS FOR THE NIDAROS BAD LARGE 1 (NBL1) SOAPSTONE SLAB.

TAB. 6. SURFACE COVERAGE (% V/V COMPOSITION) OF THE MINERALS THAT APPEAR IN THE MINERAL MAPS OF THE VARIOUS STONE SLABS FOR THE TWO MEASUREMENT ROUNDS R01 AND R02.

Minerals	**EL1**		**EL2**		**NBL1**		**NBL2**		**NGL1**		**NGL2**	
% v/v	**R01**	**R02**	**R01**	**R02**	**R01**	**R02**	**R01**	**R02**	**R01**	**R02**	**R01**	**R02**
Quartz	0.21	0.17	0.03	0.01	1.27	1.42	1.71	0.71	1.90	1.48	2.22	1.83
K-Feldspar	-	-	-	-	-	-	-	-	-	-	-	-
P-Feldspar	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biotite	0.00	0.00	0.00	0.00	4.55	4.98	4.20	2.75	1.22	1.91	1.50	1.18
Illite	0.10	0.05	0.46	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chlorite	0.01	0.00	0.00	0.01	31.35	29.19	31.23	11.82	39.09	37.69	18.84	12.95
Smectite	0.00	0.00	0.00	0.00	0.94	0.94	0.74	0.37	0.46	0.46	0.76	0.98
Kaolinite	-	-	-	-	-	-	-	-	-	-	-	-
Glauconite	-	-	-	-	-	-	-	-	-	-	-	-
Calcite	93.89	89.86	98.06	97.07	0.21	0.20	0.00	0.04	0.32	0.16	0.52	0.65
Dolomite	4.13	4.28	0.20	0.42	2.34	1.62	0.13	0.17	2.85	2.54	9.67	8.85
Ankerite	-	-	-	-	-	-	-	-	-	-	-	-
Siderite	0.00	0.00	0.00	0.00	0.36	0.53	0.26	1.24	0.14	0.11	0.06	0.40
Gypsum	0.08	0.05	0.06	0.40	7.31	10.24	3.86	7.16	0.02	0.10	0.03	4.24
Pyrite	0.00	0.00	0.01	0.03	0.30	0.18	1.24	0.57	0.23	0.25	0.13	0.34
H-Minerals	0.02	0.02	0.03	0.01	5.93	6.76	5.30	6.71	4.51	7.23	5.18	6.41
Alt-Mafics	0.00	0.01	0.00	0.02	40.20	34.16	40.82	32.66	42.98	38.55	56.89	48.81
Pores/Void	1.32	5.52	1.14	1.62	3.18	6.65	2.34	30.62	5.70	5.76	3.81	9.39
Other	0.25	0.02	0.36	0.77	2.06	2.93	8.18	5.17	0.58	3.74	0.37	3.997

Gauri, K. L. & Bandyopadhyay, J. K. 1999. *Carbonate Stone, Chemical Behaviour, Durability and Conservation*, John Wiley & Sons.

Massey, S. 1999. The effects of ozone and {NOx} on the deterioration of calcareous stone', *Science of The Total Environment* 227, 2-3: 109-21.

Moropoulou, A., Bisbikou, K., Torfs, K., van Grieken, R., Zezza, F., Macri, F. 1998. Origin and growth of weathering crusts on ancient marbles in industrial atmosphere, *Atmospheric Environment* 32, 6: 967–82.

Price, D. G. 1995. Weathering and weathering processes. *Quarterly Journal of Engineering Geology and Hydrogeology* 28, 3: 243-52.

Robertson CGG (2015), 'http://www.robertson-cgg.com/'.

Schellewald, C., Theoharis, T., Gebremariam, K. F., Kvittingen, L. 2013. State of the art report on deterioration simulation, Technical Report PRESIOUS-D3.1, NTNU, Trondheim, Norway.

Scherer, G. 2006. Internal stress and cracking in stone and masonry. In Konsta-Gdoutos, M. (ed.), *Measuring, Monitoring and Modelling Concrete Properties*: 633-41. Springer Netherlands.

Storemyr, P. 1997. *The stones of Nidaros: an applied weathering study of Europe's northernmost medieval cathedral*, Unpublished PhD thesis, Norwegian University of Science and Technology (NTNU).

Storemyr, P. 2004. Weathering of soapstone in a historical perspective, *Materials Characterization* 53, 191-207.

Storemyr, P., Wendler, E., Zehnder, K. 2001. Weathering and conservation of soapstone and greenschist used at Nidaros Cathedral (Norway), in Lunde, Ø. and Gunnarsjaa, A. (eds.), *Report Raphael II Nidaros Cathedral Restoration Trondheim Norway 2000*, EC Raphael Programme - European Heritage Laboratory.

Varotsos, C., Tzanis, C., Cracknell, A. (2009), The enhanced deterioration of the cultural heritage monuments due to air pollution, *Environmental Science and Pollution Research* 16: 590-2.

Verges-Belmin, V. 2008. Illustrated glossary on stone deterioration patterns = glossaire illustre sur les formes d' alteration de la pierre, Paris: ICOMOS (International Council on Monuments and Sites) and ISCS (International Scientific Committee for Stone). English-French ed.

Yerrapragada, S., Chirra, S., Jaynes, J., Li, S., Bandyopadhyay, J., Gauri, K. 1996. Weathering rates of marble in laboratory and outdoor conditions, *Journal of Environmental Engineering* 122, 9: 856-63.

Yerrapragada, S. S., Jaynes, J. H., Chirra, S. R., Gauri, K. L. 1994. Rate of weathering of marble due to dry deposition of ambient sulfur and nitrogen dioxides, *Analytical Chemistry* 66, 5: 655-9.

The New Trend of 3D Archaeology is … Going 2D!

Giuliano De Felice
giuliano.defelice@unifg.it
Digital Archaeology Lab, Foggia University, Italy

Abstract: Nowadays we cannot imagine any archaeological activity – fieldwork, lab work or historical analysis and synthesis – without the support of information technologies. 3D is an important part of this scenario, considering that archaeology is a reality composed of 3D entities that have to be analysed, understood and reconstructed. It comes as no surprise, therefore, that the 3D reconstruction of monuments and sites is one of the most important applications of IT to archaeology, given its ability to recreate, in a perfect and realistic form, something that no longer exists with a strong visual impact. But what if we move our aim from visualisation techniques to content? If we focus on communication aspects, we need to consider the fact that 3D may not always be the right solution: if our goal is to make the real meaning of archaeology fully understandable to a wider audience we need something more: we need a story.

Keywords: 3D archaeology, Storytelling, Digital animation, Popular communication

1 State of the art

It is impossible to imagine any archaeological activity today that does not have the support of digital technologies: their impact on archaeology has grown continuously over the last few decades. Digital technologies have become so rooted in the procedures of analysis, recording, interpretation and reconstruction that we might even begin think of the advent of a veritable digital archaeology in the near future (Evans, Daly 2006), in which the application to archaeological methodology of tools devised for other purposes will not only speed it up, automate it and make its results more efficient, but also transform it from the inside, by exploiting and supporting the innovations that digital has to offer. This is not only true of archaeology: the same kind of integration can be clearly perceived throughout all fields of cultural communication, in which it plays a growing and expanding role.

But what are the terms of this growing interaction and what can we expect for our field in the future? The challenge in the coming years will certainly not be to continue to spread digital technologies but rather to elaborate a new methodology (Barcelò 2009) that fully exploits their cultural potential. The real objective, in other words, is not to be confused therefore with technological development, which, as we can easily imagine, will grow enormously and will always lead to experimentation with new tools and solutions, in archaeology as well; but rather to construct a new and richer integration which aims to make the archaeology of the future a shared, public and sustainable one (Volpe, De Felice 2014).

In short, the new approach to a better integration between archaeology and digital technologies must necessarily overcome the present phase of 'triumphalism' (Orlandi 2009) and proceed to a complete renewal of methods (Forte 2007: 5-6; Forte, Dell'Unto, Issavi, Onsurez, Lercari 2012) involving all sectors and a wide span of possible technical solutions (Doneus, Neubauer 2006; Lieberwirth, Fritsch, Metz, Neteler, Kühnle 2013) for research, training, safeguarding, but also the profession itself, including communication (Rua, Alvito 2011; Tsiafaki, Michailidou 2015). Indeed, communication is the real channel between the discipline and the public (Fowler 2007: 90), the true path to follow toward the transformation of archaeology from a self-referential discipline to a tool for cultural growth, which is not merely illusory, but increasingly real and self-aware (Kulik 2007: 112). This means continuing to shift the objective from ever-more advanced technologies to the quality of the contents, to identifying the right languages for communication and creating the right styles for visualisation.

Historically, the rise of virtual archaeology has always been supported by the desire to recreate in 3 dimension a complex and stratified reality; on one hand renewing the documentation methods using 3D survey and analysis technologies and on the other using the potentials of computer graphics to transmit research hypotheses and reconstructions.

On the side of analysis, documentation and interpretation, the technologies of ever-more rapid and efficient three-dimensional surveys have greatly improved the phases of data collection and analysis, contributing to develop new documentation methodologies both in a site or landscape perspective. The use of 3D spatial analyses, Digital Terrain Models or large-scale 3D surveys is deeply changing the core of archaeological research. This is hardly strange when we consider that the reality investigated by archaeology is made up of three-dimensional entities that have to be measured, analysed, understood and reconstructed (Barcelò 2001).

On the side of reconstruction, digital technologies have provided valid solutions for reconstruction, visualisation and interpretation. Fascinated by the prospect of technologies that can make the process of reconstruction both rapid and precise, archaeologists have soon embraced new visualization technologies for their communicative purposes. It is not surprising that the reconstruction of monuments and sites represents today one of the most important applications of 3D digital technologies to archaeology, given their capacity to measure and recreate, in a perfect and realistic style, something which no longer exists. Relying on such strengths, 3D visualisation is today the principal medium of archaeological communication: the demand for multimedia products in museums and parks or other cultural institutions remains high, while the pursuit of ever more beautiful and attractive products is in full swing.

Nevertheless, a side effect of this approach to 3D technologies for communication is that sometimes it is the technologies that are exhibited, and archaeological heritage has sometimes swiftly become a collection of finds and monuments from which to choose, case by case, the one that will most enhance the technical capabilities of computers and software. 3D surveys of entire monumental complexes or ancient art objects, immersive models of famous archaeological sites, as well as high quality virtual reconstructions have drawn the attention away from other components of archaeology: its deductive processes, its interpretative ends, its social vocations. Indeed, archaeology is not only concerned with individual finds or huge monuments; on the contrary, it deals every day with fragments (of a whole that no longer exists) and seeks to reconstruct activities, stories, visions, cultures, of which those fragments are often the only traces. This notion, however, is not always sufficiently represented in the world of virtual archaeology, where it could constitute the basis of communication strategies by promoting more profound interconnections between research and divulgation.

2 Toward a new digital communication in archaeology

Today much of the virtual game of archaeology still involves the creation of breath-taking reconstructions and models; the rapid and uninterrupted development of computer graphic techniques seems to be taking archaeological communication (and hence most of virtual archaeology) toward what we might call a virtual neoclassicism (De Felice 2012; 2014): while archaeology continues to construct its own digital perspective (Evans, Daly 2006), the rest of the world does not seem to have realised this at all and still seems to consider it as an adventurous occupation (Brittain, Clack 2007: 16), delving into ancient secrets, strange objects and mysterious monuments, or else a dry and dusty routine of observation and cataloguing. The basic problem, therefore, is not guaranteeing, along with design quality, the scientific accuracy and reliability of the contents (Brittain, Clack 2007: 24), which should be an indisputable prerequisite, but rather to experiment with potential new forms of communication.

So what are the terms for constructing something new? This theme obviously goes beyond the limits of this paper, although I shall attempt to describe here some of the Digital Archaeology Lab's activities whose objective has been experimentation with a different approach to archaeological communication. But first some premises are necessary.

Foremost, every archaeological site, and every single find, is a complex item, which has had a long life, accumulating and superimposing many chapters of history. A site, for example, is a three-dimensional object (although these reflections can be applied perfectly well to any class of object, from the smallest fragment to the most extensive landscape); it is characterised by a multiplicity of evidence, which can be translated and recounted following various interpretative paths, not only by reconstructing its material form:

- the documentation, that is, the nearest point to a reality no longer existing.

- the diachronic dimension, that is, the successive phases of life and abandonment that are superimposed in every single object.

- the various hypotheses, which are the result of the interpretation.

- the material remains.

In other words, the significance of an archaeological object is more complex than its material aspect (Barcelò 2003; Carver 2011) and is profoundly linked to the story it conceals and yet could reveal. In only a few cases can an archaeological site be attributed to a single phase of life and just as rarely can the function of a find be easily understood. Indeed, alongside the archaeology of the monument and masterpiece there is another kind of archaeology: one which sees archaeologists involved daily in toilsome excavations without any glory, both for scientific research and professional activity. Excavations, or more generally field research (for example, the survey), rarely lead to clamorous discoveries but rather they amass, datum after datum, a quantity of knowledge which is cumulative: the same quantity of knowledge that is accumulated in archives and academic publications, in that 'grey literature' which constitutes the greater part of our knowledge and so is also the main vehicle of communication for archaeology. This is a corpus of writings destined for experts, which rarely comes into contact with didactic communication, except for being, in some cases, its remote source.

So, undoubtedly, the greatest challenge for the future of archaeological communication is that of finding new connections between technical solutions and the expressive potentials of the discipline (Forte 2006), which can go beyond the attention toward the material and monumental aspects, and aim instead to use the data and information that are the true assets of archaeological heritage and the work itself of professional archaeologists. So new languages and expressive forms are needed, which can overcome the tendency toward photorealism and an anachronistic concept of reconstruction. What is needed is the creation of writing styles and narratives that can animate the bulk of knowledge scattered throughout archaeology. Apart from requiring formal perfection and the visualisation of hypotheses in high resolution, we could require digital technologies to support a narrative plot, to tell a story, to help transmit cultural messages in different ways and forms.

3 From technologies to contents

What happens when we shift our interest from the techniques of visualisation to the contents? From the viewpoint of the message conveyed, what types of products are the outcome of the application of 3D computer graphic technologies to archaeology? The impression is that, to the detriment of a methodological evolution, which has shifted the focus from the monument to the site and from the object to the context, there persists an interest by 'virtual archaeologists' for the monumental and antiquarian dimension of archaeology, which I have called virtual neoclassicism.

But in the dissemination of archaeology, as in any other scientific discipline, it is always better to start from the need to consider objects and contents first and foremost and then to select the right technique or technology for their realisation. If we start with this consideration, we can easily reach the conclusion that sometimes 3D might not be the ideal solution. No one is trying to deny the multidimensional nature of the archaeological record, but the fact remains that every man-

Fig. 1. The archaeological collection at Palazzo Branciforte. One LCD panel in the foreground.

made fact, every eco-fact or site, is always more complex than its material aspect and that even the most accurate 3D survey and the most amazing 3D reconstruction are merely parts of the research process, or rather tools that can support interpretation.

If our goal is to make fully understandable to the public the true significance of archaeology – that is, the process of analysis / synthesis, recording / reconstruction – then a 3D model is not enough; we need a story. And in certain cases it might happen that the story an archaeologist can imagine in order to describe the results of his/her research, is not 'compatible' with the language of 3D computer graphics, but can be better conveyed by other expressive means, which can transmit and translate the messages such research bears for the community.

And so here is the next step, which has involved the Digital Archaeology Lab (LAD) of Foggia University in the production of a series of CGI films as part of the activities of the project Living Heritage, concluded in March 2015. The broader project has led to the realisation of a framework of storytelling for cultural assets, that is, to the production of narrative episodes which do not require specific technical skills but which allow the authors to create an app (see De Felice 2013b, De Felice, Santacesaria 2013 and De Felice 2015 for a more detailed description of the project) and distribute it in the major stores, both for mobile devices and desktops. In any case, perusing the episodes is extremely intuitive and simple and comes about through simple gestures on a touch screen or with the mouse on a desktop.

The storytelling framework allows for the creation of episodes composed of different scenes, cartoon strips and other types of content, but it also envisages user interaction with a series of materials for a more in-depth analysis, in a separate menu. In this way the narrative and the scientific contents are kept separate yet linked by a story. The follow-up materials can be of different types: texts, audios, images and, of course, videos.

The first experiment with this framework was the exhibition (in 2012–13) of the archaeological collection of the Fondazione Sicilia in the Palazzo Branciforte in Palermo (De Felice 2013a), for which 23 narrative episodes were created, dedicated to Greek ceramics and their social, technical and iconographic aspects (a demo is available at www.branciforte.archeologiadigitale.it).

The interaction between the 5000 objects (mostly pottery) of the archaeological collection and the visitors to the museum has been entrusted to a natural gesture interface based on common multi-touch gestures like tap, swipe, pinch and so on. By simply touching the screen of two large LCD panels installed in the museum, the visitor can browse a network of 46 different episodes linked to the history of Greek Sicily, in which the main inspiration comes from pottery and material culture. By moving objects, playing games, reading texts, browsing through images the visitor can build his/her own itinerary, experiencing a visit to the museum that is always new.

The inspiration for both the contents and the staging techniques was the vast repertory of images on the vases in the collection, given that there were not a lot of data allowing for a detailed setting of the collection pieces, which moreover lacked any context related to their discovery, as often happens in archaeological museums, in which the quantity of exhibited objects and the absence of a narrative thread create an alienating effect that does not arouse the visitor's curiosity. The second, and final, experiment, for which three episodes were created, was in the archaeological museum in Bari, which is about to reopen in a new home after being closed for 20 years (De Felice 2013b).

In both cases, among the contents populating the episodes were some brief animated clips (from 30 seconds to a minute in length) produced with computer graphics, which were inspired by the respective collections, especially the antique ceramics, and by the anthropological, social and technical aspects which these objects convey. Greek vases in the case of Palazzo Branciforte, indigenous vases from the Peucetian culture in the case of the archaeological museum in Bari. In both cases, right from the start of collecting source materials, (for the work flow see De Felice, Santacesaria 2013), it was clear that an accurate reconstruction, of the structures, homes, landscapes and so on, of these elusive peoples (for whom we have only a few traces, related to their homes and material culture) would be impossible, given the scarcity of existing studies on them and the objective difficulties of interpretation and reconstruction.

Finally, both experiments were dedicated to contexts from which it was difficult to extract data or sources of inspiration, contexts in which the finds are the 'mute' testimony of a remote world that is difficult to reconstruct. Nevertheless, it is important to reiterate, this state of affairs does not represent an exception in the archaeology of the 'everyday', which is far removed and different from the archaeology of the outstanding discovery, of the monument and the masterpiece. There are many archaeological sites and museums containing objects, finds and structures that are as numerous as they are humble, as fragmentary as they are incomprehensible.

So in order to respect and enhance this 'everyday' archaeology, not only is it possible but absolutely necessary to devise a different kind of communicative style, one that goes beyond the monumental reconstruction, which is inapplicable to such contexts. If the 20th century has taught us that archaeology is not a study of monuments but a quest for humankind and its activities, often these reflections, which are now held to be self-evident by the archaeological community, do not reach the public and society in general, for which archaeology continues to be confused with a treasure hunt.

In both cases a narrative idea – or in cinematographic terms, a subject – was immediately sought. Since computer graphics is a cinematographic technique in the full sense, it was deemed wise to follow from the beginning a process resembling the production of a film, beginning with the subject and screenplay and then moving on to the work of storyboarding. Not only. In the initial concept, the style should be considered as an integral part of the narration, since it is the fundamental visual vehicle. Computer graphics was therefore required to play the role that suits it best: creating an imaginary, invented style.

In other words, the thrust of our argument has been from the beginning to temper adequately style with content; and so straight away the idea of entrusting ourselves to photorealism seemed inappropriate, for at least two reasons:

- the glaring contrast between image quality and available data scarcity.
- the sustainability, given that the production cost in high resolution would have used up almost all the available resources to the detriment of other parts of the project.

In addition, a simple style is more sustainable to a small team, not only because it is less burdensome in terms of hardware, but also because it opens the door to animation, even from a technical viewpoint, constituting the true purpose for which CGI programmes have been developed: not just static image creation but proper animation. Indeed, there are cases in which our knowledge of certain aspects of the past is not sufficient for a technical 'reconstruction'. Yet there are also cases in which creativity can fill the gaps left by a lack of data and information, and become the prime vehicle of communication.

The videos produced for the Fondazione Sicilia are dedicated to showing the link between the static scenes on the vases, especially the representation of sporting events, and the movements to which they clearly allude (Fig. 2). In this case the link between image and scientific knowledge is highlighted by the animation, which creates a mini-story around a sporting event or gesture: long jump, javelin throwing, apobates, discus throwing all come to life on the surface of the vases and give a meaning to an action which would otherwise be incomprehensible in its static state. The desire to make a direct connection between the animated scenes and the originals has also influenced the style, which has remained strongly two-dimensional as a tribute to the iconographic culture of Greek ceramics.

On the other hand, the four videos called *Pazzi da museo* – the Italian expression is a pun on the word *pezzo* (piece) and *pazzo* (crazy) – produced for the archaeological museum in Bari are the deliberately ironic and clamorous result of a choice: to convey a message containing what little knowledge we have acquired about the Peucetians, using a simple and ironic style. The distance between the seriousness of the captions and the irony of the short clip is intended to help familiarise the public with what basic knowledge we have of this civilisation.

Actually, we know very little about the Peucetians (and we could say the same about many ancient peoples) except for their ceramics (*idem*), which is practically the only source with a visual element. Peucetian geometric vases are decorated with a myriad of motifs, amongst which stand out those with phytomorphic, zoomorphic and anthropomorphic elements, which represent the only visual traces of this population; traces which are slim and fragmentary, true, but nevertheless original, going straight back to the men who made them. In order to respect these traces and to enhance their uniqueness we decided to use the decorative motifs on the vases in order to create the setting for the clips.

4 Archaeology as a story

In both experiments the uniqueness of the context encouraged us to elaborate a style in which the objects' distinctive elements were not only represented, but constituted the *imaginarium* in which to set the stories, which were reconstructed from the specific scientific literature in each case. The style is necessarily and rigidly two-dimensional, as is almost all of ancient vase painting. Indeed, we must not confuse the plasticity of the support with the absolute flatness of the message it conveys. In the end, 3D computer graphics is merely a branch of computer graphics, a tool that belongs to the world of make-believe. Authoring software itself is just a tool for creating special effects, and is directly linked to the film industry, and more generally to the world of special effects. So it is clear that before choosing the tools with which to produce a communicative act we first need to think of a narrative plot, a director, a setting, perhaps the actors too, and so on.

Telling even a short story is indeed the best way to catch and enthral the public's attention. Telling and listening are

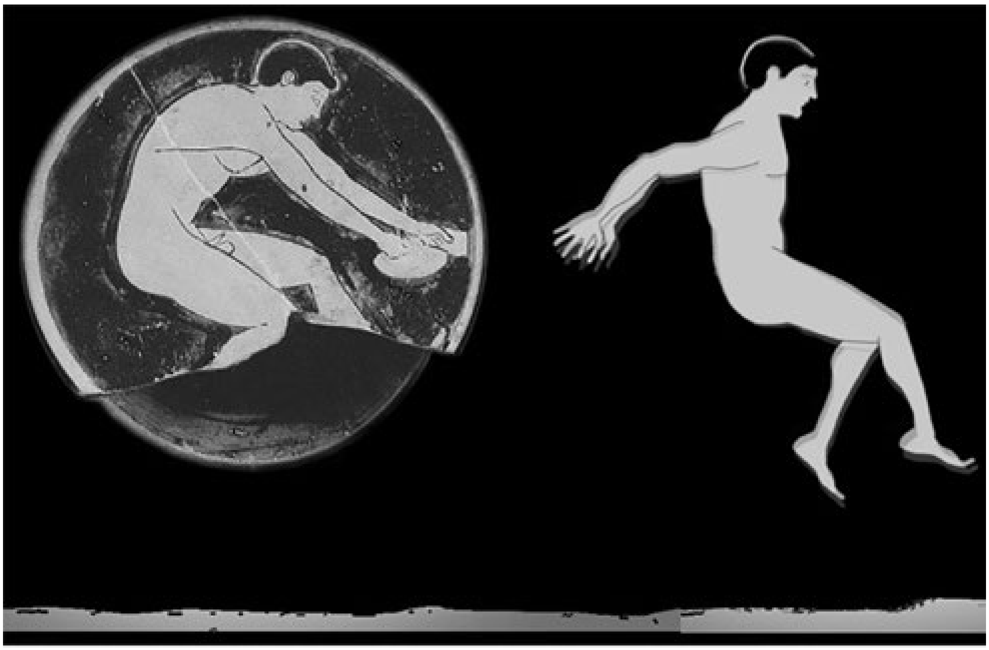


Fig. 2. From picture to animation. Long-jump scene.

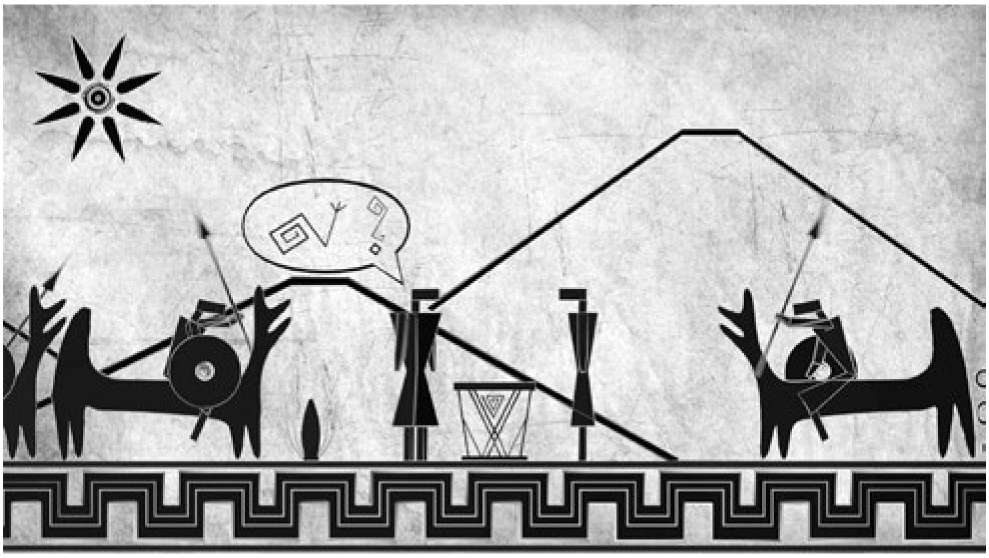


Fig. 3. A still image from 'how I won the war' videoclip.

profoundly human and perfectly serviceable ways to convey even the most difficult scientific concepts. And narrating is a true operation of reconstruction, since only in the moment of exposition to the public can we truly understand not only the object of the narration, but also the best way to make it comprehensible. Reconstruction by archaeologists is very similar to narration, since it concerns not only the material and monumental aspects, but also fully embraces the imaginary dimension. So it should never be confused with anastolysis, which restores an object to one of its many phases of life (whether in virtual mode, material, miniature or full-scale).

More generally, perhaps the basic issue is not guaranteeing the high-quality design, accuracy and reliability of the scientific contents (Carver 2011; Kulik 2007) which should be indisputable prerequisites in any case – but rather experimenting with new forms of communication. In other words, the story first of all! But the good news is that archaeology is already a story just waiting to be told. So in undertaking a communication project about archaeology, the first question to ask ourselves is 'what story do we want to tell?', next 'who do we want to tell it to?', and only then can we ask ourselves 'what is the best means for doing so?'.

All the videos quoted in the paper are on Giuliano De Felice's YouTube channel.

Bibliography

Barceló, J. A. 2003. Visualizing what might be. An introduction to Virtual Reality techniques in archaeology. In J. A. Barceló, M. Forte, D. H. Sanders (eds.), *Virtual Reality in Archaeology*, British Archaeological Reports International Series 843: 9–35. Oxford, Archaeopress.

Barceló, J. A. 2001. Virtual reality for archaeological explanation. Beyond 'picturesque reconstruction'. In *Archeologia e Calcolatori* 12: 221–44.

Barceló, J. A. 2009. *Computational Intelligence in Archaeology*, Henshey.

Carver, M. 2011. *Making archaeology happen. Design versus dogma*, Walnut Creek.

Clack, T., Brittain, M. 2007. *Archaeology and the media*, Walnut Creek.

De Felice, G. 2012. Una macchina del tempo per l'archeologia. Metodologie e tecnologie per la ricerca e la fruizione virtuale del sito di Faragola, Bari.

De Felice, G. 2013a. Living Heritage – A living lab for digital content production focused on cultural heritage, in *Digital Heritage 2013: Proceedings of the first international congress on digital heritage (Marseille, France, 28 Oct – 1 Nov 2013)*: 391–4.

De Felice, G. 2013b. Il nuovo allestimento della collezione archeologica della fondazione Sicilia fra tecnologie e creatività. In *Archeologia e Calcolatori* 24: 249–64.

De Felice, G. 2014. Racconti dalla terra. L'archeologia fra linguaggi, creatività e tecnologie. In *Opening the Past*: 24–7.

De Felice, G., Santacesaria, V. 2013. A living lab for digital content production focused on cultural heritage. In L. Marchegiani (ed.), *Proceedings of the International Conference on Sustainable Cultural Heritage Management, Societies, Institutions and Networks*: 299-306. Rome.

Doneus, M., Neubauer, W. 2004. Digital Recording of Stratigraphic Excavations. In K. Fischer-Ausserer, W. Börner, M. Goriany and L. Karlhuber-Vöckl (eds), *Enter the Past. The E-way into the four Dimensions of Cultural Heritage. CAA 2003, Computer Applications and Quantitative Methods in Archaeology*, British Archaeological Reports International Series 1227: 113–6. Oxford, Archaeopress.

Evans, T. L., Daly, P. 2006. Digital Archaeology. Bridging Method and Theory, London.

Forte, M. 2006. Tra conoscenza e comunicazione in archeologia: considerazioni in margine alla terza dimensione. In Campana, S., Francovich, R. (eds.), Laser scanner e GPS: paesaggi archeologici e tecnologie digitali 1, Atti del convegno, Grosseto, 3 March 2005: 26-40. Firenze, All'Insegna del Giglio.

Forte, M., Dell'Unto, N., Issavi, J., Onsurez, L., Lercari, N. 2012. 3D Archaeology at Çatalhöyük, *International Journal of Heritage in the Digital Era* 1, 3: 351-78.

Forte, M. 2008. *La villa di Livia. Un percorso di ricerca di archeologia virtuale*, Roma.

Kulik, K. 2007. A short history of archaeological communication. In T. Clack, M. Brittain (eds.), *Archaeology and the Media*: 111–124. Walnut Creek, Left Coast Press.

Lieberwirth, U., Fritsch, B., Metz, M., Neteler, M., Kühnle, K. 2015. Applying Low Budget Equipment and Open Source Software for High Resolution Documentation of Archaeological Stratigraphy and Features', in A. Traviglia (ed.), *Across Space and Time, Papers from the 41st Conference on Computer Applications and Quantitative Methods in Archaeology (Perth, 25-28 March 2013)*: 7-22. Amsterdam, Amsterdam University Press.

Rua, H., Alvito, P. 2011. Living the past: 3D models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage – the case-study of the Roman *villa* of Casal de Freiria'. In *Journal of Archaeological Science* 38: 3296-308.

Orlandi, T. 2009. Informatica archeologica e non archeologica. In *Archeologia e Calcolatori* 20: 17–26.

Tsiafaki, D., Michailidou, N. 2015. Benefits and problems through the application of 3d technologies in archaeology: recording, visualisation, representation and reconstruction. In *Scientific culture* 1, 3: 37-45.

Volpe, G., De Felice, G. 2014. Comunicazione e progetto culturale, archeologia e società. In *European Journal of Post-Classical Archaeologies* 4: 405–24.

Documentation and Analysis Workflow for the On-going Archaeological Excavation with Image-Based 3d Modelling Technique: the Case-study of the Medieval Site of Monteleo, Italy

Giulio Poggi
giuliopoggi87@gmail.com
LTTM, Department of Historical Sciences and Cultural Heritage,
University of Siena, Italy

Abstract: The proposed method consists of a systematic 3D documentation of each archaeological stratigraphic unit and of a procedure, entirely based on 3D data, for management and analysis. This method has been initially developed to meet quality requirements and to improve the informative potential of the archaeological documentation at the excavation of Monteleo (Italy), a late-medieval alum production site, investigated by the University of Siena since 2008. The sector documented in 3D measures 80m², and more than 60 stratigraphic units have been 3D modelled and geo-referenced. Then the models have been contextualized in 3D GIS system, where the cognitive significance of each model is enhanced by the interaction with several 3D models and the interface with different types of data (photographs, geographical-spatial data and alphanumeric data). This platform enables several types of 3D data analysis, among which, one of the most promising, is the automatic volume computation of the layers. This analysis provides important information to archaeologists for enhancing the quality of the archaeological interpretation.

Keywords: Image-Based 3D modelling, 3D Documentation, 3D GIS, Volume computation.

Introduction

Nowadays the Image-Based 3D modelling technique has been tested successfully, both in terms of geometric precision and versatility, in the documentation of many different archaeological contexts. Besides these great qualities, the large spread of its application in archaeology is due to other important factors such as the low-cost impact on research funds and the linear operation, which allow good results to be obtained more quickly than with conventional method. Among the vast literature about this topic, in many cases 3D models are simply handled as a standalone product, separate from the data coming from different sources and used mainly for their geometric precision and visual impact (Barceló 2000). In this way the informative potential of 3D data remains partially unexploited. What is important to focus on, is that 3D recording technologies generate a type of data that must be managed and processed in a different and proper way, preserving its own unique properties while remaining in compatibility with the archaeological research methods. These technologies generate an 'objective' documentation, which carries information (such as geometry, structure and colour) that is not directly filtered by the interpretation of the archaeologist on site. Different recording technologies and methods produce different types of complementary data, each one with its own unique informative potential and its individual management process (D'Andrea 2006).

The procedure proposed in this paper is based entirely on 3D data and covers the whole archaeological research process, from documentation, to management and analysis, up to the disclosure steps. The main difference between this method and the conventional documentation system lies not in the variation of the research process, which remains unchanged, but it lies in the different conditions, timings, and approach towards the context, depending on the specific requirements of each instrument and of the data we are dealing with.

The method will be demonstrated with particular reference to the compatibility with the conventional documentation system used at the excavation of the site of Monteleo, conducted by the University of Siena since 2008. Some of the most promising features of this method will be discussed.

1 The case study: the site of Monteleo

Since 2004 the School of Medieval Archaeology of the University of Siena has been carrying out an archaeological survey on the territory of Monterotondo Marittimo, in south-west Tuscany, Italy. The aim of this research is to define the diachronic settlement tendencies and clarify the mutual interactions with the exploitation of the natural resources in this part of the Colline Metallifere, a territory particularly rich in mixed sulphates and alunite. In the narrower area of the site of Monteleo, some topographical analyses have identified substantial evidence of the presence of an ancient 'allumiera', a small geographic area where the mineral alunite [KAl3(SO4)2(OH)6] was extracted and transformed into alum [$KAl(SO_4)2 \cdot 12H_2O$] (Dallai, Poggi 2012). Alum was a very important salt in the past: it was used for its astringent and corrosive properties in the tannery, metallurgy, pharmacy industries, and in the conservation of food, amongst others. In the area of Monteleo some quarry faces, bore holes and tunnels were identified and a battery of four XV century kilns for the calcination of the alunite has been excavated.

Since the beginning of the excavation, the strict relation between the archaeological deposit and the vestiges of the productive plants, today still standing and well preserved, has been pointed out very clearly. After being abandoned these structures were completely covered by destruction layers, and for that reason evident traces of restoration, structural changes and collapses are still visible (Dallai, Poggi 2012). It is possible to recognize each action of the productive process in different detectable traces, some of them visible in the structure and

Fig. 1. The territory of Monterotondo Marittimo.

Fig. 2. The battery of four kilns for the calcination of the alunite.

others in the layers which form the stratigraphic deposit, inside and in front of the structure itself. The connection of these traces is fundamental to address elements spatially disconnected to the same action of the productive process, returning important information for understanding the nature, quantity and speed of the production of the calcination kilns. In this perspective, the recording of the third spatial dimension through an appropriate documentation method is fundamental to enable the connection between vertical architectural stratigraphy and the horizontal archaeological deposit.

2 Digital methodology

An Image-based 3D Modelling technique has been chosen to obtain an accurate and reliable documentation of the context in three dimensions. This technique elaborates 3D models through the automatic matching and processing of a set of uncalibrated photographs, taken on the scene following specific rules. Image-based 3D modelling combines some photogrammetric basics with algorithms developed by the scientific branch of Computer Vision (Remondino, El-Hakim 2006), producing 3D models with high geometric precision and textures with colour information. Moreover, high quality results can be obtained with basic equipment (a digital camera and a PC or notebook), to keep archaeological research costs down. Agisoft Photoscan was chosen for its clear and linear operation, which provides reliable and high quality results in full compatibility with the needs of the archaeological excavation (Doneus *et al*. 2011).

A preliminary evaluation of interactions and compatibility between the 3D model acquisition process, specific for the use of this technique, and the methodology of the archaeological excavation, is a fundamental step. This evaluation provides the basis for developing a reliable, flexible and accurate 3D documentation method that would be compatible with the specific methods and timings of the archaeological fieldwork in a specific context of application (Forte, 2012). The proposed method consists of a systematic 3D documentation of each archaeological stratigraphic unit, according to the methodology defined by the consolidated conventional documentation, and the development of a procedure for management and analysis, entirely based on 3D data. In Monteleo this 3D documentation method has been tested and developed since 2012 in an 80m^2 sub-area of the entire excavation area, where more than 60 stratigraphic units have been recorded and modelled. The procedure can be summed up in three steps: 3D recording, management and analysis.

2.1 3D recording

The key point of a functional documentation system is that the process must be perfectly integrated into the methodology of the discipline where it applies. Therefore the 3D recording process must be carried out in parallel with the conventional documentation method, observing its timings and methods. With Image-based 3D modelling this goal is easily accomplished because the on-site acquisition usually takes a very short time, even less than the hand drawing method. Moreover, this task involves only one operator, who can supervise the documentation of a whole area and can validate in real-time the quality of each elaboration, repeating, when necessary, the acquisition of the photographs before the stratigraphic unit is excavated.

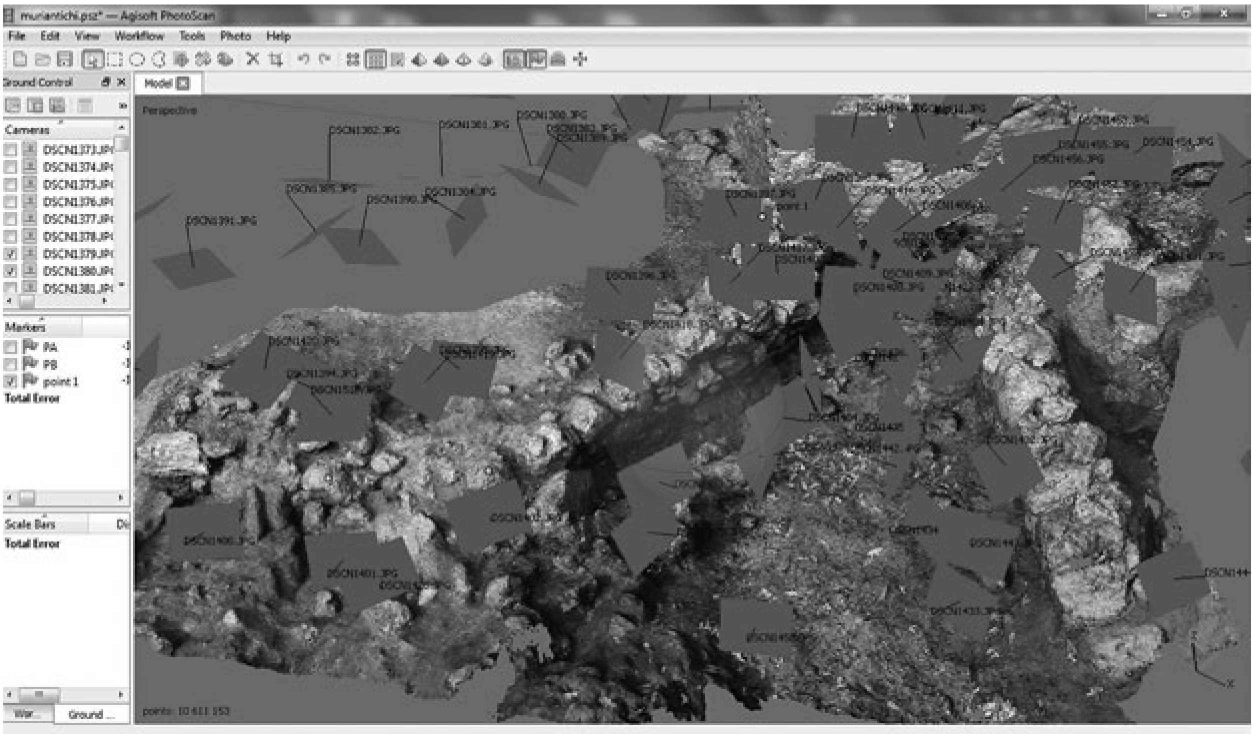


Fig. 3. Agisoft Photoscan. The scene is modelled from an unordered set of pictures. The output of the elaboration process is a textured 3D mesh.

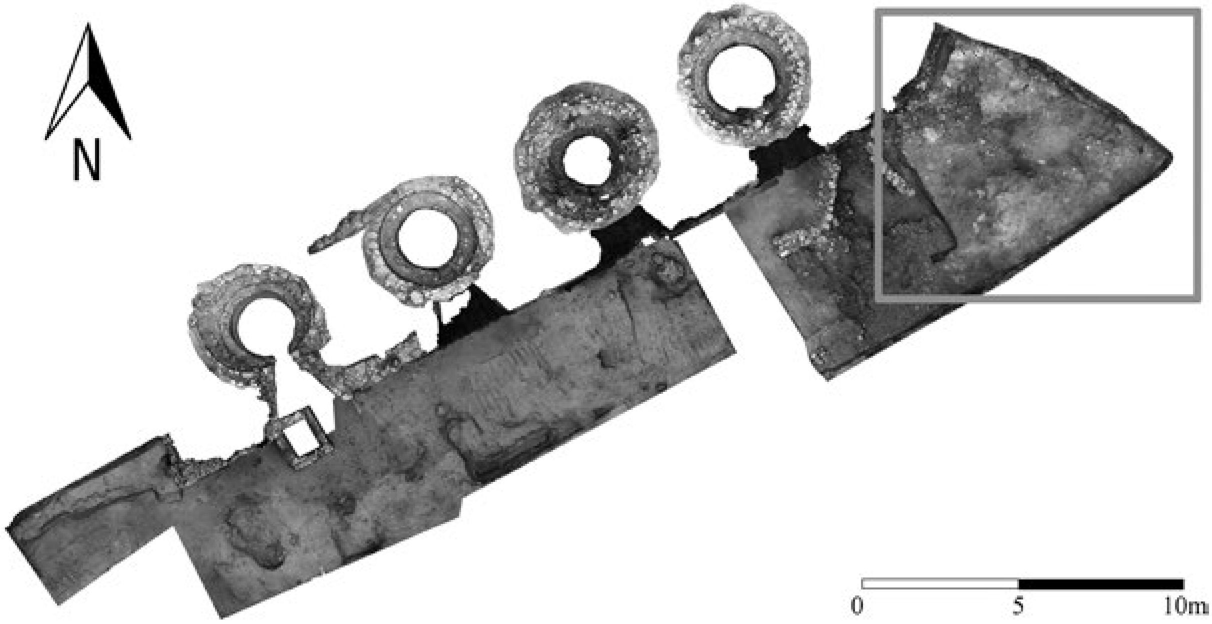


Fig. 4. The site of Monteleo: Orthographic views of the battery of four alunite kilns and of the excavation area. The sector where the 3D documentation method has been tested is outlined.

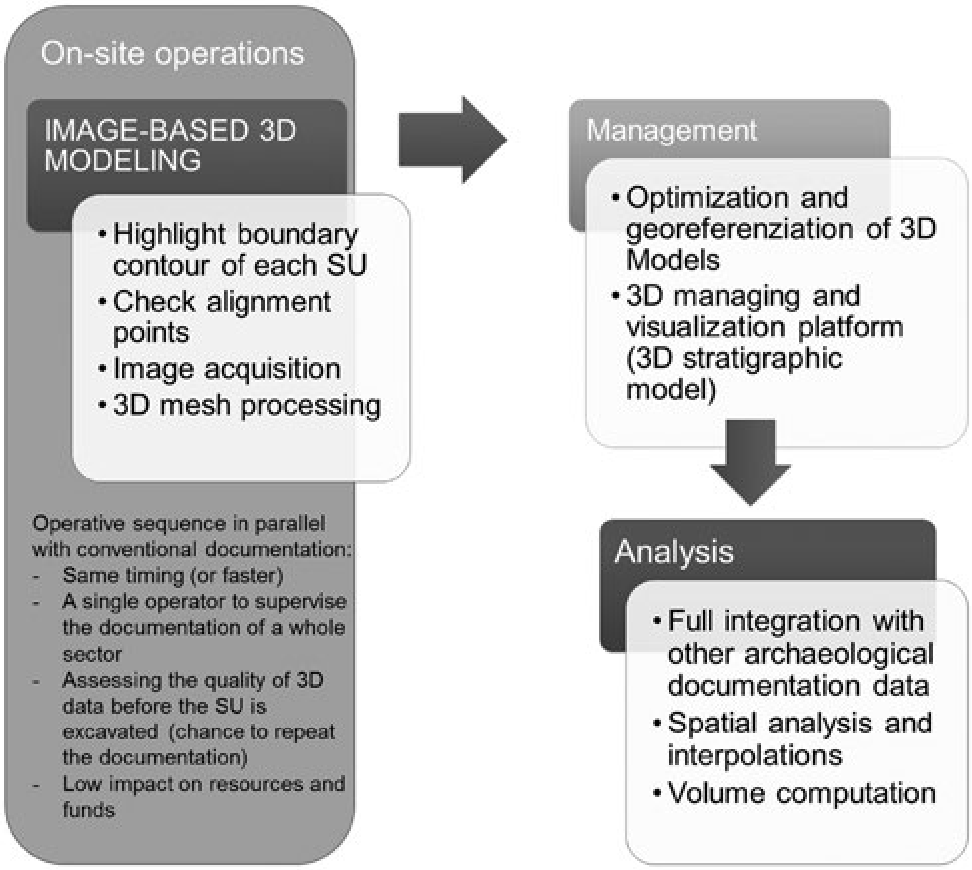


Fig. 5. The procedure for documentation, management and analysis.

Even if the process of excavation can be considered ‘subjective’, because it is highly influenced by the personal interpretation of the archaeologists on the field, the Image-based 3D modelling ‘objectively’ records the condition of the stratigraphy in a certain moment during that subjective process. Consequently we obtain a kind of documentation that is not further affected by the archaeologist’s on-site interpretation. This greater objectivity makes it possible to assess afterwards, in a 3D visualization and management platform, the quality of the excavation process, to formulate new hypotheses and interpretations, and to let those archaeologists who were not participating personally in the excavation give their personal opinion (Dellepiane *et al*. 2013).

To exploit their full informative potential, 3D data must be processed together with data coming from other sectors of the research. For example, the definition of the boundary contour of the stratigraphic units introduces an additional interpretative level to the documentation, essential to recover the geometric information of a surface and to calculate the volume of a layer.

When decomposing the archaeological deposit we need to identify the discontinuities between the components (Stratigraphic Units). These spatial discontinuities represent the limit between separate consistent actions, natural and human, that have modified the physical space (Barceló 2003). In archaeology discontinuities between the components are underlined by several observational criteria, such as changes in colour, shape, and texture; therefore the definition of the boundary contour of a stratigraphic unit is influenced by the archaeologist interpretation and needs to be completed in the field, when the features are still clear and visible. Working entirely on digital data implies that the same operations of distinction need to be transposed in the digital environment, where the criteria, on the other hand, rely only on the visual appearance. For that reason it is important that the 3D models keep the traces of the previous on-site distinction.

We are experimenting several approaches to the issue: the most advanced require the use either of a Total Station or DGPS. With these technologies it is possible to draw automatically a polyline in the virtual space by tracing the contour of the layer in the field with the rover. This method allows to define the contour of the stratigraphic unit in a reliable way, and then to use the digital polyline as a shape for the intersection with 3D model, reproducing the real extension of the layer in the virtual environment. Another easier low-cost approach is marking the contour of the stratigraphic unit with a threat, stretched on it on the ground before the acquisition process starts. This operation introduces into the scene an artificial element, the threat, which is perfectly modelled in 3D by the technique, increasing the perception of the contour during the following operation of cutting the mesh along its edges. As a result of the insertion of a subjective element (the boundary contour distinction) into an objective documentation method, it would be appropriate to follow two separate operative sequences for modelling: one solely intended for objective documentation and the other, filtered by interpretation, to be used for further analysis.

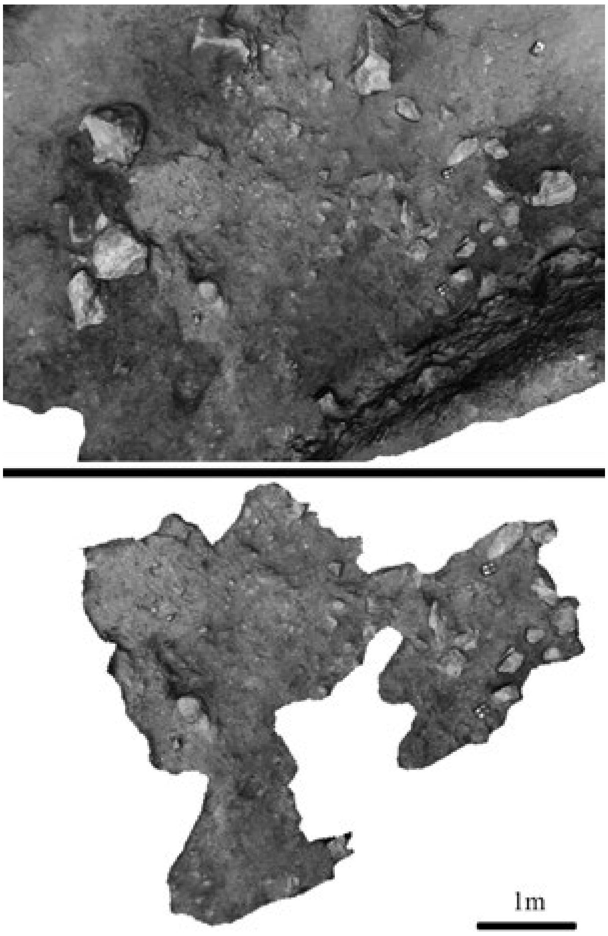


Fig. 6. 3D model (top) and 3D model cut along the edges of the Stratigraphic Unit (bottom).

2.2 Management

The cognitive significance of each 3D model is expanded by the interaction with the other models and the interface with different types of data (photographs, drawings, geographical-spatial data and alphanumeric data). Therefore the models must be contextualized in a composite management and visualization system where the spatial attribute is the unifying element across all the available data. Alignment and georeferentiation of the models are essential to achieve proper management and full integration. One of the most impressive examples of that application is the accurate three-dimensional reproduction of the entire archaeological stratigraphy into a visualization and management platform (3D GIS). In the platform all the layers are placed in the virtual space in the same position they occupied in real space, keeping the mutual spatial relationships with each other. Within this platform we can explore and manipulate the stratigraphy in three dimensions, measure distances between different layers, take coordinates of any point, draw cross sections, compute area automatically, perform spatial analysis and interpolations (Callieri *et al*. 2011). The definition of the boundary contours introduces additional information to the system, essential to perform measurements (distances, area, volumes) and to point out the stratigraphic relationships between the layers. These relationships are evident in the 3D view and can be printed out automatically into clear and understandable charts, used to build Harris' matrix or to review some relationships already defined during the excavation process.

2.3 Analysis and volume computation

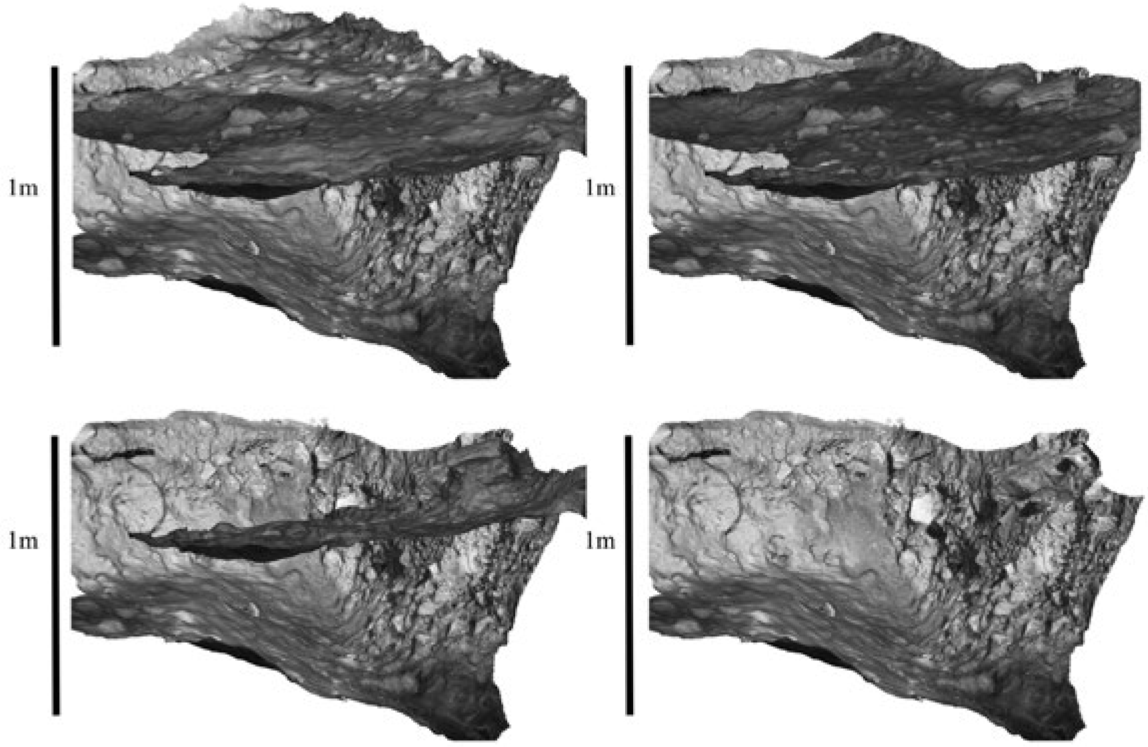
The 3D documentation enables the automatic computation of the volumes of the stratigraphic units, independently from the complexity of their shape, with a degree of accuracy that is generally enough for archaeological purposes. The volume is defined as the amount of space occupied by a solid or enclosed by some boundary. In an archaeological excavation, for each stratigraphic unit, this space is delimited by two surfaces: the upper surface of the unit and the surface that remains at the end of the digging action. In the GIS the former surface is obtained by cutting the corresponding 3D model along the boundary contour of the stratigraphic unit; the latter can be either recorded separately in 3D or interpolated by combining the upper surfaces of the units below, with which this unit has stratigraphic relationships. The more accurate the 3D modelling and management processes are, the narrower is the gap between the edges of the two surfaces and consequently the higher is the accuracy of the volume computation. The GIS is the perfect tool for interpolating the points of the models in order to obtain volumetric data. Moreover, with the interpolation between separate surfaces, it is possible to elaborate the solid that visually describes the volume of the unit. A virtual stratigraphy composed of solids, instead of surfaces, is way more efficient in reproducing the relationships between the stratigraphic units and in describing the sub-surface space, and constitutes the starting point for thinking and implementing a 3D topology that regulates the relationships of all the data coming from the archaeological research.

The volume computation provides additional data for statistical analysis and archaeological interpretations, and can be used in the estimate of the spatial variation of a certain variable in the archaeological context. We can, for example, determine the concentration of a specific element in relation to the total volume of the stratigraphic units, and then make comparison between different units under a different and fresh perspective. Moreover, this allows connections to be made within the horizontal stratigraphic deposit and with the vertical stratigraphy of the buildings.

By following the same procedure, the volume of the building stratigraphic units and of the cuts can be easily calculated. For example, one of the possible applications of this new feature is the connection between the destruction layers in the deposit and the collapsed part of a structure. If we know the volume of the two units we can assess with greater certainty whether there is a direct correlation or not, and, if not, what is the cause of this inconsistency.

3 Conclusions

The Image-based 3D modelling is an accurate and reliable technique for 3D documentation, compatible with the method and the timing of the archaeological excavation. Data produced with this technique is supplementary to the data made by other documentation systems, carrying important additional information about structure, geometry and colours of the archaeological context, and therefore providing an important input for research. In Monteleo 3D documentation



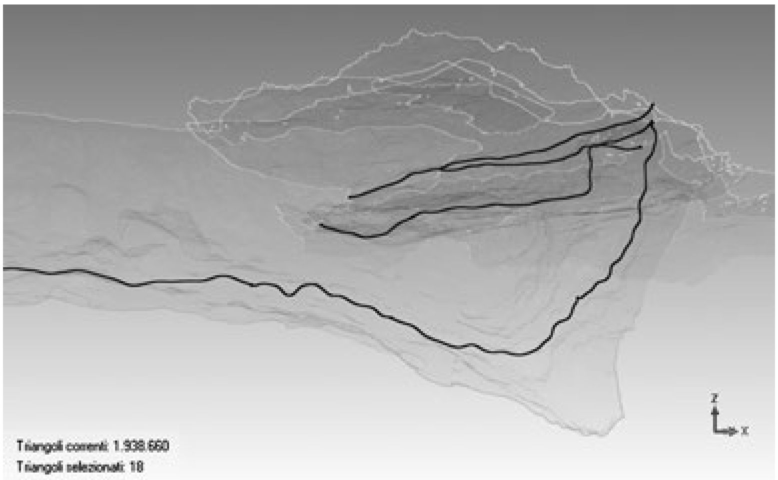


Fig. 7, Fig. 8. Stratigraphic relationships are evident in the 3D view and can be defined through the cross-section tool.

has overcome the problem of how to connect horizontal and vertical stratigraphy, two strictly connected elements that had been managed separately. Furthermore, the opportunity to easily calculate the volume of the layers opens the door to new archaeological questions and research lines, today largely unexplored due the fact that 3D modelling techniques have, up to now, been expensive, slow and hardly compatible with the research process. The new data coming from 3D recording gains even more importance when dealing with a productive site, or with any other archaeological context where there is a strict correlation between the deposit and the structures, the containers and the contents. In Monteleo the volume computation of the layers has provided additional information to the estimate of the quantities and timing of the production of calcination kilns.

Bibliography

Barceló, J. A. 2000. Visualizing what might be. An introduction to Virtual Reality in Archaeology. In Barceló, J. A., Forte, M., Sanders, D. (eds.), *Virtual Reality in Archaeology*, British Archaeological Reports International Series 843: 9-36. Oxford, Archaeopress.

Barceló, J. A., De Castro, O., Travet, D., Vincente, O. 2003. A 3D model of an archaeological excavation. In Doerr, M., Sarris, A. (eds.), *The Digital Heritage of Archaeology.*

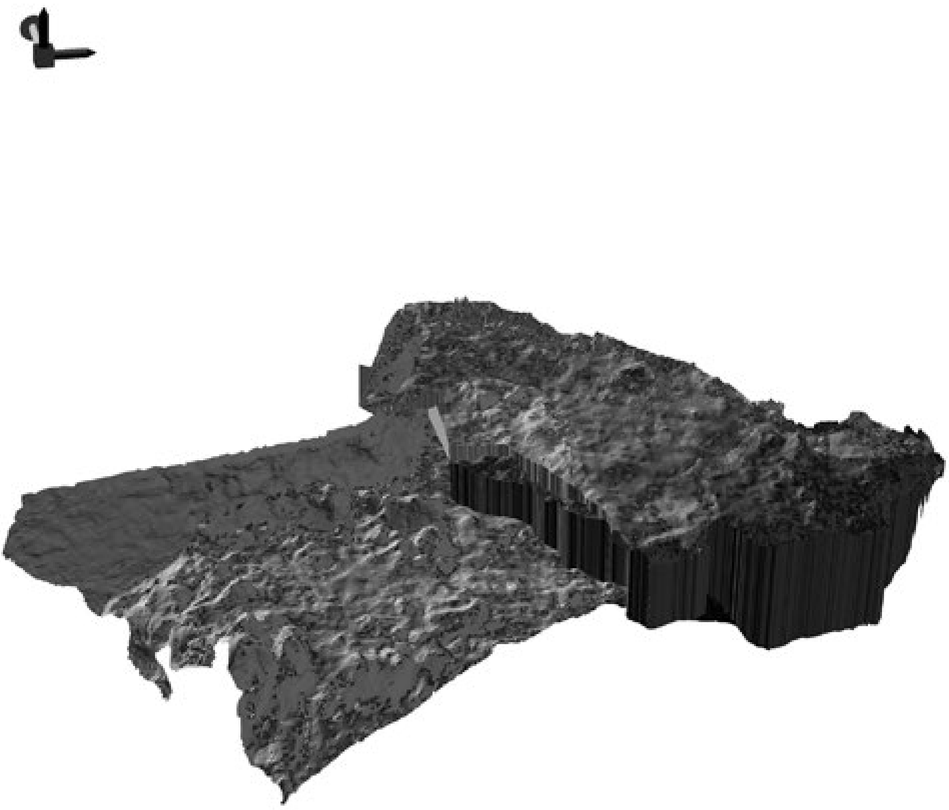


Fig. 9. The volume of the layers is represented as a solid in the 3D GIS system.

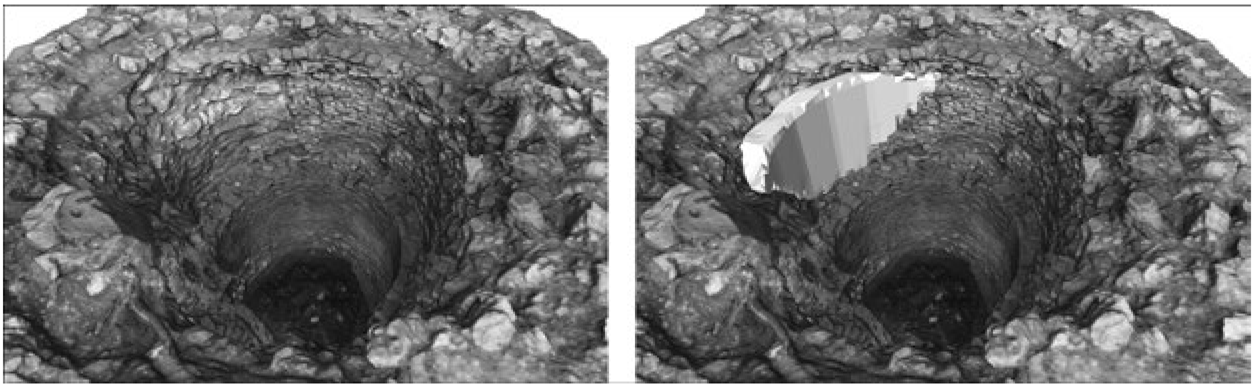


Fig. 10. In this example we defined and measured the volume of a collapsed part of the kiln chamber in order to find a connection with the volume of destruction layers in the deposit.

CAA2002. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 30th CAA Conference, Heraklion, Crete, April 2002: 85-90. Athens, Hellenic Ministry of Culture.

Callieri, M., Dell'Unto, N., Dellepiane, M., Scopigno, R., Soderberg, B., Larsson, L. 2011. Documentation and interpretation of an archaeological excavation: an experience with Dense Stereo Reconstruction tools. In Dellepiane, M., Niccolucci, F., Pena Serna, S., Rushmeier, H., Van Gool, L. (eds.), *Proceedings of VAST 2010: The 11th International Symposium on Virtual Reality, Archaeology and Cultural Heritage*, *Palais du Louvre, Paris, France, 21-24 September, 2010*: 33-40. Aire-La-Ville, Geneva, Eurographics.

D'Andrea A. 2006. *Documentazione archeologica, standard e trattamento informatico,* Collana del Centro Interdipartimentale di Servizi di Archeologia dell'Università degli Studi di Napoli L'Orientale, Budapest, Archaeolingua.

Dallai, L., Poggi, G. 2012. Monteleo (GR) una ‘fabbrica dell’allume’ alla fine del Medioevo. In Redi, F., Forgione, A. (eds.), *Atti del VI Congresso Nazionale di Archeologia Medievale*, *L’Aquila, 12-15 settembre 2012*: 635-9. Firenze, All’insegna del Giglio.

Dellepiane, M., Dell’Unto, N., Callieri, M., Lindgren, S., Scopigno, R. 2013. Archaeological excavation monitoring using dense stereo matching techniques. In *Journal of Cultural Heritage* 14, 3: 201-10. Elsevier Masson SAS.

Di Carlo, M., Di Giulio, N., Franceschini, P., Moretti, C., Torretti, F. 1984. *La società dell’allume. Cultura materiale, economia e territorio di un piccolo borgo*: 16-7. Roma, Litografia Eurotip.

Doneus, M., Verhoeven, G., Fera, M., Briese, Ch., Kucera, M., Neubauer, W. 2011. From deposit to point Cloud - A study of low cost Computer Vision approaches for the straightforward documentation of archaeological excavations. In C. Ales (ed.), *Geoinformatics, 23rd International CIPA Symposium* 6: 81-7. Prague, Faculty of Civil Engineering.

Fiumi, E. 1943. *L’utilizzazione dei Lagoni Boraciferi della Toscana nell’industria medievale*. Firenze, Casa editrice del dott. Carlo Cya.

Forte, M., Dell’Unto, N., Issavi, J.,Onsurez, L., Lercari, N. 2012. 3D Archaeology at Çatalhöyük. In Ioannides, M. (ed.), *International Journal of Heritage in the Digital Era* 1, 3: 351-78.

Remondino, F., El-Hakim, S. 2006. Image-Based 3D Modeling: A review. In *The Photogrammetric Record* 21, 115, September 2006: 269-91.

3D Technology Applied to Quantification Studies of Pottery: Eve 2.0

Miguel Busto-Zapico
bustomiguel@uniovi.es
University of Oviedo

Miguel Carrero-Pazos
miguel.carrero@usc.es
University of Santiago de Compostela

Abstract: In archaeological excavations, pottery fragments are the most common remains. As a consequence, it seems appropriate to propose a methodology that can help in their study. Therefore, we intend to propose a method that will allow us to identify from a fragment of pottery, the size of the vessel it came from, basing on partially completed pieces. This approach is not new, since between the 1980s and 1990s, C. Orton, P. Tyers and A. Vince started discussing about the estimated vessel equivalent (EVE). However, despite its advantages, it is a system which is not implemented fully. On this basis, we have designed a reviewed EVE, adapted to the new technologies (3D) that allow us to go further and talk of EVE 2.0.

Keywords: Methodology, Quantification, Pottery, Estimated vessel equivalent, 3D technology.

Introduction

In any archaeological excavation, pottery fragments are the most frequent quantitative remains. Specific approaches are needed for their study, which can include a precise quantification approach. For this reason, we considered it appropriate to plan a study, to revise and adapt the main methodologies that have been used for this purpose, because quantitative studies are necessary to obtain an accurate picture of the pottery that was used in a determined archaeological context and to compare that information with others.

Our aim is to propose a quantification method in which we could ascertain from a small fragment of pottery, the percentage of the complete pottery piece, by applying 3D technology on well preserved sherds. We are attempting to develop a new adaption of the EVE based on the application of new technologies that did not previously exist. As a result, we have developed the EVE 2.0 (Busto and Linares, 2013), a methodological approximation to pottery studies. It can be defined as a quantitative analysis system, which allows us to assign each fragment a percentage value with respect to the whole vessel of which they were part, regardless of other factors or variables that may alter it. Provided that, at the beginning, we have the full profile of the piece, because this method only applies to largely preserved materials which may be documented at some contexts. However, the Eve 2.0 should be implemented and applied only where it could serve to achieve the objectives in research, and when the pottery repertoire would make it possible.

1.1 The quantification studies on pottery

The basic need for a suitable quantification method is a well-known problem (Fletcher and Heyworth, 1987). Many methods have been used, but none have been successful. Over the last decade, the main quantification methods were: sherd count, sherd weight, sherd volume/area (n.b. not vessel capacity), vessels represented (minimum, maximum or estimated) and estimated vessel equivalents or EVEs (Orton 2009: 5). All of them have clear advantages and disadvantages that can convey some problems to research conclusions. In several occasions, the solution may lie in a combined study, which integrate some of these proposals.

In the 1980s and 1990s, C. Orton first, and then with the collaboration with P. Tyers and A. Vince started to implement the quantification methods with the 'estimated vessel-equivalent' (EVE). In the book *Mathematics in Archaeology*, C. Orton (1980) with the intention of resolving the quantification problems of the pottery, described the theory of the vessel-equivalents (V.E.), although that method had been presented before (Egloff 1973; Orton 1975). A few years later, C. Orton, P. Tyres and A. Vince, in *Pottery in Archaeology* (1993) further explained the 'estimated vessel-equivalent' (EVE). Recently, it has been published a second edition of *Pottery in Archaeology* (Orton and Hughes 2013) where it is revised deeply the first edition.

In their opinion, this new method was 'the only measure that is unbiased, both for measuring proportions within an assemblage and for comparing them between assemblages' (Orton *et al*. 1993: 171; Orton and Hughes 2013: 207). The scientific community, especially in the United Kingdom and Ireland, has mainly accepted this quantification method. Despite its advantages, it is a system whose applications are constrained.

C. Orton starts from the premise that 'if one has one sherd, its vessel-equivalent is simply the proportion of the vessel that it constitutes' (Orton 1980: 164), and for this reason 'every sherd is a certain proportion of the whole pot of which it once formed part' (Orton *et al*. 1993: 21; Orton and Hughes 2013: 22). However, to estimate the complete pottery that a fragment represents, C. Orton falls back on approximation methods, and here is where we can find, in our opinion, the main limitation of EVE. What C. Orton, P. Tyers and A. Vince measure is the percentage that a fragment from the rim represents with respect to the complete pottery piece using a rim chart. So 'one can

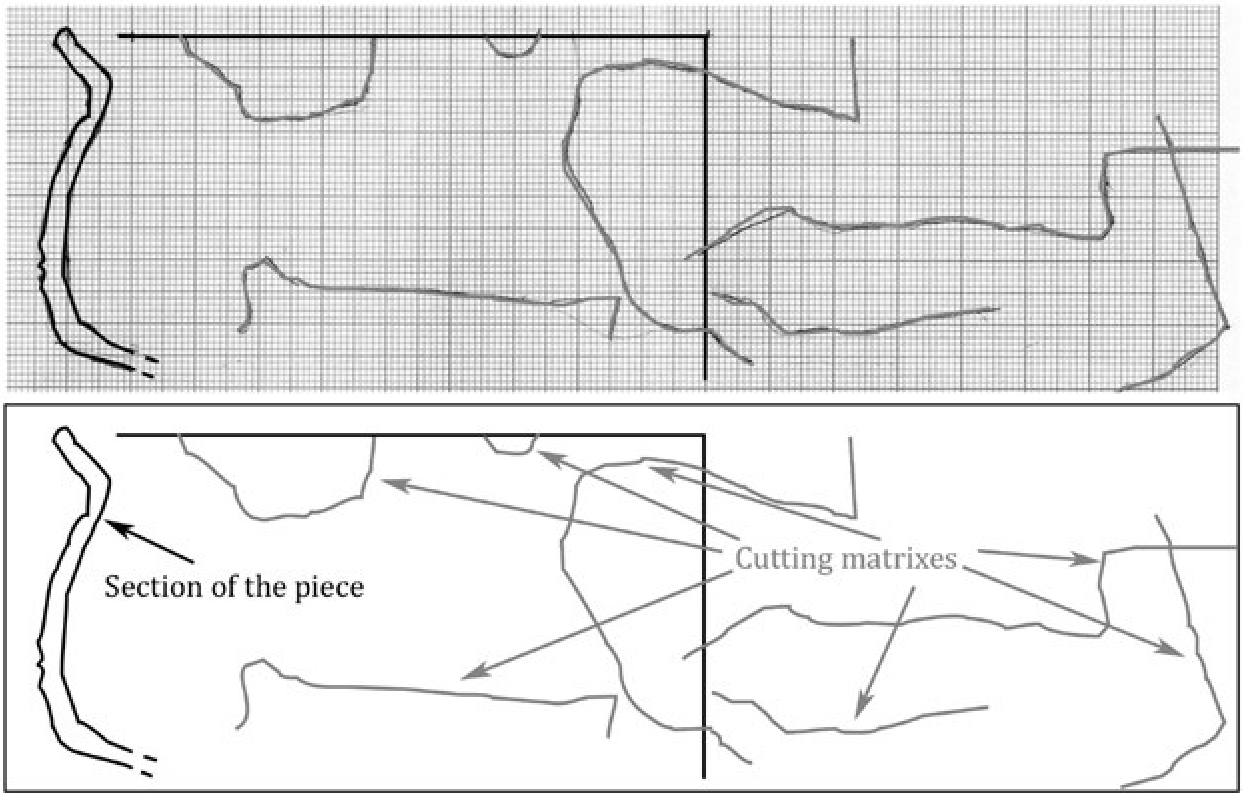


Fig. 1. EVE 2.0 creation: Phase I.

then let the rim stand representative of the whole pot and use this figure as the EVE' (Orton *et al*. 1993: 172; Orton and Hughes 2013: 210). The same method will be applied to the base of the pottery (Orton and Hughes 2013: 210). However, this statement can be understood as excessive, an attempt to avoid system restrictions.

1.2 Walking towards to EVE 2.0

Starting from this theoretical approach, we tried to develop an EVE that integrates new technologies.

Nowadays we are able to develop some changes, not to the aims of the system, but to its application method. It is therefore not only a matter of change and an adaptation of forms, but also a methodological revision that uses three-dimensional representations of sherds as an informative element. In this sense, we can get a more accurate quantification studying specific pieces. Sometimes this can lead to a more accurate interpretation, having considered a part of a set of pieces.

We have tried to change the system to make it more current. It is an upgrade or a new version of EVE that adds new features to the method. Therefore, the revised EVE that we are proposing, or EVE 2.0 as we have called it, is not an end in itself, but a tool to allow Archaeology to continue developing, although in small-scale approach.

2 The EVE 2.0

In order to apply the EVE 2.0, we must carry out a previous typological study of pottery vessels, trying to rebuild them in order to get all the profiles as many of them as possible. Also, we must create the ceramic types basing on a set of specific attributes, derived from morphometric factors, because the EVE 2.0 starts from the 3D model of the piece, to quantify it.

The most useful morphometric variables for the application of EVE 2.0 may be those relating to diameters (border, base and maximum diameter), height (of the whole piece and maximum diameter), a variable range of thicknesses and, above all, the weight. Our aim is to create a pottery collection that could allow us to connect the largest number of fragments with the different types that are in it.

The working process to obtain the EVE 2.0 is easy, and we will only have to go a few steps further than a usual pottery study. In order to make the text comprehensible, it is necessary to explain three concepts:

- Section of the piece (A). This term refers to a perpendicular cut from the rim to the centre of the base, which allows us to establish the different thicknesses of the pottery piece.
- Cutting Matrices (B). This term refers to all cuts and breaks that contain the pottery piece.
- Real piece (C). With this term, we are referring to the shreds of pottery, or group of them that constitute our pottery piece.

According to our theory A-B= C. To demonstrate this simple hypothesis, we have set in motion a methodological work that

Fig. 2. EVE 2.0 creation: Phase II.

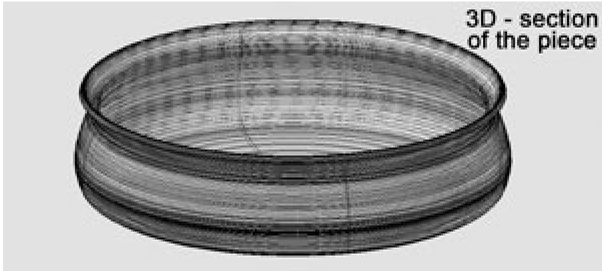


Fig. 3. EVE 2.0 creation: Phase III, 3D section of the piece.

we have divided in different phases: Drawing, Vectorisation, 3D creation and Calculus of the EVE 2.0.

Phase I: Drawing (Fig. 1). For EVE 2.0 we need the section of the piece (A) and its diameter. At the same time, we need to mark all the cuts and breaks on our fragment, recording their real dimensions real dimensions and positions, to develop the cutting matrices (B).

Phase II: Vectorisation (Fig. 2). Once the image is inserted and scaled, we vectorise it. To do so, we use the polyline to redraw A and B.

Phase III: 3D creation (Fig. 3-8). The fragment will be submitted to the rotation axis at its centre 'A' (3D-A). Thus, we will construct series of different objects in 3D from B (3D-B). To create the 3D section of the piece we will use the *CAD revolution* command. Thus, we will be able to create surfaces and revolution solids, submitting them to the rotation axis at a feature centre. Therefore, in our case, the fragment will be submitted to the rotation axis at its centre. In this way, we will obtain a 3D solid (Fig. 3). We will build a few objects from our cutting matrices, with the command *extrusion*. The new piece built has the same section than the matrix one (Fig. 4).

Finally, the last step of this method is perhaps the most complicated one. To create the 3D of the real piece (3D-C) we will carry out *boolean* operations with solids, especially with a *difference*. The entity that results will be another object with all the points of the first one, except for those that were occupied by the second (Fig. 5).

Then, we have to place the 3Ds on the cutting matrices (3D-B) in those parts that we want to eliminate from the 3D copy of the section of the piece (3D-A'). In this sense, we will be able to eliminate the unwanted portions of the entity. Therefore, we are dealing with a solid that approximates to the piece that we have found in reality. With 3D we have obtained a virtual model that reproduces the volume of the real object. We will repeat the procedure but choose the solids in an inverse way, to obtain a representation of the fragments which have not been preserved (Fig. 6-8).

Phase IV: The calculus of the EVE 2.0 (Fig. 9). To summarise, with 3D we have obtained a virtual model that reproduces the volume of the real object. Through the vectorisation

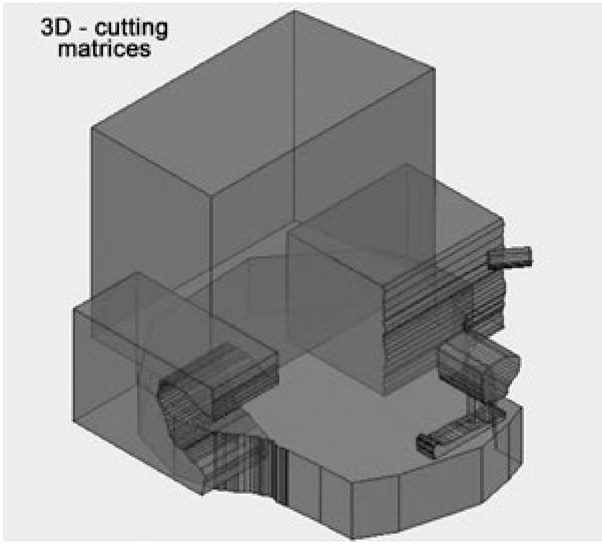


Fig. 4. EVE 2.0 creation: Phase III, 3D cutting matrices.

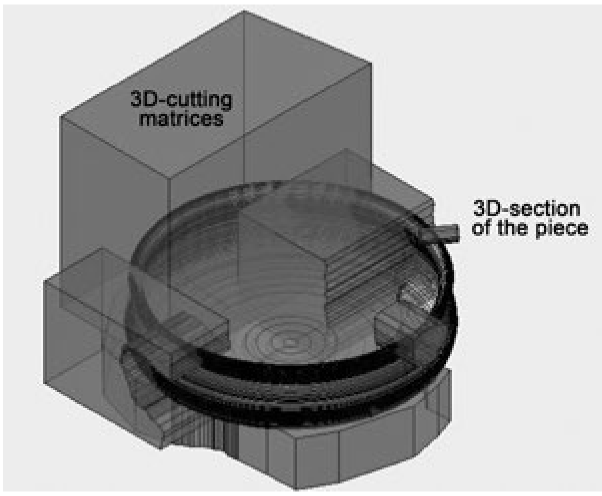


Fig. 5. EVE 2.0 creation: Phase III, *boolean* operations with solids.

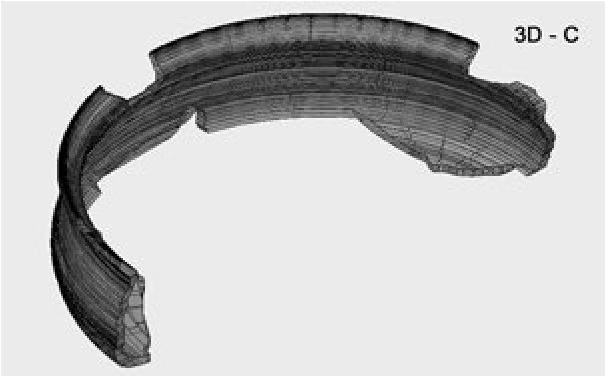


Fig. 6. EVE 2.0 creation: Phase III, 3D-C.

Fig. 7. EVE 2.0 creation: Phase III, 3D-B.

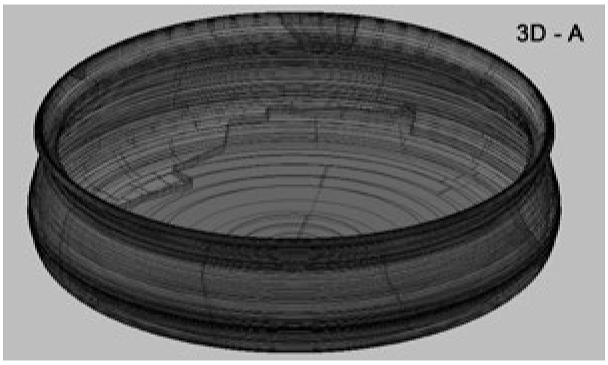
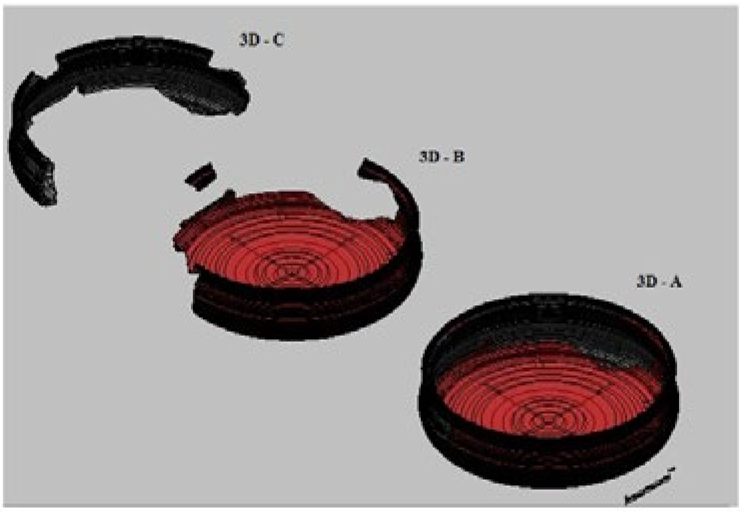


Fig. 8. EVE 2.0 creation: Phase III, 3D-A.

of the fragment (A) we have created a three-dimensional representation of the complete piece (3D-A). Through the 3D-A, using simple mathematical operations, we can obtain the specific 3D of our initial fragment (3D-C). Furthermore, we can study the volume and mass of all these objects, so we could know the percentage of the piece that we have in relation to the totality. In this sense, if we know the weight of the different fragments we have analysed (C), we could deduce the approximate weight that that piece could have (Fig. 9).

In other words, with the vectorisation, the realisation of the 3D model and the use of Boolean algebra, we have enough data to calculate the EVE 2.0 of all ceramic types recreated in 3D. This is because we have recreated this objects, even those that do not exist, in a specific 3D space.

Accordingly, we are able to know the volume and mass of all of them, and calculate the EVE 2.0, which is the percentage of the piece that we have with respect to the whole. Besides, to facilitate the rapid quantification of the pottery sherds, the EVE 2.0 has another key application. If we are able to know the weight of the fragments, we would be able to infer the approximate weight that would have had the piece that existed at some point, due to the proportionality between these quantities.



EXAMPLE	3D-A	3D-B	3D-C
Volume CAD	205.9176	142.3304	63.5872
Estimated weight	**304.4 g**	**210.4 g**	**94 g**
EVE rim	100%	55%	45%
EVE base	100%	85%	15%
EVE 2.0	**100%**	**69.12%**	**30.88%**

Fig. 9. EVE 2.0 creation: Phase IV, calculus of the EVE 2.0.

3D-A	3D-B	3D-C	RU-09-162
Volume Autocad: 368438.4666	Volume Autocad: 11036.4930	Volume Autocad: 358474.6740	E.V.E. rim: 95%
Estimated weight: 989,7g	Estimated weight: 29,7g	Weight: 960 g	E.V.E. base: 100%
EVE 2.0: 100%	EVE 2.0: 3%	EVE 2.0: 97%	Weight: 960 g

3D-A	3D-B	3D-C	RU-09-171
Volume Autocad: 232392.3110	Volume Autocad: 92629.0532	Volume Autocad: 139759.7765	E.V.E. rim: 50 %
Estimated weight: 670 g	Estimated weight: 268 g	Weight: 402 g	E.V.E. base: 60 %
EVE 2.0: 100%	EVE 2.0: 40%	EVE 2.0: 60%	Weight: 402 g

3D-A	3D-B	3D-C	RU-09-172
Volume Autocad: 189627.6452	Volume Autocad: 133150.1786	Volume Autocad: 56492.6278	E.V.E. rim: 27.5 %
Estimated weight: 620,8 g	Estimated weight: 435,8 g	Weight: 185 g	E.V.E. base: 0 %
EVE 2.0: 100%	EVE 2.0: 70,2%	EVE 2.0: 29,8%	Weight: 185 g

Fig. 10. Different case studies.

2.1 Practical example

Every methodology has its beginnings in experimental parts, and in this paper, we intend to plan an empirical demonstration through a repetitive trend. To put it in another way, we want to show that EVE 2.0 can be put into practice with different samples. In order to test our method, we have chosen the pottery of the excavations that have been carried out at the *Museo de Bellas Artes de Asturias* (Oviedo, Spain). They are pieces with a high level of conservation and with a timeline stretching from the mid-sixteenth century to the mid-seventeenth century (Busto, 2013). Starting the treatments with these varied pieces (with a diverse pottery profile) we obtained the following data:

The EVE 2.0 has allowed us to study with a more in depth approach the percentage of the piece that we managed. In addition, we were able to determine the approximate weight of a particular case, information that was previously unknown (Fig. 10).

2.2 Improvements and limitations of EVE 2.0

Perhaps the most important improvement of EVE 2.0 compared with the previous EVE is the substitution of an estimation index for a percentage. Replacing the estimate (EVE) with the actual measurement (VE= Vessel-Equivalent), it would greatly improve the accuracy of pottery quantification. But unfortunately its application is only possible under certain pieces.

On the other hand, 3D modelling makes other approaches possible, like the statistical analysis of the obtained data (Esquivel *et al*. 2008). Moreover, there is the possibility to create visual galleries, and to plan studies of the potential of artefacts (Rubio *et al*. 2009). However, we are dealing with a methodology that shows an approximate perspective. 3D representations that we have studied often offer perfect geometric features. Of course, it does not correspond to real vessels. Pottery is not usually perfect, and therefore, the accuracy of results always depends on the study area.

This limitation can be clearly rectified with the use of a 3D scanner or photogrammetric techniques, which provide more accurate information about the piece, and let us apply the method to every piece. In this moment, some phases of the method are too slow in some of their phases, but we are still improving them to make them faster. Perhaps the introduction of the photogrammetric techniques might be faster.

On the other hand, EVE 2.0 is not applicable to all fragments. It is a very restricted method that can only be applied to specific pieces. To apply it, we need pieces with a complete section, that is to say, we need parts of the rim, wall and base in the same fragment. However, it is readily applicable to ceramics with high level of standardisation, demonstrating, in these cases, large quantitative profits (Busto 2014). Similarly, if we can group fragments around typologies, getting the weight of some types, we could be able to work with almost all of the material, reducing initial restrictions. In this field, it can yield great advances in quantification studies.

Although none exists at present, the EVE 2.0 allows us to obtain the approximate weight of a complete piece of a specific typology. Therefore, this quantitative technique provides data hitherto unknown and inaccessible at present (Fig. 9-10). In fact, such data may become as a key part in technological and productive analyses of pottery. In addition to this, the weight is a quantification method which allows avoiding the distortion problems derived from other quantitative methodologies.

3 Conclusion

EVE 2.0 reinforces a path within archaeological studies. The appropriate method of analysis is that which combines different techniques and instruments for each case to complete the archaeological information record. Each method provides different information and complements the others, and for this reason, it should not be exclusive or prioritise one over the others.

This method of quantification or EVE 2.0 is able to assign to each fragment, a percentage value with respect to the whole vessel which were part, regardless of other factors or variables that may alter it. Therefore, we can relate these units of analysis (or pottery sherds), with a basic device (or pottery container). It also allows to know the approximation weight of a complete piece.

From a quantitative point of view, although the EVE 2.0 is not applicable to the entire material, it is an impartial measure unaffected by fracturabilty, which in fact is able to obtain data on the proportions of a specific type within a set, and allows to compare the proportions between it and other groups. The use of a percentage values is a procedure required, which allows to start more sophisticated quantitative methods.

Bibliography

Busto, M. 2013. *Conjuntos cerámicos del Oviedo bajomedieval y moderno. Los materiales de la casa Carbajal Solís*. Unpublished Degree dissertation, University of Oviedo.

Busto, M. 2014. Una aproximación a las cerámicas recuperadas en la excavación arqueológica del restaurante de El Polinario. *@rqueología y Territorio* 10: 117-32.

Busto, M. And Linares, M. J. 2013. EVE 2.0: Una revisión y adaptación de un método para el estudio cerámico. In Padilla, J. J. and Alarcón, E., *II Congreso Internacional de Estudios Cerámicos. Etnoarqueología y Experimentación: Más allá de la Analogía*, Granada, 5-9 March 2013.

Egloff, B. J. 1973. A method for counting ceramic rim sherds. *American Antiquity* 38:3: 351-3.

Esquivel, J. A., Esquivel, F. J., Alemán, I. 2008. Análisis estadístico de los parámetros morfométricos de un vaso carenado utilizando un láser escáner 3D. *Cuadernos de Prehistoria y Arqueología de la Universidad de Granada* 18: 357-70.

Fletcher, W. and Heyworth, M. P. 1987. The quantification of vessel fragments. In Gaffney, C. F. and Gaffney, V. L. (eds.), *Pragmatic Archaeology Theory in Crisis?* British Archaeological Reports, British Series 167: 35-46. Oxford, British Archaeological Reports.

Orton, C. 1975. Quantitative Pottery Studies: some progress, problems and prospects. *Science and Archaeology* 16: 30-5.

Orton, C. 1980, *Mathematics in archaeology*. Cambridge, Cambridge University Press.

Orton, C. 2009. Four pots good, two pots bad?: exploring the limits of quantification in the study of archaeological ceramics. *New Perspectives on Ancient Pottery Conference, University of Amsterdam*: 1-10.

Orton, C. and Hughes, M. 2013. *Pottery in Archaeology*. Second Edition. Cambridge, Cambridge University Press.

Orton, C., Tyers, P., Vince, A. 1993. *Pottery in Archaeology*. Cambridge, Cambridge University Press.

Rubio, D., Martínez, J., Baena, J., Fernández, J. J., Finat, J. 2011. Nuevos métodos para viejas tecnologías: análisis y documentación de los materiales arqueológicos mediante la aplicación de sistemas de Láser-scanner 3D. In A. Grande, V. M. López-Menchero, A. Hernández-Barahona, (eds.), *I Congreso Internacional de Arqueología e Informática Gráfica, Patrimonio e Innovación, Arqueología 2.0. Sevilla, 17-20 june, 2009*: 345-9. Sevilla, Sociedad Española de Arqueología Virtual.

3D Recording of Archaeological Excavation: the Case of Study of Santa Marta, Tuscany, Italy

Matteo Sordini
sordini@atsenterprise.com
ATS ldt, Italy

Francesco Brogi
francesco.brogi@alice.it
Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Stefano Campana
srlc3@cam.ac.uk
Faculty of Classics, University of Cambridge, UK

Abstract: The archaeological excavation is a destructive and not repeatable process: the documentation of archaeological stratigraphy and relations between the layers is an essential component of the work of the archaeologist aimed at the understanding the site object of researches. The traditional techniques of documentation, based on direct survey and manual drawing, are time consuming to be executed and they are also characterized by some poor level of precision and accuracy that, spread over time, can lead archaeologist to errors and misunderstandings. The use of traditional techniques of survey does not allow any margin of error in the interpretation: once produced documentation, layers are destroyed and it is hardly possible to make further corrections in documentation. Over the last two decades technological innovations have progressively reduced these issues: survey instruments such as total stations and dGPS have gradually replaced the direct survey. The introduction of digital SLR cameras has eliminated the cost of production of photographs and allowed the archaeologists to produce a massive documentation of contexts, mainly qualitative. The laser scanners have been tested within various excavation sites: the possibility to record excavations in three dimensions have been found to be of great interest by archaeologists, but the high cost of the instrumentation and the complexity of the whole process of processing and management of laser data have limited its use and dissemination. In recent years, the advent of photogrammetric software based on the 'Structure from Motion' technique has gradually made accessible three-dimensional survey within the excavation sites. During the excavation of the roman site of Santa Marta, in Cinigiano (GR), we developed a pipeline for fast 3D recording of excavation. Through an integrated approach of topographic instruments, aerial and terrestrial images, semi-automated photogrammetric packages and GIS system we have been able to systematically recording in tree dimension the stratigraphy of the sites. This approach allowed us to overcome issues related with precision and accuracy of the documentation and different datasets can be integrated to create diachronic 2D and 3D documentation. The high resolution and precision of recorded surfaces allow us to improve both quality and speed of documentation, optimizing all the work in excavation site.

Keywords: Archaeological excavation, 3D recording, SFM, UAV, Survey

Introduction

Archaeological excavation is a destructive and non-repeatable process: the documentation of archaeological stratigraphy and relationships within and among layers and structural features are an essential component of the archaeologist's work in trying to understand the site under investigation. Traditional techniques of documentation, based on direct survey and manual drawing, are time-consuming in execution and are often characterized by poor levels of accuracy that, over time, can lead to errors and misunderstandings. The use of traditional techniques of survey does not allow any margin of error in the interpretation: once that the documentation has been produced, the layers and other features are destroyed, and it becomes difficult or impossible to make further corrections in both the documentation and in its interpretation. Over the last two decades technological innovations have progressively reduced the impact of these issues: survey techniques, such the use of total stations and GPS, have gradually replaced direct survey and manual drawing. The introduction of digital SLR cameras has virtually eliminated the cost of photography, allowing the archaeologist to collect an almost inexhaustible mass of documentation, albeit mostly qualitative. Laser scanners have been tested within various excavation projects and the possibility of recording excavations in three dimensions has attracted great interest amongst archaeologists (Doneus, Neubauer 2005; 2008; Peripimeno 2009; Campana *et al*. 2008; Campana, Remondino 2008). But the high cost of instrumentation, along with the inherent complexity of data acquisition, processing and management system for laser data, has limited its use and dissemination. In recent years, however, the advent of photogrammetric software based on multi-image photogrammetry (Structure from Motion) has gradually made three-dimensional digital recording accessible and practical within the excavation process (Arrighetti, Cavalieri 2012; Cavalieri *et al*. 2009; Caldarelli *et al*. 2012; Callieri *et al*. 2011; Doneus *et al*. 2011; Panella *et al*. 2011). During the excavation of the Roman site in Santa Marta (Cinigiano, GR), the Laboratory of Landscape Archaeology and Remote Sensing of the University of Siena has developed a pipeline for the rapid 3D recording of excavation evidence. Through an integrated approach to the use of topographic instruments, using both aerial and terrestrial images along with semi-automated photogrammetric packages and an appropriate GIS system, it has become possible to record systematically in three dimensions the structural and stratigraphical character of the

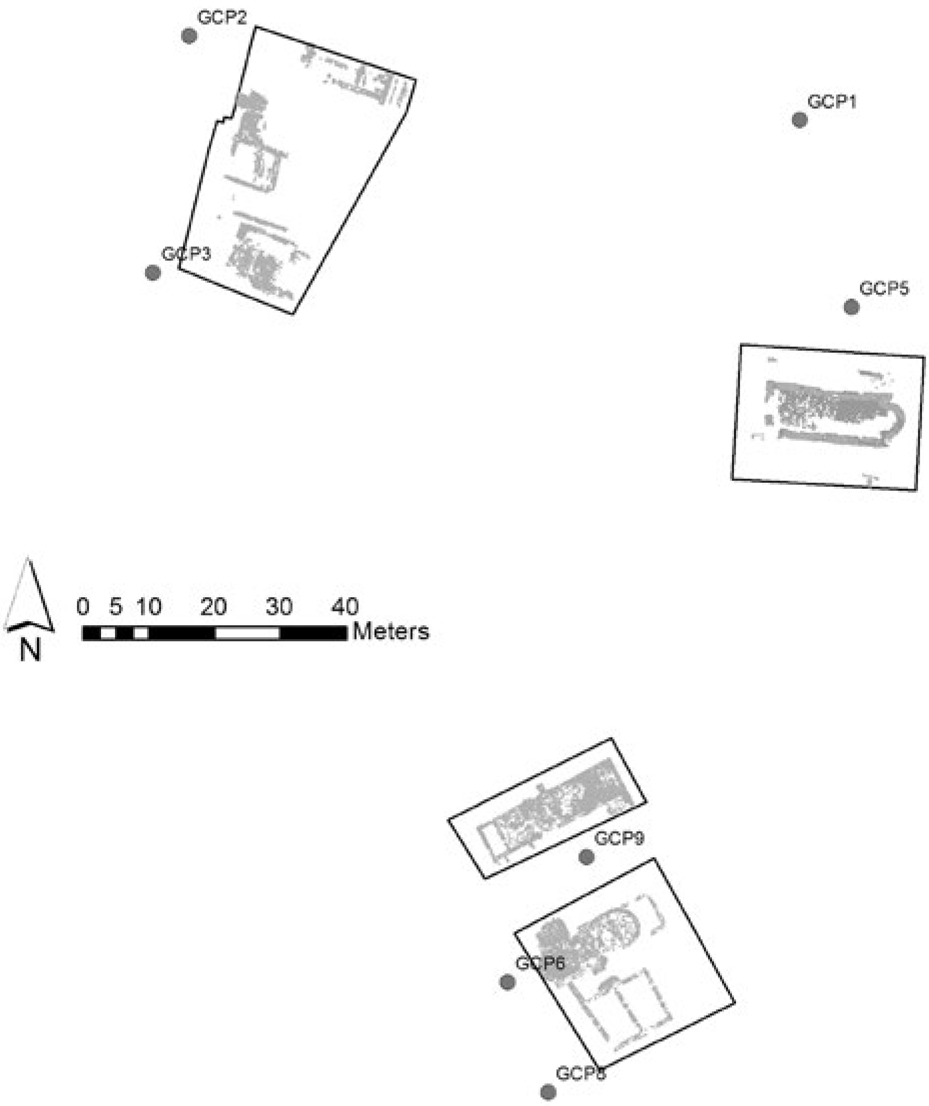


Fig. 1. Excavation areas and ground control points.

site. This approach has reduced or eliminated issues relating to precision and accuracy of the information within the differing datasets, which as a result can be integrated with one another to create 2D, 3D and 4D documentation. The high resolution and precision of the recorded surfaces increases both the quality and speed of documentation, optimizing the speed and cost-effectiveness of the work on site.

1 Fieldwork: terrestrial documentation

Our experience in digital documentation of archaeological excavations started in 2004 with Pava projects (Campana *et al*. 2012) (Tuscany, Italy) and it had a significant improvement during our recent project focused on the excavation of Santa Marta (Tuscany, Italy), started since July 2011 (Campana, Ghisleni 2014). Through those direct experiences we experimented with integrated technologies to improve both quality and speed of documentation. During ten years of researches we built and consolidated a pipeline of intervention to record archaeological stratigraphy. In addition to the definition of a procedure to replace the direct survey and manual drawing on site, we paid particular attention to the added value that this kind of techniques can provide to the work of archaeologists. In particular the possibility of using three-dimensional model for a systematic documentation of all excavation phases interpreted during fieldwork.

The first aspect of the workflow in the field is the topographic approach: we use a topographic GPS with real time differential correction for absolute coordinate measurement and a total station to measure points during fieldwork. In order to obtain a precise georeferencing of archaeological documentation we arranged the excavation site with some sparse ground control points (GCP). Each GCP is built with concrete and stuck in the ground to preserve thought the time. Absolute coordinates of each point have been calculated using topographical GPS with real-time differential correction, with 30 minutes of static measurement. Finally, we calculate GCP coordinates in Italian grid system, Gauss-Boaga, using Verto3 software:[1] this software

[1] IGM Verto 3 (http://www.igmi.org/prodotti/elementi_geodetici/software.php).

FIG. 2. MONOPOD USED IN TERRESTRIAL IMAGE ACQUISITION.

FIG. 3. MICRODRONES MD 200.

uses a grid of known points to maximize the accuracy in the coordinates' transformation process. During the fieldwork the total-station is used for surveying the stratigraphic unit limits, as well as the control points used in photogrammetric process. The instrument is oriented using the GCP on the ground, getting all the surveyed points directly in Gauss-Boaga coordinate system. It enables the excavation to be carried out with no post-processing operation, producing a documentation that can be related in real-time to the geophysical prospection, used to plan the first excavation areas and the further interventions.

The second aspect of workflow is the image acquisition to produce a systematic 3D documentation: in this activity the proper acquisition of terrestrial images is a fundamental aspect to ensure reliable results. We use reflex camera (Canon EOS 50D, Nikon D7000) and mirrorless camera (Sony Nex 7) to acquire images, keeping the parameters of focal length and aperture constant. Images also require a good depth of field and focus. Usually the distance between camera and object is variable, depending on both the available space and the shape of the surveyed element. To detect all the areas each surface is acquired by convergent and nadir images, with a significant overlap (Gonizzi *et al*. 2011). In case of stratigraphic contexts of larger extension, the images are taken with the aid of a monopod or stand, acquiring zenithal and oblique images. Each image dataset contains a congruous number of markers, measured by the total station. Compared to the traditional survey methods, this approach enables the performance of all the field-activities in a short time, solving many problems in terms of accuracy and management of the other excavation activities.

2 Fieldwork: aerial documentation

The use of terrestrial images is limited to small and medium size areas: the documentation of large excavation can take several hours or a day to be carried on with terrestrial tools: the short distance between camera and surface needs to shoot a large amount of images and many control point to survey, making the post-processing interventions slower. To solve this limit we use aerial images. We started to experiment this technique since the beginning of Pava excavation (Tuscany, Italy), in 2004 (Campana 2005). During the first years, we acquired images using a Cessna light aircraft and digital SRL camera, taking picture of the site from many points of view (oblique aerial photography). However this kind of approach presented many limitations, mainly because the high flight of Cessna aircraft does not allow the recording of details and small objects;[2] furthermore flying systematically with Cessna is too expensive. To overcome this limits we started experimenting the use of UAV in 2007 in cooperation with Zenit s.r.l. company and FBK Foundation, using Microdrones MD 200.[3]

FIG. 4. AIBOT X6V2.

This UAV was equipped with 4 rotors, carrying 200g of payload; MD-200 can fly by remote control or autonomously with a GPS navigation system, but it revealed some hardware limitations related to aircraft: first of all the equipment of Microdrones required a long preparation before it was ready to fly, then it was strongly affected by weather conditions. Moreover the MD-200 can carry only some specific kind of compact camera: the images acquired with that hardware produced very poor images that in most cases unfit the requirements for the photogrammetric processing. Even if the data resolution and details acquired with MD-200 were higher compared to those of Cessna Aircraft, they both were insufficient to perform archaeological interpretation on digital datasets, so traditional/manual drawing in the field was still required. During Santa Marta excavation we started the experimentation of Aibot X6 Hexacopter System. This system has 6 rotors protected by a carbon fibre structure. It can fly by manual control or

2 For safety reasons we cannot fly below 150m of altitude.
3 http://www.microdrones.com

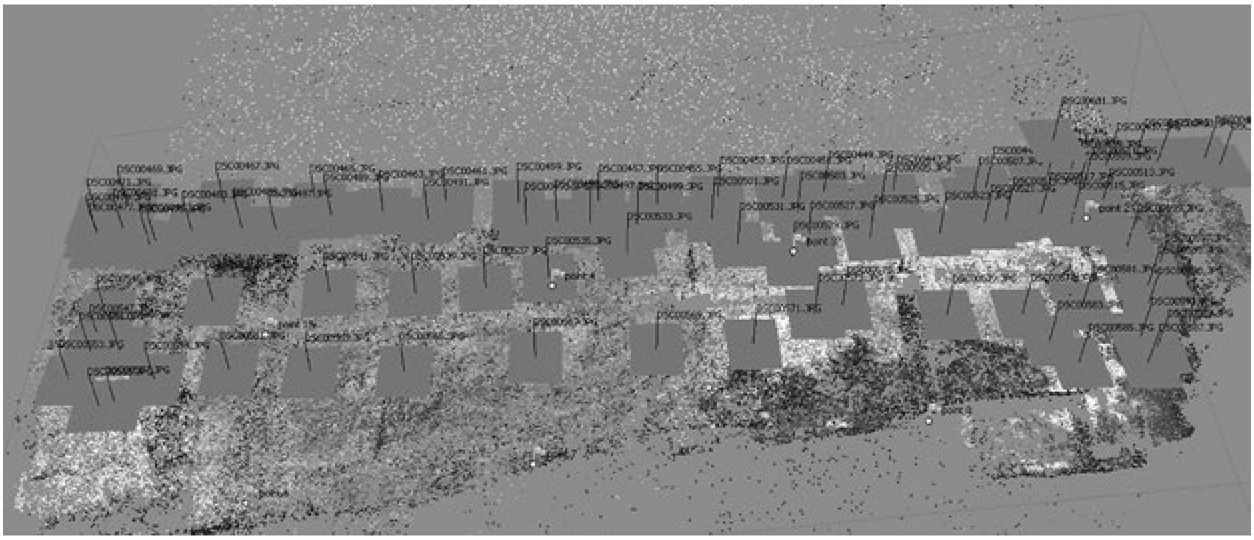


Fig. 5. Alignment of image dataset.

autonomously with the integrated GPS navigation system. The hexacopter is less affected by atmospheric conditions, making the system more versatile in archaeological fieldwork.

The carbon fibre structure protects the six rotors from collision, so the aircraft can fly in low spaces and/or in low distances from the object with a very high grade of reliability. The camera mount minimizes the oscillations, allowing producing images with good depth of field and focus. The set-up system is very fast, in few minutes it is ready to fly. The UAV can carry up to 2kg payloads;[4] for this reason it is possible to use a reflex or mirrorless camera producing a very high quality images. This system has been used in 2013 and 2014 to record Santa Marta excavation: the documentation of open areas, ($2000m^2$ in total), has been performed in less than 2 hours, including topographic survey. The quality of images detail, the repeatability of flights with identical parameter and the high speed in performing the photogrammetric survey, make this instrument particularly suitable to the diachronic documentation of the excavation (Sarazzi *et al*. 2011: 1933-4).

3 Data processing

To process our image datasets we choose a low cost automated photogrammetry package, Agisoft Photoscan Pro.[5] This program is based on the approach known as 'Structure from motion' (SFM). The extraction and features matching in Photoscan are made with an algorithm similar to the well-known SIFT:[6] it detects points in the source photos which are stable in viewpoint and lighting variations, generating a descriptor for each point, based on its local neighbourhood. These descriptors are used later to detect correspondences across the photos. Since some layers in archaeological excavation have very homogenous texture, the algorithm can have problems to detect and match the features properly. To overcome this limit is important to use control points, measured with TS and match them *a priori* in the images. Furthermore, to solve intrinsic and extrinsic orientation parameters, Photoscan uses a greedy algorithm to find approximate camera locations, later refined using a bundle-adjustment algorithm. After the estimation of intrinsic and extrinsic parameters, it is important to optimize the alignment using control points to achieve higher accuracy and to correct possible distortion.

In general it is important to proceed in the workflow keeping a good level of accuracy to produce reliable documentation in which the spatial relationships among layers are properly expressed. A high level of accuracy is also needed to integrate different diachronic models. After the orientations, Photoscan can extract dense point cloud from the dataset, matching images through different algorithms, according to the requirements of the user. It is important to choose appropriate resolution to describe the context: all significant details must be recorded without creating redundant points that can increase the dimensions of the dataset, making it hard to manage. As described before, in many cases it is difficult to manage the resolution during the image acquisition by adjusting the distance between the camera and the target-object.[7] One solution is setting up the parameter of dense point cloud algorithm to use 50% or less pixel of source images during the generation process; otherwise it is possible to decimate the point cloud in external software. As for the point cloud processing operations, we use the open-source software Meshlab[8] that offers several tools for processing and analyse 3D data. Point clouds can be interpolated with the filter Poisson Surface Reconstruction: this algorithm minimizes possible noise in point cloud, producing fine results. Furthermore, through setting up meshing parameters, it is possible to manage the resolution of the resulting mesh. The meshes can be rapidly cleaned from outer triangles generated by the filter (which tends to create closed mesh), through the selection and editing tools of MeshLab. This software is also a powerful tool to integrate different point-clouds to create diachronic models, a very useful aspect in archaeological research and dissemination. For

4 http://www.aibotix.com/technical-data.html

5 For more information: *http://www.agisoft.ru*

6 Scale-invariant feature transform: algorithm to detect and describe local features in images.

7 Ground sample distance (GSD) can be estimated by this formula: GSD = focal plane (width or height in mm) X elevation above ground (in meters) / Focal length in mm.

8 MeshLab is developed by ISTI-Cnr http://meshlab.sourceforge.net

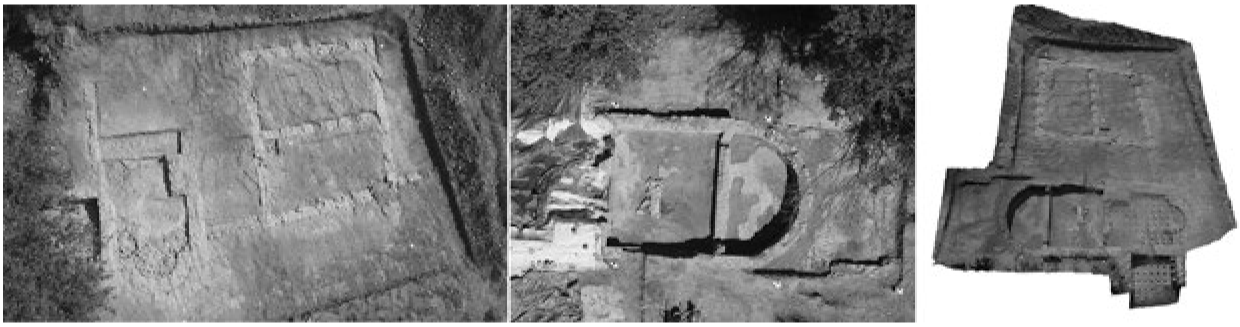


FIG. 6 A-B. AERIAL IMAGE AND DIACHRONIC MODEL WITH TEXTURE OF THERMAL AREA OF SANTA MARTA.

example, the rooms excavated in 2013 within the thermal area of Santa Marta, have been covered for conservation reasons. In 2014 it was possible to survey only the area investigated during the same campaign: removing the coverage was too expensive and archaeologists did not have the possibility to see the whole excavated area at the same time. To overcome this limit we proceed creating the diachronic model of all the area by integrating different datasets acquired in 2013 and 2014.The integration of dataset has been creating following this steps:

- Each point clouds have been carefully cleaned removing points from the older areas that overlap with the newer ones.
- The cleaned point clouds have been merged in a global cloud, using their intrinsic absolute coordinates.
- The global point cloud has been exported to Meshlab to produce a mesh with the algorithm described before.

The last step of the workflow is the textures mapping on polygonal meshes and the creation of orthophotos of each areas: these processes are automatically performed in PhotoScan, which produces high-quality textures and orthophotos. This feature is extremely important for documentation purposes because the colour is, along with the geometry, a key-feature of archaeological stratigraphy. A proper texture resolution is chosen to represent correctly the surfaces, whereas the algorithm for colour correction is used to minimize differences of exposure among the source images. In case of mesh generated from diachronic datasets, was necessary to pay attention to the masking of the source images used for texture mapping. Afterward, the resulting textures have been edited with the open source software Gimp[9] to eliminate some imperfections and reduce some colour differences due to the integrated use of images taken in different lighting situations and site conditions.

4 Interpretation, drawings and dissemination

The documentation produced in the previous workflow is used for layers interpretation and drawing of excavation maps. Orthophotos are imported into the 2D geographic information system used to manage spatial and alphanumeric data of excavation: each stratigraphic unit has been interpreted and rendered with vector drawing. The high precision, accuracy and resolution of the images means that each layer can be drawn to a higher scale and greater detail in an extremely shorter time, compared to the traditional manual drawing on site.

The possibility of drawing within the GIS system nearly simultaneously to the excavation increases the speed of the fieldwork, leaving at the same time the opportunity for archaeologists to review the context in case of doubt. 3D model of stratigraphic units are loaded on MeshLab: the software can therefore manage large datasets as individual layers, to visualize or hide them in a three-dimensional navigable space. Archaeologist can explore archaeological data with a more complete perception, compared to the top view of 2D GIS orthophoto. Furthermore the third dimension lets us to see in overlapped layers more intrinsic information, such as the thickness and the inclination of layers.

MeshLab also allows 3D measurements to change the representation of the models and to vary the lighting direction: the use of a different shader combined with different lighting conditions might improve the visualization of micro-morphological details, otherwise invisible to the naked eye.

Despite the high detail of three-dimensional data set, vector drawing was considered an essential activity for the interpretation of archaeological data: indeed, through drawing, the graphic transposition of the interpretation process is performed. It is a key-phase of the interpretation, in which archaeologists can highlight some detail and exclude irrelevant features from the objective documentation produced with digital technologies.

Finally the documentation has been used for dissemination purposes. The datasets related to the archaeological excavation of Santa Marta have been uploaded in the portal Sketchfab:[10] this service enables the publication of online models, allowing Internet users to view and explore the model in three dimensions. Through the functions of the embed HTML code, the model can be inserted into the web pages of the project, in order to communicate the results of the investigation to a larger public and researchers in a more effective way.

5 Conclusions

The documentation of the archaeological excavation is a process that goes beyond the graphical representation of the contexts: it is the essence of archaeologist's interpretation process, aimed

[9] Gimp is open source software for 2D image editing. www.gimp.org

[10] https:www.sketchfab.com/ATS: sketchfab is a web portal to share interactive 3D models.

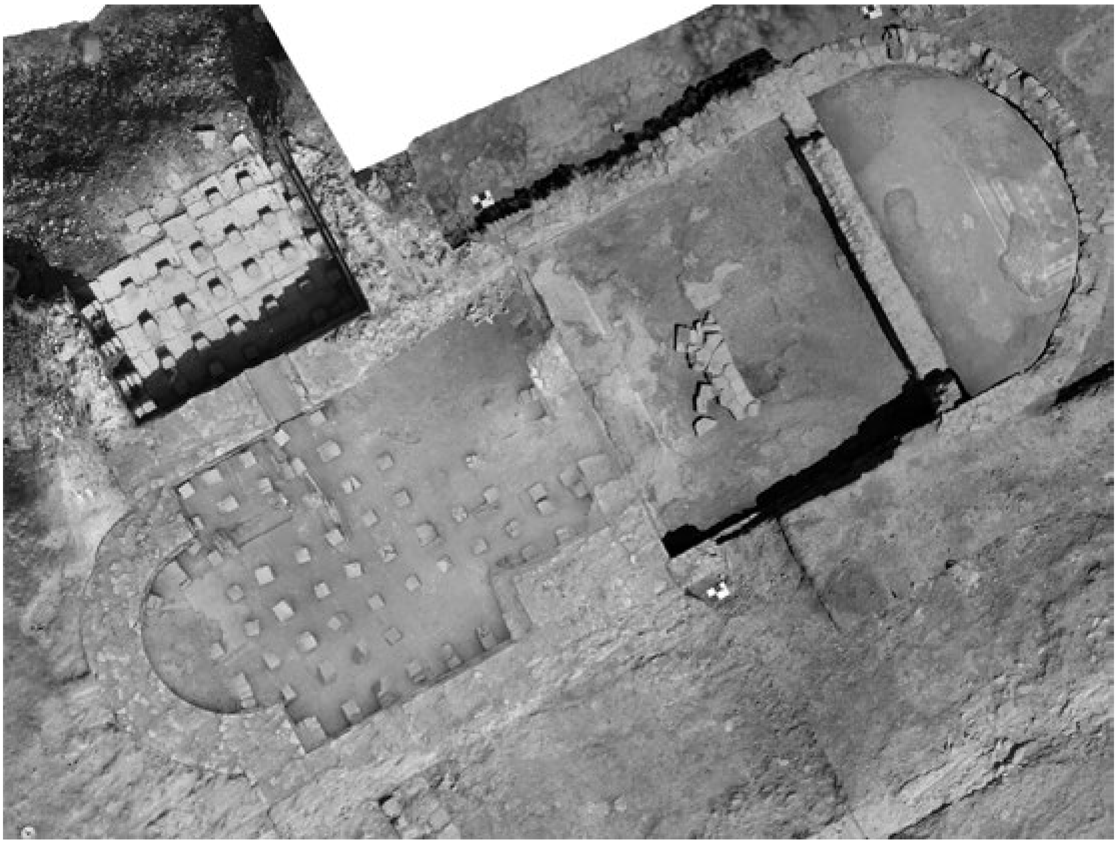


Fig. 7. Diachronic mosaic of orthophotos acquired during two years of excavation.

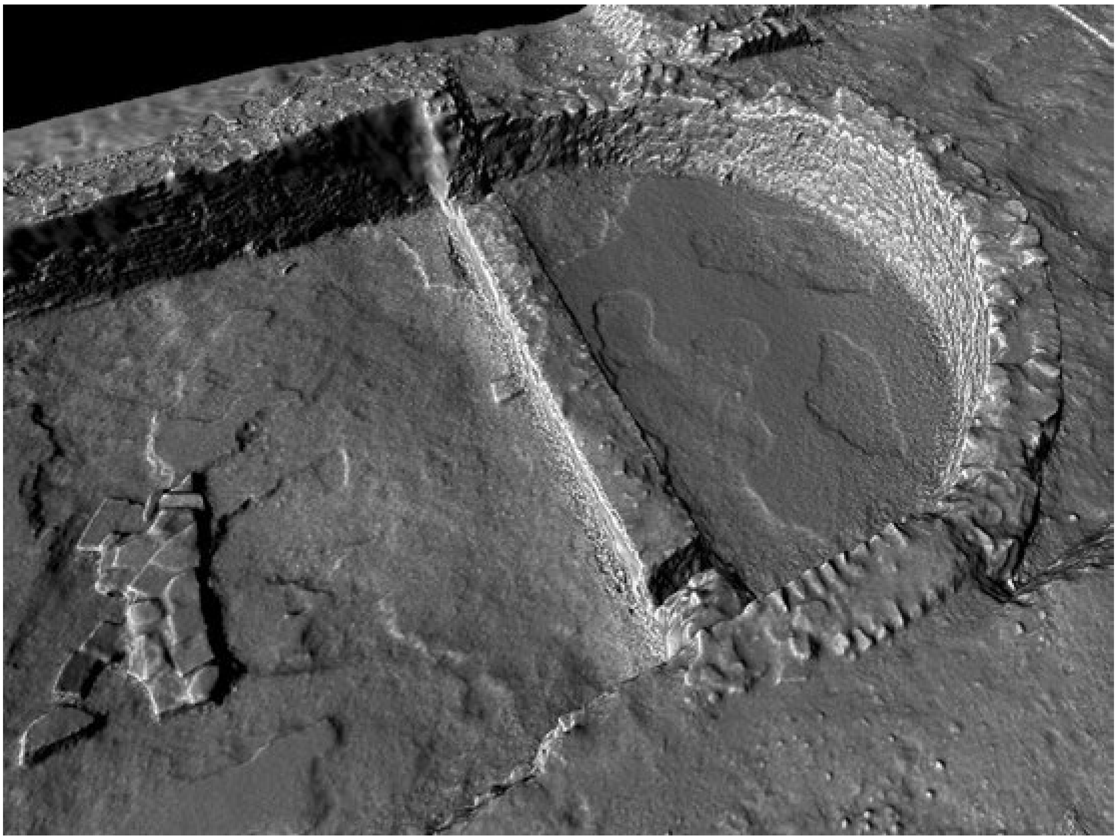


Fig. 8. Radiance scaling shade with incident light.

FIG. 9. INTERPRETATION AND VECTOR DRAWINGS.

at understanding the history of the site. Currently, digital survey techniques and three-dimensional modelling are actually the best tools to document the archaeological evidence in term of detail, accuracy and precision. However the graphic rendering through drawing remains a key-stage within the process of archaeological interpretation, which can be improved but not avoided. Traditional surveying techniques and manual drawing, in most of contexts, can be considered totally obsolete, both for the time required to produce them and for their poor level of precision and accuracy. The case of Santa Marta highlighted the advantages of integration between topographic survey instruments and images, based on modelling to produce documentation faster and, at the same time, with a higher level of accuracy, precision and detail that can integrate acquired datasets in different years and conditions. This approach gave benefits in the organization of the activities on site, allowing archaeologist to proceed faster in excavation actions that are not anymore affected by manual drawing. UAV provided a further aid in recording large areas quickly, capturing images perfectly suitable for the photogrammetric process. Data processing in the laboratory is not affected by a heavy work time as the traditional approach or laser scanning. The most expensive step is related to computer time calculation for the alignment of images and the generation of point clouds. However, these activities do not require a constant interaction with the user, and they can work at night or simultaneously with other activities. The vector rendering of dataset through the digital drawing has allowed us representing correctly all the identified evidences, with greater detail than the traditional draw in scale 1:20. Vector drawings are made directly on orthophotos or point clouds with an up to 1mm resolution. Moreover, this activity did not require operators with special skills in manual drawing, but just experienced archaeologists with basic GIS/CAD software skills and digital drawing rules. Besides to produce the usual 2D documentation of archaeological contexts, the three-dimensional documentation has improved the interpretation process and the context dissemination. The reversibility of the excavation through the overlap of different 3D models lets archaeologist evaluate aspects such as the thickness of the stratigraphic units without the abstraction process belonging to the traditional documentation. This information might be quantified by the measure, to produce an unlimited number of sections. The possibility of integrating different datasets means that certain situations can be represented which cannot be seen in the reality: the integration between diachronic dataset was the only solution to show both the archaeologists and the public the entire thermal area.

However this process had some limitations: whereas the geometry of the surfaces has been properly represented through the integration among different datasets, the colour still represents a problem and it is an issue that needs to be further developed. The images are characterized by different exposures and represent situations that only partially match. Through the image masking it was possible to exclude the main elements of divergence, but areas, which were not excludable, generated artefacts and unwanted elements in the resulting texture; the colour correction algorithm cannot compensate properly the variations among images very different both in exposure and colour. Another limitation is represented by the inability to manage within a GIS system the three-dimensional models and to perform 3D digital drawings: this aspect will be another issue that will be developed by the LAP&T research team in the next future. Despite some limitations outlined above, the 3D documentation has proved to be an indispensable tool in archaeological excavation. In addition to improving the technical execution of activities, it provides an increase in the informative power of the collected data, creating a correspondence with an objective documentation, the 3D model, and its interpretation: the archaeological map.

Bibliography

Arrighetti, A., Cavalieri, M. 2012, Il rilievo fotogrammetrico per nuvole di punti RGB della 'sala triabsidata' del sito archeologico di Aiano-Torraccia di Chiusi (SI). In *Archeologia e Calcolatori 23*: 121-33.

Alsadika, B, Remondino, F., Menna, F., Gerkea, M., Vosselmana, G. 2013. Robust extraction of image correspondences exploiting the image scene geometry and approximate camera orientation, in International Archives of the Photogrammetry. In *Remote Sensing and Spatial Information Sciences* XL-5/W1.

Balletti, C., Guerra, F. 2006. Il rilievo per la rappresentazione 3D: la città romana di *Grumentum*. In F. Guerra and A. Adami, *Modelli 3D della città e del territorio: uno strumento per l'analisi urbana e territoriale, Atti del convegno nazionale Sifet 'Le nuove frontiere della rappresentazione 3D', Castellaneta Marina, Taranto, 14-16 giugno 2006*.

Balletti, C., Guerra, F., Pillon, M., Sartorelli, L. 2007. *The Grumentum's Arena: measure, geometry and shape*. In *Proceeding of CIPA 2007 XXI International Symposium 'Anticipating the future of the cultural past', Athens, 1–6 october 2007*.

Benedetti, B., Gaiani, M., Remondino, F. 2010. *Modelli digitali 3D in archeologica. Il caso di Pompei*. Pisa: Edizioni della Normale.

Bláha, M., Eisenbeiss, H., Sauerbier, M., Grün, A. 2013. *Photogrammetric Modeling of Drapham Dzong (Buthan)*. IGP Bericht 312, Zurich, ETH.

Caldarelli, D., Cantini, F., Ceccaroni, F., Fatighenti, B. 2012. Nuove tecnologie per il rilievo speditivo in archeologia: il caso di San Genesio. In *Archeomatica* 2: 16-20.

Callieri, M., Dell'Unto, N., Dellepiane, M., Scopigno, R., Soderberg, B., Larsson, L. 2011. Documentation and Interpretation of an archaeological excavation: an experience with dense stereo matching. In *VAST: The 11th International Symposium on Virtual Reality, Archaeology and Cultural Heritage*: 33–40.

Campana, S., Ghisleni, M. 2014. Santa Marta: risultati preliminari della seconda campagna di scavo. In *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 9/2013: 494-6. Firenze, All'Insegna del Giglio.

Campana, S., Sordini, M., Remondino, F. 2008. Integration of geomatics techniques for the digital documentation of heritage areas. In R. Lasaponara and N. Masini (eds.), *1st International EARSeL Workshop, CNR, Rome, 30 september - 4 october 2008, Advances in Remote Sensing for Archaeology and Cultural Heritage Management*: 309–12. Roma, Aracne.

Campana, S., Remondino, F. 2008. Fast and Detailed Digital Documentation of Archaeological Excavations and Heritage Artifacts. In A. Posluschny, K. Lambers, I. Herzog (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology*, Berlin 2-6 april 2007: 36–42. Bonn, Rudolf Habelt Gmbh.

Campana, S., Rizzi, A., Sordini, M. 2009. 3D modelling of a romanesque church in Tuscany: archaeological aims and geomatic techniques. In *Proceedings of the 3rd ISPRS International Workshop 3D-ARCH* 2009, 3D *Virtual Reconstruction and Visualization of Complex Archtectures, Trento, Italy, 25-28 february 2009. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVIII-5/W1.

Campana, S., Bianchi, G., Fichera, G. A., Lai, L., Sordini, M. 2012. 3D Recording and Total Archaeology: From Landscapes to Historical Buildings. In *International Journal of Heritage in the Digital Era* 1, 3: 443-60.

Campana, S., Remondino, F. 2014. 3D Recording and Modelling in Archaeology and Cultural Heritage Theory and best practices. *British Archaeological Reports International Series* 2598, Oxford.

Cavalieri, M., Mainardi Valcarenghi, G., Novellini, A. 2009. Il rilievo fotogrammetrico: un metodo alternativo di documentazione dello scavo archeologico. Casi applicativi presso la villa romana di Aiano-Torraccia di Chiusi (SI). In *Fasti Online Documents&Reserches*.

Cowley, D. C., Opitz, R. S. 2013. *Interpreting Archaelogical Topografy: Lasers, 3D Data, Observation, Visualisation and Applications*. Oxford, Oxbow.

D'Andrea, A., Barbarino, M. 2012. Modellare lo scavo stratigrafico: esperienze e tecniche a confronto. In *Archeologia e Calcolatori 23*: 229-45.

De Felice, G., Mangialardi, N. M., Sibilano, M. G., Volpe, G. 2008. Late Roman villa at Faragola (Foggia, Italy). Laser scanning for a global documentation methodology during field research. In A. Posluschny, K. Lambers, I. Herzog (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology*, Berlin 2-6 april 2007: 98-9. Bonn, Rudolf Habelt Gmbh.

De Felice, G., Sibilano, M. G., Volpe, G. 2008. Ripensare la documentazione archeologica: nuovi percorsi per la ricerca e la comunicazione. In *Archeologia e Calcolatori 19*: 271-91.

Doneus, M., Neubauer, W., Studnicka, N. 2003. Digital recording of stratigraphic excavations. In K. F. Ausserer, W. Börner, M. Goryany, N. Karlhuber, N. Vöckl (eds.), *Enter the Past. The E-way into the four Dimensions of Cultural Heritage. Proceedings of the 31st International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA). British Archaeological Reports International Series* 1227: 451-6. Oxford, Archaeopress

Doneus, M., Neubauer, W. 2005. 3D laser scanners on archaeological excavations. In *Proceedings of the XX International CIPA Symposium, Torino, Italy, 26 september–1 october, 34:* 226-31.

Doneus, M., Neubauer, W. 2008. Digital recording of stratigraphic Archaeological excavations using terrestrial 3D laser scanners. In *ViaVIAS 02*: 45-52.

Doneus, M., Verhoeven, G., Fera, M., Briese, C., Kucera, M., Neubauer, W. 2011. From Deposit To Point Cloud – A Study Of Low-cost Computer Vision Approaches For The Straightforward Documentation Of Archaeological Excavation. In *Proceedings of the XXIIIrd International CIPA Symposium,* Prague: 81–8.

Eisenbeiss, H. 2009. *UAV Photogrammetry*. Unpublished PhD thesis, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, Mitteilungen N.105 Available at: doi:10.3929/ethz-a-005939264

Eisenbeiss, H., Sauerbier, M. 2011. UAVS for the documentation of archaeological excavations. In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Science*s XXXVIII-5/V: 526–31. Newcastle upon Tyne.

Fassi, F., Fregonese, L., Ackermann, S., De Troia, V. 2013. Comparison between laser scanning and automated 3d modelling techniques to reconstruct complex and extensive cultural heritage. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W1.

Felici, C., Campana, S., Frezza, B. 2012. La chiesa battesimale di San Pietro in Pava (San Giovanni d'Asso – SI – Italia): un incontro di dati stratigrafici, studio territoriale e attestazioni d'archivio. In A*tti del XV Congresso Internazionale di Archeologia Cristiana, Toledo 8– 12 Settembre 2008*: 463-80

Fiorini, A. 2008. Esperienze di fotomodellazione e stereofotorammetria archeologica. In De Felice, G., Sibilano, M. G., Volpe, G. (eds.), L'informatica e il metodo della stratigrafia, Atti del Workshop, Foggia 6-7 giugno 2008: 175-86. Bari, Edipuglia.

Fiorini, A. 2012. Tablet PC, fotogrammetria e PDF: strumenti per documentare l'archeologia. In *Archeologia e Calcolatori 23*: 213-27.

Forte, M., Dell'Unto, N., Issavi, J., Onsurez, L., Lercari, N. 2012. 3D archaelogy at Çatalhöyük. In *International Journal of Heritage in the Digital Era* 1, 3: 351–77.

Gonizzi Barsanti, S., Remondino, F., Visintini, D. 2012. *Photogrammetry and Laser Scanning for archaeological site 3D modelling. Some critical issues*. In V. Roberto, L. Fozzati (eds.), *Proceeding of the 2nd Workshop on The New Technologies for Aquileia*, B1–B10.

Gruen, A., Zhang, Z., Eisenbeiss, H. 2012. *UAV photogrammetry in remote areas – 3D modeling of Drapham Dzong (Bhutan)*, in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIX-B1*: 375-9. Melbourne.

La Rosa, N. 2012. *La metodologia di rilievo e documentazione tridimensionale applicata al caso studio della capanna B14 nello scavo archeologico dell'età del Bronzo di Mursia, Pantelleria (TP)*. Unpublished MA thesis, Facoltà di Lettere e Filosofia, Università di Bologna.

Masci, M. E., De Santis, A. 2011. The EU Project CARARE and the Scuola Normale Superiore contribute: Giving Access to 2D and 3D representations of Pompeii monuments through Europeana. In *Proceedings of the EVA 2011 Florence – Electronic Image & Visual Arts*: 34-9. Bologna.

Musson, C., Palmer, R., Campana, S. 2005. *In volo nel passato*. Aerofotografia e cartografia archeologica. Firenze.

Panella, C., Gabrielli, R., Giorgi, C. 2011. Le 'Terme di Elagabalo' sul Palatino: sperimentazione di un metodo fotogrammetrico 3D applicato allo scavo archeologico. In *Archeologia e Calcolatori 22*: 243-60.

Peripimeno, M. 2009. Documentazione 3D dello scavo archeologico: prime conclusion. In P. Favia and G. Volpe (eds.), *V Congresso Nazionale di Archeologia Medievale*: 63–7. Firenze, All'Insegna del Giglio.

Piani, P. 2013. La strumentazione UAV nel rilievo e nella modellazione tridimensionale di un sito archeologico. In *Archeomatica 1*: 6-10.

Rapanà, M. 2010. Verso nuove forme di documentazione archeologica. La modellazione tridimensionale tra applicazioni e limiti di utilizzo. In *Archeomatica 4*: 14-8.

Remondino, F., El-Hakim, S. 2006. Image-based 3D modelling: A review. In *The Photogrammetric Record*, 21, 115: 269–91.

Remondino, F., Gruen, A., Von Schwerin, J., Eisenbeiss, H., Rizzi, A., Girardi, S., Sauerbier, M., Richards, H. 2009. Multi-Sensor 3D Documentation of the Maya Site of Copan. In *Proceedings of the 22nd Symposium CIPA XXII, Kyoto, Japan, 11-15 october 2009*.

Remondino, F., Rizzi, A. 2010. Reality-based 3D documentation of natural and cultural heritage sites-techniques, problems and examples. In *Applied Geomatics* 2: 85–100.

Remondino, F. 2011a. *Rilievo e modellazione 3D di siti e architetture complesse*. In *Disegnarecon*: 90–8. Available at: doi: 10.6092/issn.1828-5961/2573

Remondino, F. 2011b. Heritage Recording and 3D Modelling with Photogrammetry and 3D Scanning. In *Remote Sensing* 3: 1104–38.

Remondino, F., Pizzo, S., Kersten, T., Troisi, S. 2012. Low-Cost and Open-Source Solutions for Automated Image Orientation – A Critical Overview. In M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino, R. Caffo (eds.), *Progress in Cultural Heritage Preservation*, *4th International Conference, EuroMed 2012, Lemessos, Cyprus, LNCS 7616*: 40-54.

Rinaudo, F., Chiabrando, F., Lingua, A., Spanò, A. 2012. Archaeological site monitoring: UAV Photogrammetry can be answer. in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIX-B5: 583-8. Melbourne.

Russo, M, Remondino, F., Guidi, G. 2011. Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico. In *Archeologia e Calcolatori* 22: 169–98.

Valenti, M. (ed.) 2008. *Miranduolo in Alta Val di Merse (Chiusdino-SI). Archeologia su un sito di potere del Medioevo toscano*, Firenze.

Von Schwerin, J., Richards Risetto, H., Remondino, F., Agugiaro, G., Girardi, G. 2013. The MayaArch3D project. A 3D WebGIS for analyzing ancient architecture and landscapes. In *Literary and Linguistic Computing 28*, 4: 736-53.

Visual Space, Defence, Control and Communication: Towers and Fortresses System of the Tuscan Coastal Belt and Islands

Michele De Silva
Dipartimento di Storia, Archeologia, Geografia, Arti e Spettacolo,
University of Florence, Italy

Abstract: The paper presents a research project focused on the investigation of the visual space related to the towers and fortresses system of the Tuscan coastal belt and archipelago in different historical periods. Some preliminary data acquisition, chronological classification and visibility analysis has been carried out in order to check the dataset, model and procedures.

Keywords: Visual space, Viewshed, Defensive structures, Coastal towers, Tuscany.

Introduction

From late medieval times to the end of the 19th century, the coastal belt of Tuscany has been controlled by a towers and fortresses system. The first coastal towers were built by the Republic of Pisa in the 12th and 13th centuries. As early as the mid-14th century these formed an efficient coastal warning and communication system along the mainland coast and in the islands (Giglio, Elba, Capraia e Gorgona). The towers constituted a control and communication network in which each tower was able to alert its neighbours by means of smoke signals during the day and with the lighting of fires by night. The sighting of a danger coming from the sea (enemy ships or pirates) could be communicated from one tower to another along the coast from the Giglio island up to Pisa, giving way to organize the defence and allowing the people to find sanctuary in the region's fortified villages (Carrara 2000).

Although with a different emphasis in the various ages, the main functions of towers and fortresses system are the control of the shore lines, the defence of mainland from pirates and enemies coming form the sea, the control of maritime commerce and of smuggling and to provide, as we have seen, a fast and efficient communication system. All these functions involve the priority of visibility and inter-visibility issues, and underline the importance of investigating the visual space of these types of military structures.

Although the role of these control structures is in general well known, it is worth investigating the weight that the various functions of these structures may have had in different periods. Moreover, it is not always clear which structures had been in use at one time. Furthermore, in some cases, we may ignore their existence or location.

In other words, visual space analysis seems to be one of the main keys to investigate this control system and to understand relationships between different military structures and between these and other elements of the landscape such as roads, settlements, countryside, productive areas, ports and harbours. In fact, the location of the towers is very oriented, not as a function of absolute maximum visibility, but rather to a target space (the sea) and according to a mutual inter-visibility that becomes a communication network.

1 The research

The research presented here, today at an early stage, is focused on the investigation of the visual space related to the towers and fortresses system of the Tuscan coastal belt and archipelago in different historical periods.

Inter-visibility, cumulative viewshed and other visual and spatial analysis will be carried out to investigate, for different periods, this hierarchically structured system (consisting in fortified towns and villages, fortress and towers) and his relationship with other elements of the landscape. In particular, the visibility from/to the connecting military road network, derived from historical cartography, will be analysed.

Despite the known limitations of 2.5D visibility (Hurtado *et al.* 2013; van Leusen 2004), we believe that, because of the particular characteristics of these types of structures (height and location), the disturbances of visibility (mainly vegetation) are a negligible factor. From the beginning of the nineteenth century, however, we have sufficient data on land use that could make the simulation process more reliable. As a further step the possible use within the GIS framework of the historical cadastres (De Silva 2010; De Silva and Pizziolo 2004) may allow us to acquire specific information related to land use and vegetation cover.

In addition to reconstruct the system of towers and fortresses in different phases, main goals are – through visual and spatial analysis – to support the historical interpretation of the landscape and to locate structures whose traces were lost. In fact, 'holes' in the global visual space and in the inter-visibility network may indicate lacks in the documentation or the presence of unknown structures. Moreover, where gap in the inter-visibility are present, cumulative viewshed analysis from nearby towers can help us in identifying the missing structures.

Recently published data collected in the context of the PERLA European Project (Guarducci, Piccardi, Rombai 2014) provide detailed information about the location, typology, chronology and reference sources relative to each single structure such as fortified settlements, fortresses, towers and military houses in the coastal belt and islands of Tuscany. Thanks to this study it is possible to investigate the visual space of more than 160

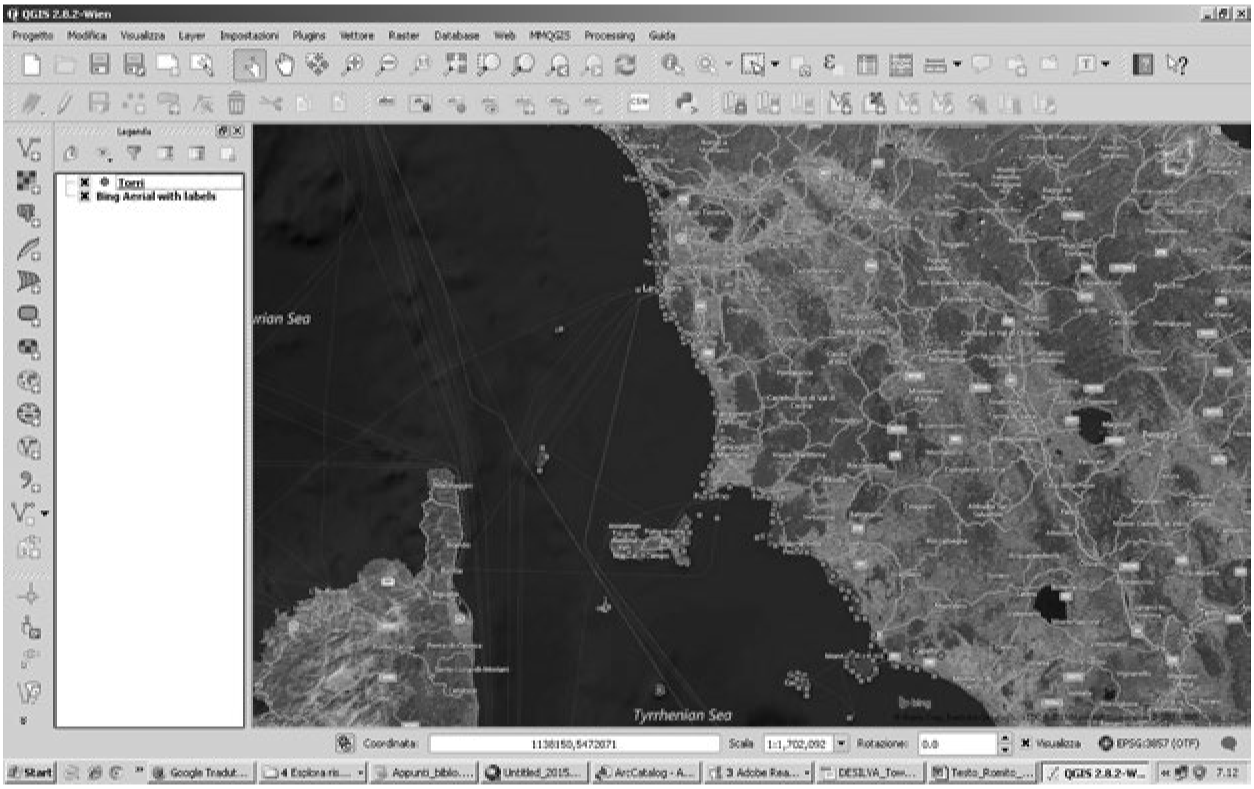


Fig. 1. Location of towers and fortresses in the coastal belt and islands of Tuscany.

structures dating from late mediaeval times to the end of the nineteenth century.

Starting from this *corpus* of data, as a first step, the military structures have been georeferenced in a GIS environment as accurately as possible using current and historical cartography and aerial photos (Fig. 1).

The second step consists in defining which control structures were active in different periods so to obtain sets of contemporary 'observer points' in order to investigate the visual space and to check inter-visibility in different historical phases. The possibility of building a synchronic framework depends on the availability of extensive information in the historical sources, so we decided to set our chronological layers on the basis of such availability.

In order to check the dataset, model and procedures, we have chosen, as an experimental case study, to investigate the Grosseto coastal belt (Southern Tuscany) in 1825, for which we have sufficient information.

For the visibility and inter-visibility analysis we used a 10m resolution DEM and a range of offset values (10-15m) for the observation points based on the available evidence.

The viewshed analysis confirms a complete view of the shoreline and of the facing sea. Furthermore, visibility extends inland to Grosseto (Fig. 2).

The analysis of linear inter-visibility (line of sight) between pairs of nearby towers shows some breakpoints (Fig. 3). These results may be the product of data issues or incorrect modelling parameters (e.g. DEM errors, inaccurate georeferencing or inappropriate offset values), or may suggest a non sequential model of visual communication between nearby towers. Further data and model validations will be carried out to investigate these.

Another experimental case study concerns the location of a tower dating to the mid-14th century. A document of this period mentions, sequentially from South to North, the towers involved in the alert communication by means of smoke and fires. After the '*roccha di Piombino*' the document mentions '*una montagna che si chiama Cuglianera*' and then the '*Cavo della Campana*' before citing San Vincenzo (Carrara 2000: 10; Vigo 1905).

We have lost every trace of the place names 'Cuglianera' and 'Cavo della Campana', although the latter is almost certainly identifiable with the 'Torraccia'. The first was probably located in the territory of Piombino but we do not know where.

In order to delimit the area in which we can locate the missing tower, a cumulative viewshed from Piombino and Torraccia has been carried out (Fig. 4). The resulting overlapping zone of the viewsheds from both towers represents the area where most probably the tower was located.

2 Final remarks

Although the research is only at an early stage, the preliminary results of experimental case studies are encouraging.

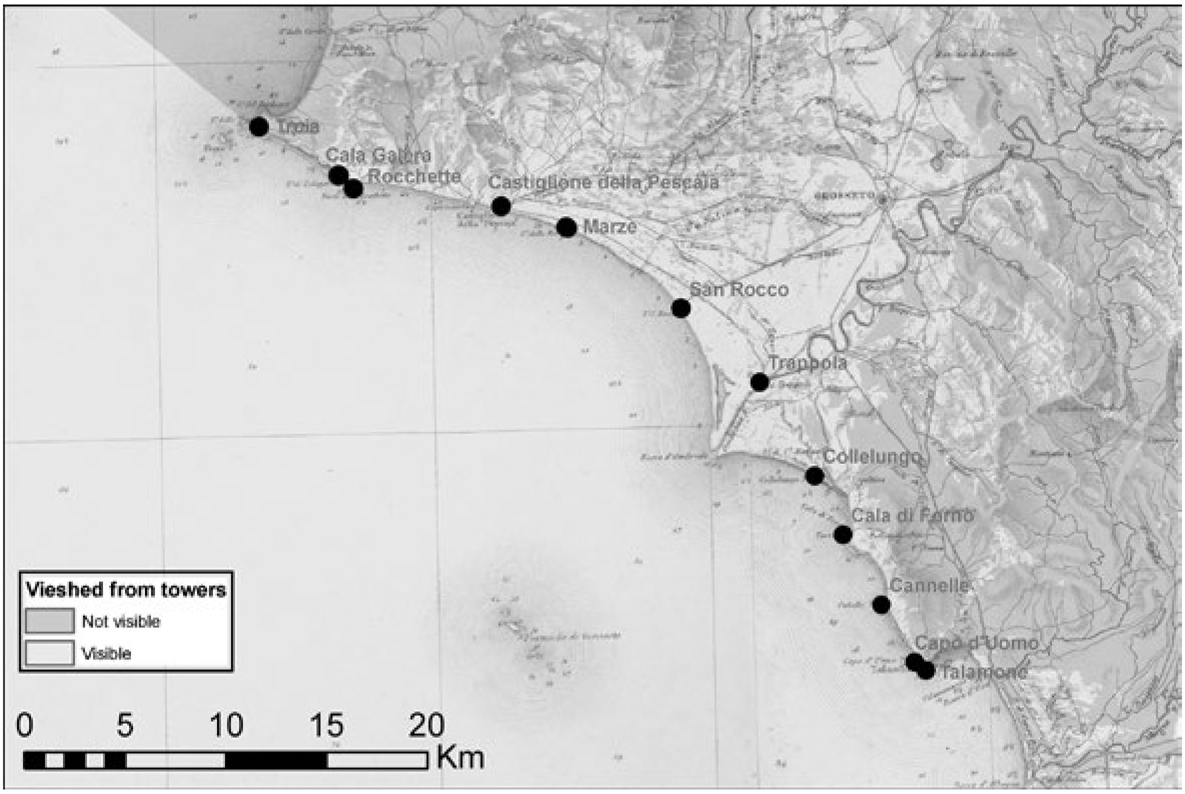


FIG. 2. VIEWSHED FROM CONTROL STRUCTURES IN THE GROSSETO COASTAL BELT IN 1825 (GREEN=IN VIEW, PINK=NOT IN VIEW. BACKGROUND: INGHIRAMI, G. 1830. CARTA GEOMETRICA DELLA TOSCANA).

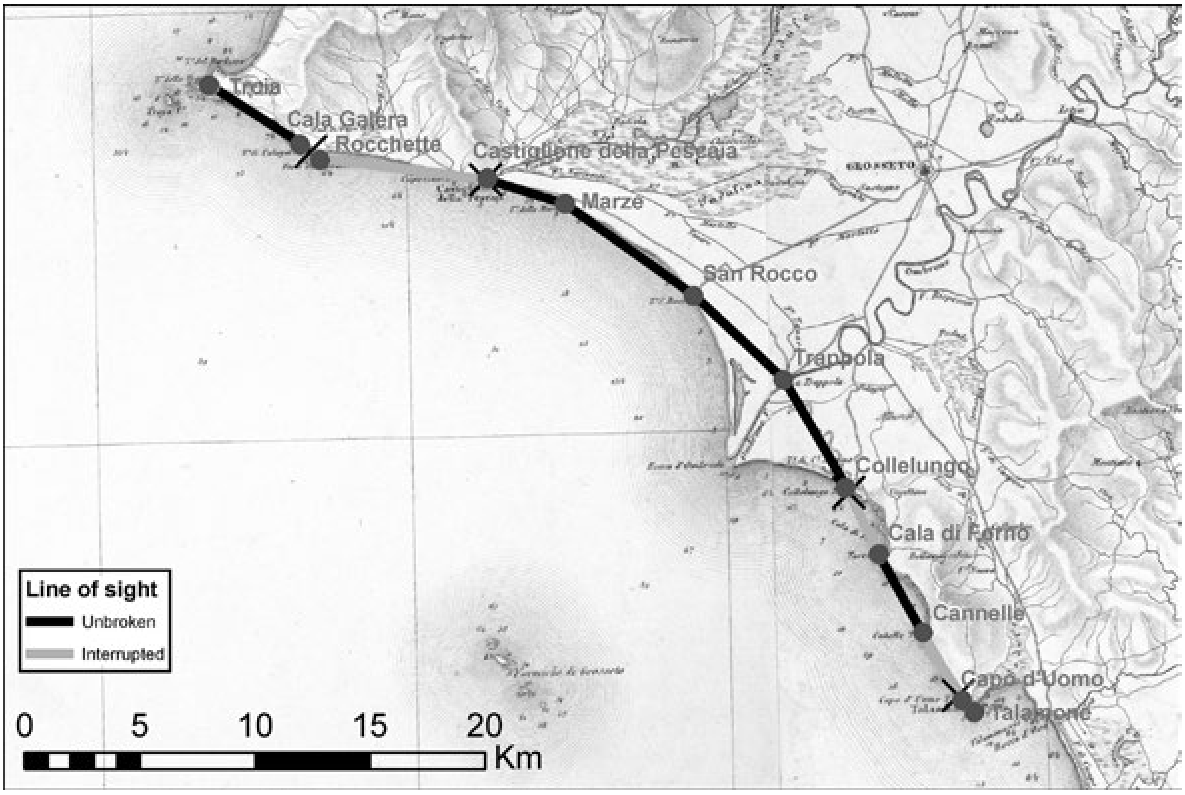


FIG. 3. UNBROKEN (IN BLACK) AND INTERRUPTED (IN GRAY) LINES OF SIGHT FROM CONTROL STRUCTURES IN THE GROSSETO COASTAL BELT IN 1825 (BACKGROUND: INGHIRAMI, G. 1830. CARTA GEOMETRICA DELLA TOSCANA).

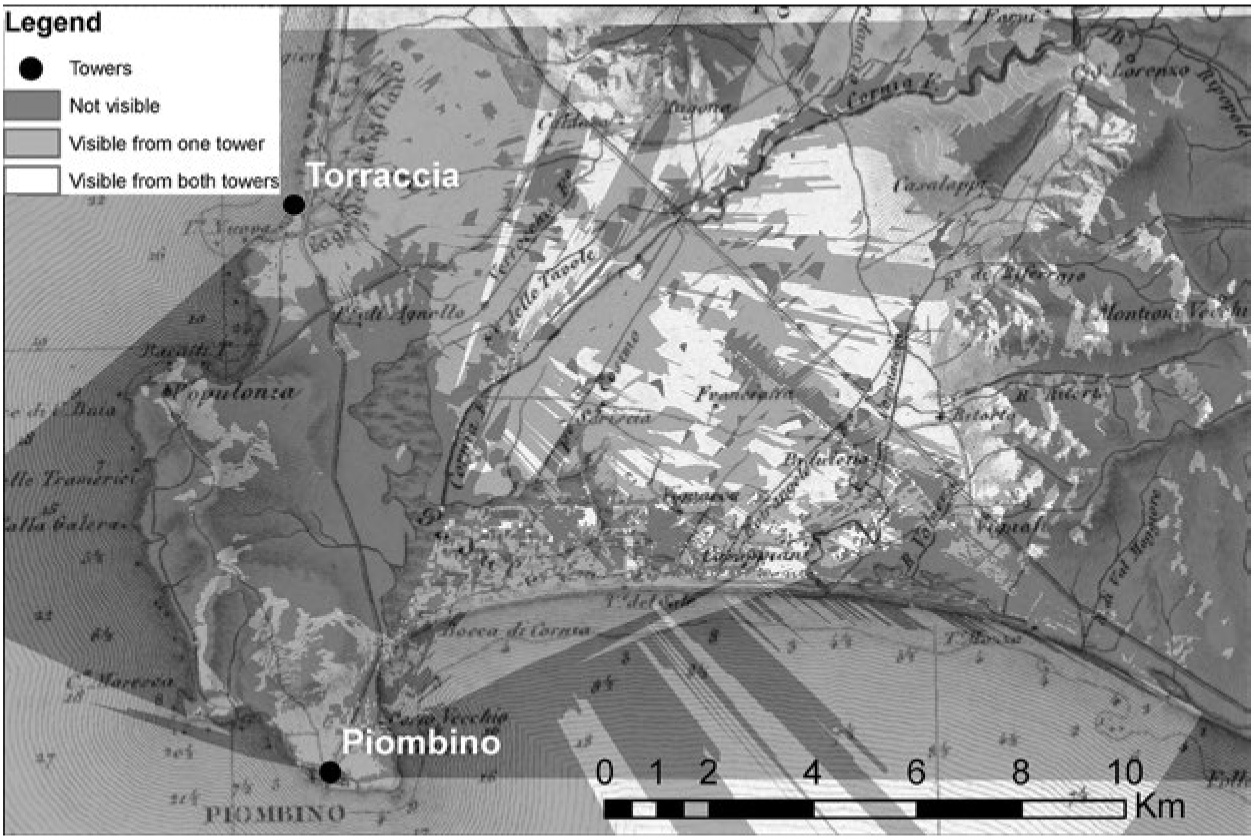


Fig. 4. Cumulative viewshed from Torraccia and Piombino towers (Background: Inghirami, G. 1830. Carta Geometrica della Toscana).

It is clear, however, that synchronic analysis of the visibility and inter-visibility of the towers and fortresses of the coast and islands of Tuscany will deepen our understanding of the region, the relationships between these and other features of the landscape, and how those relationships changed over time.

Bibliography

Carrara, M. 2000. *Torri e difese costiere del Principato di Piombino*. Pontedera, Pisa, Bandecchi & Vivaldi.

De Silva, M. 2010. Landscape of the Past: the Maremma Regional Park and the Grosseto Coastal Belt. Methodology and Technical Procedures. In F. Niccolucci and S. Hermon (eds.), *Beyond the Artifact – Digital Interpretation of the Past, Proceedings of Computer Applications and Quantitative Methods in Archaeology 2004, Prato, Italy 13-17 April 2004*: 166-70. Budapest, Archaeolingua.

De Silva, M. and Pizziolo, G. 2004. GIS Analysis of Historical Cadastral Maps as a Contribution in Landscape Archaeology. In K. Fischer Ausserer, W. Börner, M. Goriany, L. Karlhuber-Vöckl (eds.), *Enter the Past. The E-way into the Four Dimensions of Cultural Heritage Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 31st Conference, Vienna, Austria, April 2003. British Archaeological Reports International Series* 1227: 294-8. Oxford, Archaeopress.

Guarducci, A., Piccardi, M., Rombai, L. 2014. *Torri e fortezze della Toscana tirrenica. Storia e beni culturali*. Livorno, Debatte Editore.

Hurtado, F., Löffler, M., Matos, I., Ssacristán, V., Saumell, M., Silveir,a R. I., Staals, F. 2013. Terrain Visibility With Multiple Viewpoints. In L. Cai, S. W. Cheng, T. W. Lam (eds.), *Algorithms and Computation. Proceedings of the 24th International Symposium, ISAAC 2013, Hong Kong, China, 16-18 December 2013*. *Lecture Notes in Computer Science* 8283: 317-27. New York, Springer.

Van Leusen, M. 2004. Visibility and the Landscape: an exploration of GIS modelling techniques. In K. Fischer Ausserer, W. Börner, M. Goriany, L. Karlhuber-Vöckl (eds.), *Enter the Past. The E-way into the Four Dimensions of Cultural Heritage Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 31st Conference, Vienna, Austria, April 2003. British Archaeological Reports International Series* 1227: 352. Oxford, Archaeopress.

Vigo, P. 1905. I segnali del medioevo e un documento pisano. In *Miscellanea di erudizione* 1, 3-4. Pisa.

CHAPTER 6
Integrating 3D Data

Photomodelling And Point Cloud Processing. Application in the Survey of the Roman Theatre of *Uthina* (Tunisia) Architectural Elements

Meriem Zammel
meriem.zammel@gmail.com
University of Carthage, Tunisia;
University Paris 1 Panthéon Sorbonne, France

Abstract: This paper aims to describe the results obtained concerning the archaeological survey of architectural elements of the theatre of Uthina (Tunisia) by using new technologies. In particular using image based modelling, ARC3D, 123DCatch, point cloud processing and low altitude aerial photograph. The representation of each architectural element of the roman theatre of Uthina has been obtained from multiple data sources. The representation of architecture is no matter a two dimensional graph, it is now possible to represent and describe each part using 3D modelling. The archaeological description was made using web system Theatrum in which we can find multiple data sources: photographs, aerial photograph, image based modelling, and text. In synthesis we can talk about a sequence composed by survey-representation-description, in which new technologies are as an articulation between disciplines: Computer Science, Architecture, and Archaeology.

Keywords: Photo modelling, Point cloud processing, Digital description.

Introduction

In 2004-2005, a digital survey of the roman theatre of *Uthina* (Tunisia) has been undertaken by the MAP laboratory using new technologies. The excavation of the theatre has been performed under the scientific direction of two archaeologists: Habib Ben Hassen for the National Institute of cultural heritage (Tunis, Tunisia) and Christian Landes for the National Institute of Art History (Paris) in the context of bilateral cooperation between Tunisia and France. The two archaeologists have carried out the excavation in order to specify the conservation state of the monument and its chronology. This paper aims at describing the results obtained in my PhD thesis in Archaeology at the University of Paris1-Panthéon Sorbonne in the MAP and ARSCAN laboratories under the direction of Professor Alain Schnapp.

1 Data acquisition on the field

During the data acquisition process multiple techniques have been used: Topography, Photography, Scanning and low altitude aerial photography. A point cloud survey from 3D laser scanner and from an aerial low attitude RC helicopter were carried out. The point cloud survey allows viewing the entire monument including its architectural elements, stucture and even vegetation, providing metric information and a 3D view. This data acquisition process generates millions of coordinate points (De Luca 2006).

The principal elements of the theatre of *Uthina* have been pointed out on the point cloud survey in order to locate the aerial photographs and to scale them. This low altitude photograph survey is an important result because it shows the different parts of the theater and its structure.

A manual survey of each element was done in order to draw and measure the main elements on the field. Each architectural element was numbered and photographed. This roman theater has a complex shape and geometry. Pictures were taken all around each element in order to perform the photomodelling. Points were placed on the surface stone in order to help the software to do the calibration of the cameras.

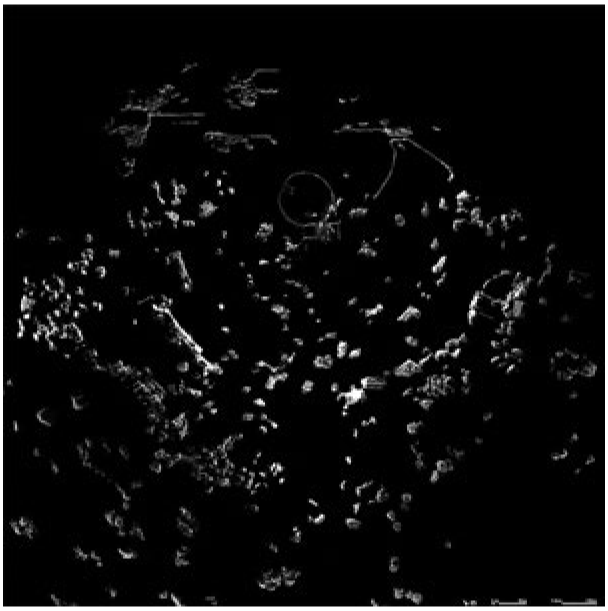


Fig. 1. Point cloud survey of the theatre of *Uthina*.

2 Data processing

On the basis of the manual architectural survey, a 2D representation (plans, façade) was produced before going on with the 3D modelling of each architectural element.

In order to experiment the representation technique from the manual survey, as well as 3D modelling and image based modelling we chose one of the surveyed elements (element E6), which is a complex arch situated in the *summa cavea.*

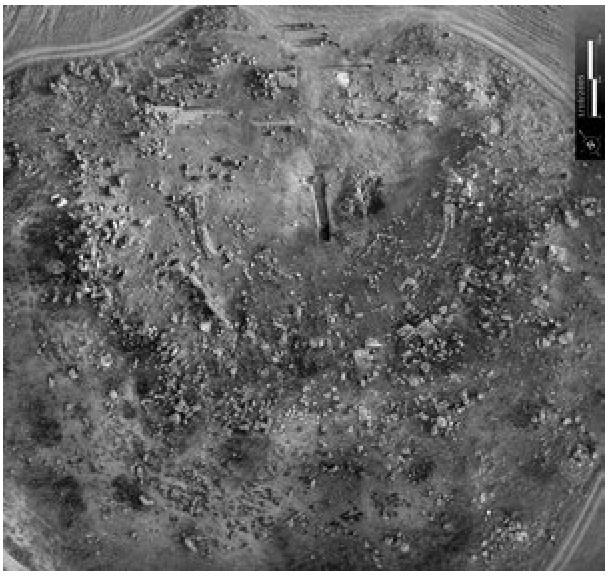


Fig. 2. Low altitude aerial photograph of the theatre of *Uthina*.

Before performing the photomodelling of the elements some control points have been place on the surface of the stones in order to assist the calibration of the digital camera for the image-based modelling software. Then, the free software ARC3D (Baratin *et al*. 2013) and 123Dcatch by Autodesk (Casu and Pisu 2013) were used a few years later in order to experiment automatic photomodelling of the theatre of *Uthina* architectural elements. Indeed when I started my thesis in 2005 automatic photomodelling did not exist. I used Image modeller in 2007 on the field and then in 2014 I performed automatic photomodelling with the pictures taken in 2007.

A point cloud survey was done in order to scan the whole monument. The 3D geometrical models in .obj format obtained from the photomodelling process were replaced on the point cloud survey of the entire monument in the laboratory using the software Maya; the result was the 3D representation of the whole building with its architectural elements. The point cloud and the 3D model are the interface to access to multiple scale representation.

3 Digital description

The element E1 is an *opus quadratum* wall. It is well preserved in the *ima cavea* of the theatre (Landes and Ben Hassen 2007). Above the wall, we found the remains of vaults made in *opus caementicus*. In the middle, the vault reaches the centre of the theatre. The construction technique using *opus quadratum* and *opus caementicum* is also used in other theatres such as the roman theatre of Carthage or the theatre of *Bulla Regia* (Ksouri 2012).

The image based modelling of the element E1 shows the apparatus stones and the texture. There are three arcs in the down part of the wall. The middle one is bigger than the two others on each side.

The image based modelling of those elements (E2-E2bis) is not a very accurate case because of the shape complexity.

The different image-based models of each element are placed on the point cloud of the theatre.

On each side of the wall, there are pillars with vaults (Elements E4 and E5). All of the elements E1-E4-E5 are the best preserved structures of the *cavea* and are visible clearly also in the low altitude aerial photograph. In front of the wall there are the elements E2 and E2bis composing the *vomitorium*.

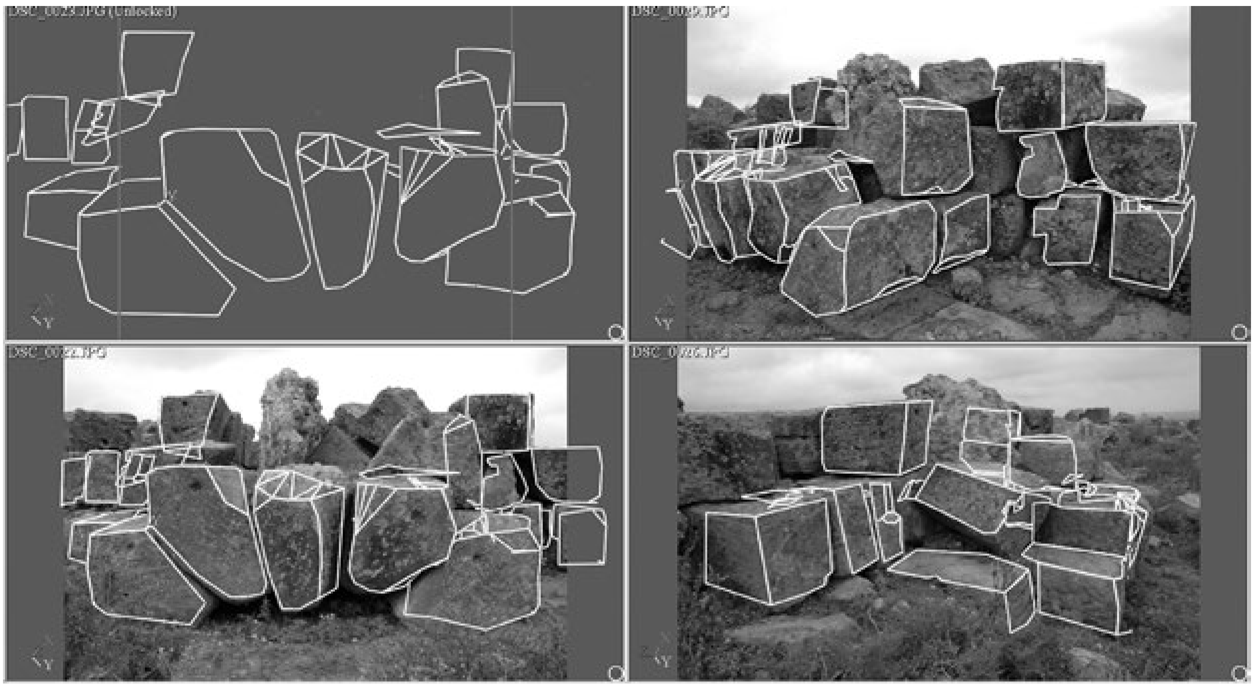


Fig. 5. Photo modelling of element E6 using image modeller.

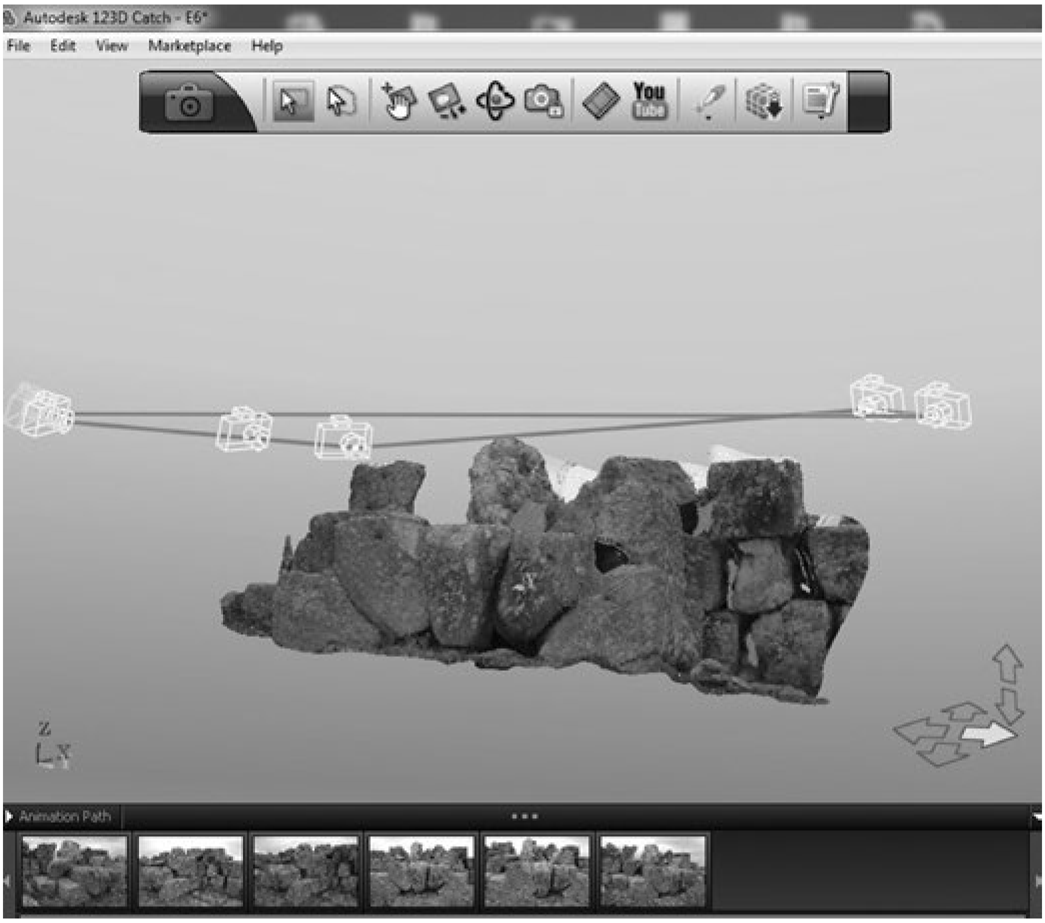


FIG. 6. PHOTO MODELLING OF ELEMENT E6 USING 123DCATCH BY AUTODESK.

FIG. 7. POINT CLOUD PROCESSING OF THE ELEMENT E6.

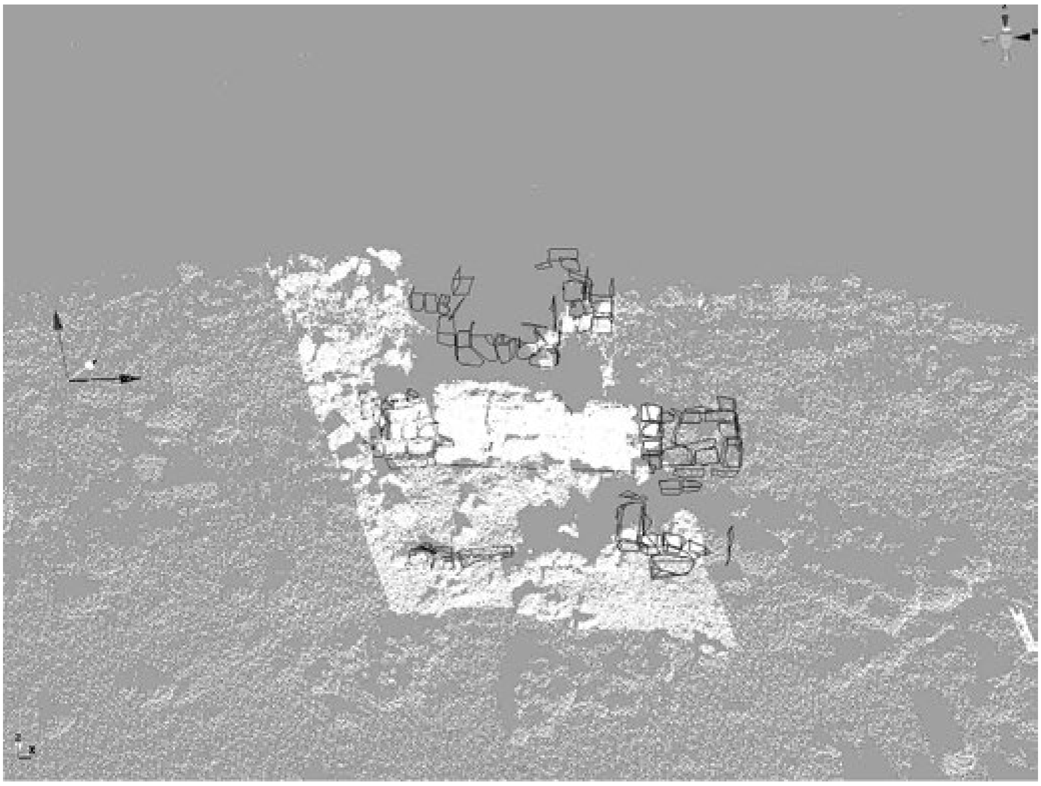


Fig. 8. Photo modelling of elements on 3D point cloud survey.

The archaeological description has first of all grounds on a visual inspection on the field, then on anatomical drawing, on dimensions, and finally, on investigation, all that you need for an expertise (Schnapp 1998).

The digital description was done at the monument scale and also in comparison with other theatres in the roman times in the *Theatrum* online platform, a web system with multiple scale representation, such as pictures, photomodelling, bibliography, text etc.

The model description of the monument is useful for a 3D reconstruction and also to add structure information in a database (De Domenico 2006). Indeed the architectural system can be described as objects collection structured and identified by a precise vocabulary, for example: capital, moulding, column.

The digital description of roman theatres presented in the platform *Theatrum* continues from the work coming from the online platform *Nubes* (De Luca 2006) in regards to model description, survey, and dimensions. Furthermore the chronology was incorporated thanks to the platform *Nubes Tempus* (Stefani 2010), which shows building transformations in 3 D. The *Nubes* platform answers to the need of managing multiple and heterogeneous data obtained during the study of a monument and from various disciplines based on different media using 3D modelling. It allows also the management of 3D representations of monuments using web technology. Moreover this platform relates quantitative information obtained from the survey and qualitative information obtained from the interpretation of documentary sources.

The methodology begins by creating a 3D digital model, which is the interface access to data concerning the actual state of the building, the geometrical interpretation and the hypothetical restitution of previous states. Then the spatial referencing of heterogeneous information and documentary sources are used to establish relationships between two-dimensional and three-dimensional representation of the objects.

In the *Theatrum*'s platform, we first found principal components of the theatre, *cavea, orchestra, scaenae*. Then multiple 3D survey techniques were used: image based modelling, two-planar survey, digital photographs, etc. Its architectural elements testify its importance and the role it played in the ancient city. Epigraphy, decor, numismatics testify that the theatre of *Uthina* was built in the II century (Landes and Ben Hassen 2007).

In this platform it is necessary to compare theatres according to definite parameters: situation, dimensions, chronology. From the ID value in the database sheet it is possible to access its digital description. Different theatres are thereby studied.

3.3 Description of the database sheets

The sheets used for the digital description of the roman theatres in the relational database *Theatrum* are composed by:

- Theatre sheet with: ID, the name of the theatre, the name of the ancient city, its orientation. This sheet is in relationship with that devoted to dimensions, survey, and chronology.

- The data sheet for the *orchestra*, the *scaenae*, and the *cavea* in which it is possible to find morphological parts

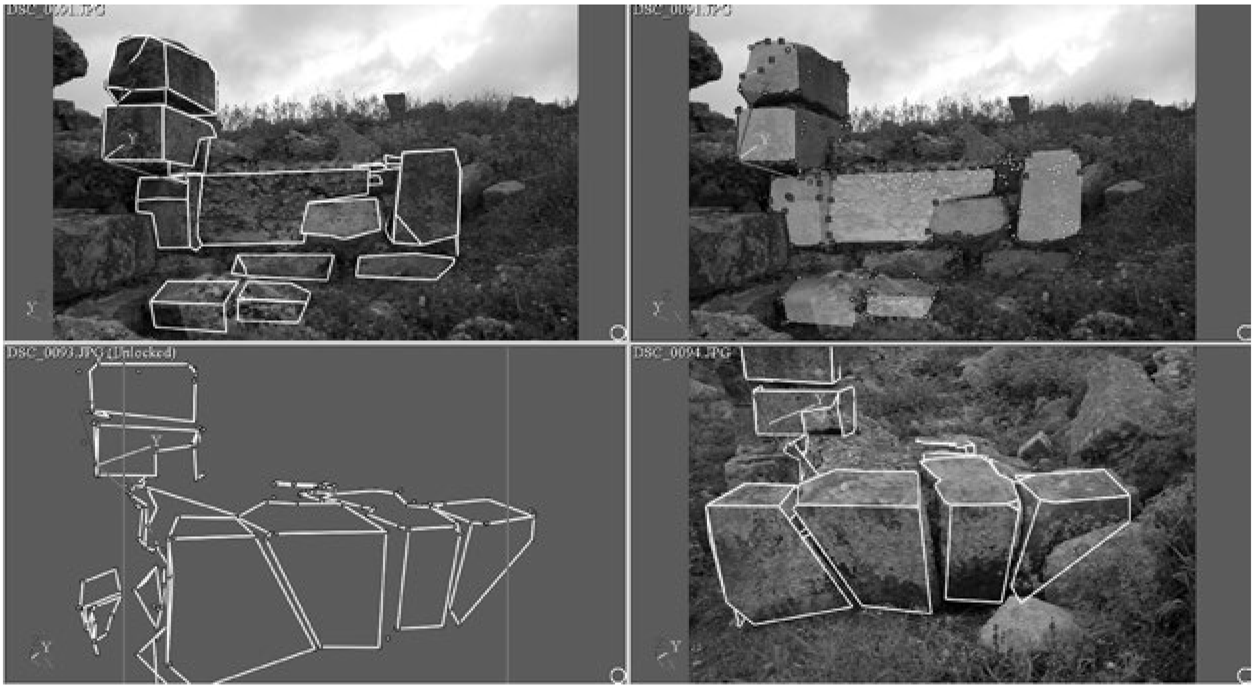


Fig. 10. Photo modelling of element E4.

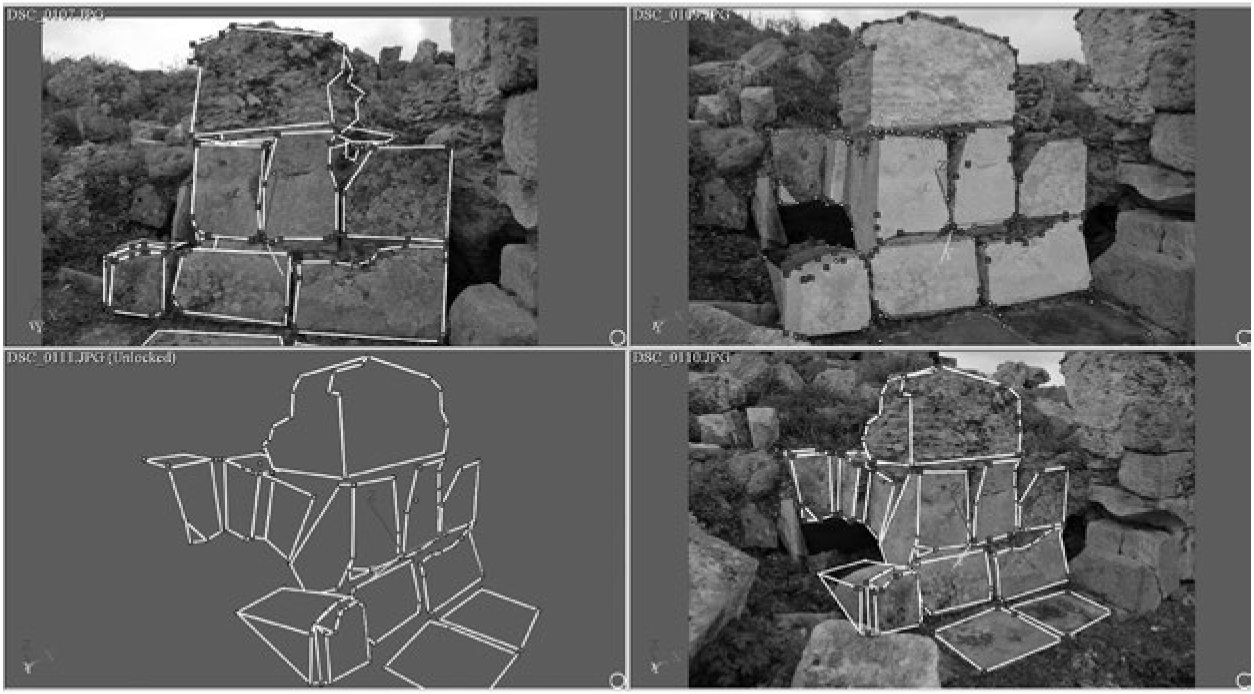


Fig. 11. Photo modelling of element E5.

of the theatre with the description and the dimensions of each element. *Cavea*'s sheet is more detailed and shows the number of *maeniana*[1], the number of steps, the diameter, and the type of structure. Pictures and sketches are associated in URL.

- Point cloud, flat survey, photo, and image based modelling sheet concern the acquisition and processing of data. Files are associated in URL.

- Chronology sheet, which contains information about sponsors, emperors, construction date and restoration date.

[1] The concentric bands that divided the *cavea* into different sections.

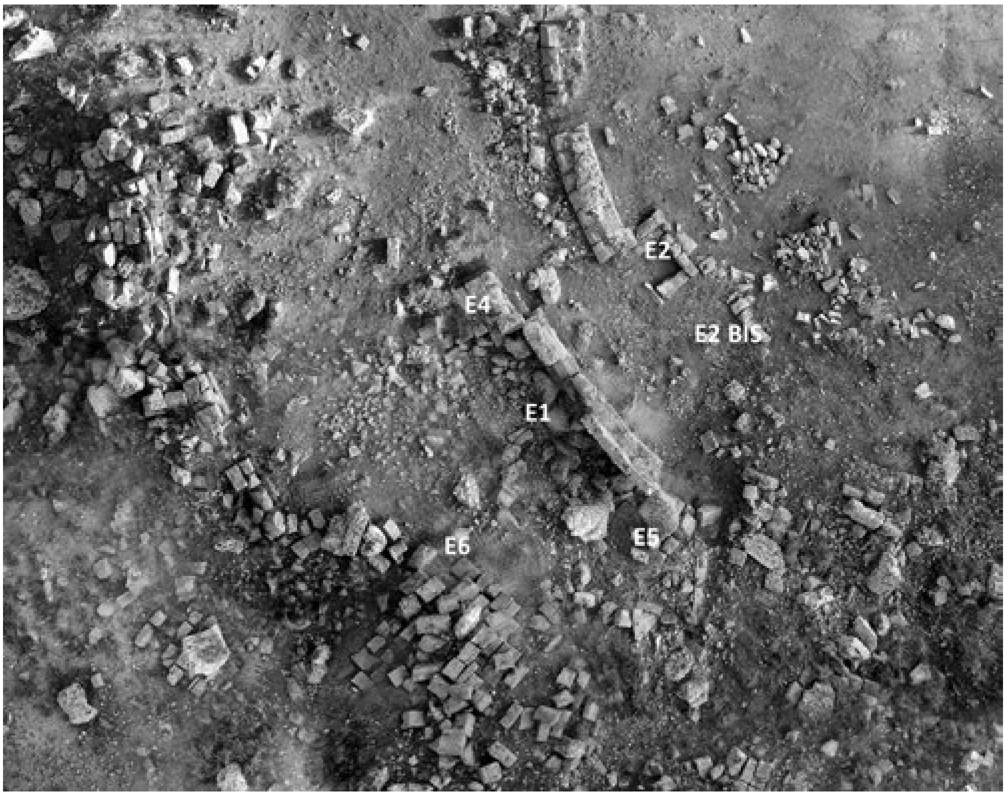


Fig. 15. Low altitude aerial photograph showing the elements.

4 Results and discussion

The complexity of the shape of the architectural element and its cost define the choice of the survey tool. We have chosen to work using Image based modelling and cloud computing in order to have the 3D model of each element on the point cloud of the theatre. The aim is to have multiple scale representation.

The survey methods resulted from the application of a particular instrument in order to measure the coordinates of a point in the space (Saint Aubin 1992). In the case study of the roman theatre of *Uthina* the photomodelling technique was chosen because of its manoeuvrability, accuracy and low cost.

The architectural elements of the cluster of Saint Guillem Le Desert (Driscu 2006) were scanned using a triangulation 3D scanner laser Minolta. This work aimed to gather 3D models of objects situated both in France and in the United States in a virtual space in order to represent the gallery of the cluster in the 12th century. Whereas Image based modelling was used in the survey of theatre of *Uthina* architectural elements.

Photogrammetric restitution allows extracting from the pictures a set of coordinate expressed in model space (Grussenmeyer *et al*. 2001).

The aerial photograph obtained can be used like one picture, in order to draw a plan as it was done for the roman theatre of *Uthina* (Zammel 2014).

And in a study whose aim is to present a combined method of acquisition and data processing relating to a monument based on the use of orthophotography (Akbaylar *et al*. 2007) representing one flat image. And moreover one photograph can be used in the automatic creation of low relief from a single image (Lorenzini *et al.* 2013).

The image based modelling of the architectural elements related to theatre of *Uthina* allowed us to obtain a complete 3D model of each feature. This technique was used also in the photomodelling of the architectural elements of the theatre of Arles (De Domenico 2006), but in the case of *Uthina* we had to place coloured markers on the stone surface in order to help the software image modeler calibrating the photos, for image recognition and to ensure the accuracy of the model. We first used the software image modeller for photo modelling and few years later we used the free software ARC3D and Autodesk 123Dcatch in order to experiment automatic image based modelling. The 3D model of E6 obtained from 123Dcatch allows the introduction of dimensions so that it can be exported in .obj format in 3D modelling software in order to be manipulated and processed. This technique is very interesting because free software can be used on the field, with the aid of an Internet connection and a laptop.

Each architectural element of the theatre is described in a web page which contains: the name of the theatre, the position of the element in the theatre (*scaenae*, *orchestra, cavea*), the number of the element and its topography (Zammel 2014), the name of the element, the dimensions, a relationship of the element described and others in the theatre which have similarities with it placed on the aerial photography. There are also the 3D survey, the 2D survey, bibliography and interpretation. This

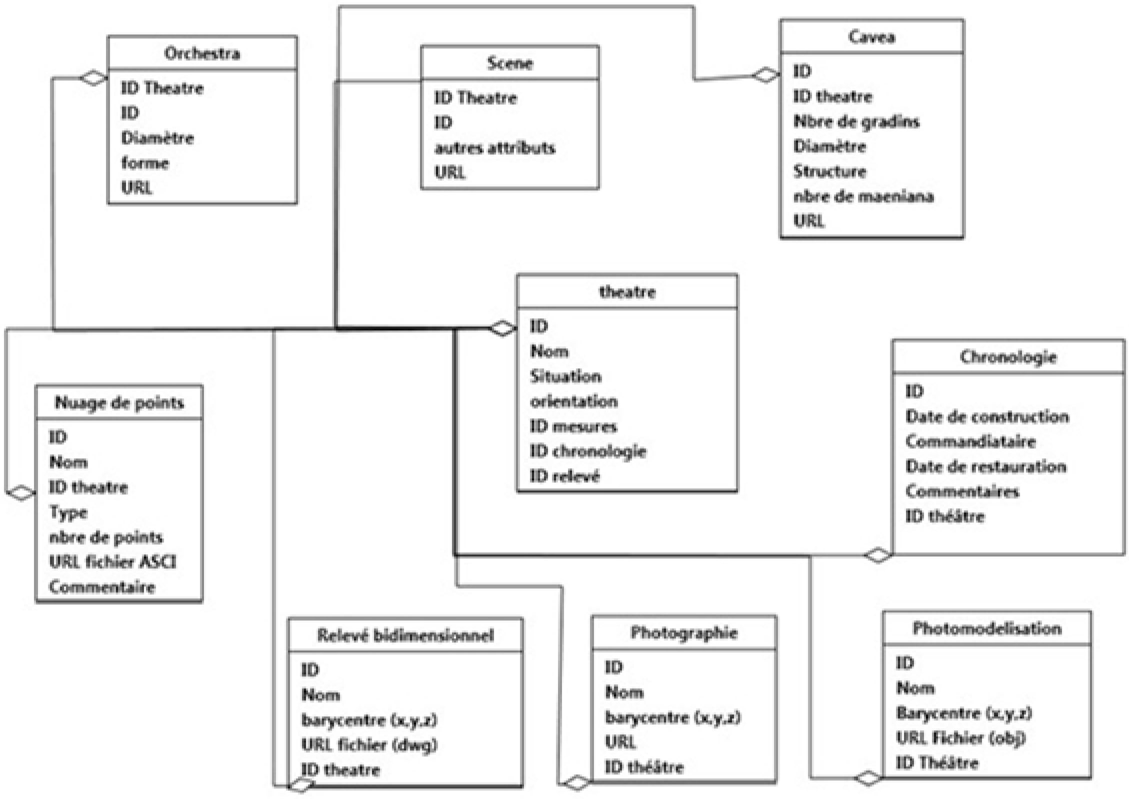


Fig. 17. Model description of the database *Theatrum*.

last information does not use a single piece of data but multiple data and shows hypothetical restitutions.

In the platform *Theatrum,* there is the theatre's sheet, which is in relationship with the different parts of the theatre (*orchestra, scaenane, cavea*) dimensions, chronology, and survey.

Indeed, different theatres are described in the platform *Theatrum* in the same way. In this database we it is possible to find multiple scale representations and multiple data sources. The point cloud and 3D model constitute the interface access to digital data.

5 Conclusion

In this study we have used various survey techniques, such as topography, point cloud processing, image based modelling and low altitude photographs. All the workflow survey-representation-description is based on new technologies. We think that digital description leads to the apparition of new methodology in archaeology, which reinforces Digital Archaeology. Indeed we notice the importance of description in Archaeology. This new methodology is based on structuring digital data in a platform in which 3D modelling is the interface to access to multiple scale information and using a web system.

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Bibliography

Akbaylar, I.and Hamamcioglu-Turan, M. 2007. Documentation et diagnostic d'une maison traditionnelle en Turquie en utilisant une ortho photographie. *Proceedings of the XXI International Symposium CIPA 2007, 'Anticipating the future of the Cultural Past', 1-6 october 2007, Athens, Greece*.

Baratina, L., Giuliano, M. and Checcucci, G.2013.The art of war frieze in Urbino: a blend of virtual reconstruction and scientific accuracy. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W1. 3D-ARCH 2013 - 3D Virtual Reconstruction and Visualization of Complex Architectures, 25–26 February 2013, Trento, Italy.*

Ben Hassen, H. and Maurin, L. 1995. *Oudhna (Uthina), La redécouverte d'une ville antique de Tunisie*. Paris -Tunis, Ausonius De boccard.

Ben Hassen, H. and Maurin, L. 2004. *Oudhna (Uthina) colonie de vétérans de la XIIIe légion, histoire urbanisme, fouilles et mise en valeur des monuments*, Bordeaux-Paris-Tunis, Ausonius édition.

Casu, P. and Pisu, C. 2013. Photo modelling and cloud computing application in the survey of late gothic architectural elements. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W1, 2013 3D-ARCH 2013 - 3D Virtual Reconstruction and Visualization of Complex Architectures, 25–26 February 2013, Trento, Italy*.

Ciancio-Rossetto, P. and Pisani-Santorio, G.1994. *Teatri greci e romani: alle origini del linguagio rappresentato: censimento analitico*, Roma, Seat.

De Domenico, F. 2006. De l'acquisition des données spatiales à la représentation architecturale : le cas des vestiges du théâtre antique d'Arles, *Journal MIA,Vol. 0, 1*.

De Luca, L. 2002. *Relevé et représentation de l'architecture : Le capitole de Dougga*. Rapport de mission Dougga, UMR 694 MAP.

De Luca, L. 2006. *Structuration sémantique et multireprésentation en Architecture*, Biarritz, virtual Retrospect

De Luca, L.2011. *La fotomodellazione architettonica. Rilievo, modellazione, rappresentazione di edifici a partire da fotografie*. Palermo, Dario Flaccovio.

Driscu, T. 2006. Pierre et Parchemin, *MIA journal Vol. 0, 2*.

Grussenmeyer, P. Hanke, P. Russenmeyer, P. and Streilein, A.2001. *Photogrammétrie architecturale, chapitre du livre, Photogrammétrie numérique*. Editions Lavoisier-Hermès.

Ksouri, H. 2006.Essai de restitution des limites extérieures et de l'environnement urbain du théâtre romain de Carthage. *CEDAC Carthage Bulletin*.

Ksouri, H. 2012. *Le théâtre de Bulla Régia dans son contexte urbain*. Unpublished PhD thesis, University of Michel de Montaigne Bordeaux 3.

Landes, C. and Ben Hassen, H.2007. Le théâtre antique d'Oudhna-Uthina (Tunisie): Diagnostic et état dans l'antiquité tardive. *Jeux et spectacles dans l'Antiquité tardive*, *Antiquité tardive* n°15.

Lorenzini, C. Carrozino, M., Techia , F. and Berganasco, M. 2013. Automatic creation of bas-relieves from single images. *Proceedings of the Digital Heritage Marseille, 28 October - 1 November 2013, Marseille, France*: 417-420. IEEE.

Millette, D. 2008. Monuments of Spectacle as Places of Cultural Interaction: Initiating Explorations at the Theatre of Uthina (Oudhna), Tunisia. *International Congress of Calssical Archaeology, Meetings between Cultures in the Ancient Mediterranean, Roma 2008, Bollettino di archeologia online*: 15-21.

Muzzupappa, M., Gallo, A., Spadafora, F., Manfredi, F., Bruno, F., Lamarca, A. 2013. 3D reconstruction of an outdoor archaeological site through a multi-view stereo technique. In Digital Heritage International Congress (DigitalHeritage), 1, 28 October – 1 November 2013: 169-76. doi: 10.1109/DigitalHeritage.2013.6743727

Saint Aubin, J. 1992. *Le relevé et la représentation de l'Architecture*. Paris, Association Etudes, Loisirs et Patrimoine, Documents et méthodes.

Schnapp, A. 1998. *La conquête du passé, aux origines de l'Archéologie*, Paris, Librairie générale française, Collection le livre de Poche, Référence.

Stefani, C. 2010. *Maquettes numériques spatiotemporelles d'édifices patrimoniaux Modélisation de la dimension temporelle et multi restitution d'édifices*. Ecole nationale supérieure d'Arts et métiers, Aix en Provence, France.

Zammel, M. 2014. Apport des outils numériques dans l'étude des théâtres de l'Afrique romaine. *Actes du colloque patrimoine et horizons, Gammarth, Tunisia.*

Zammel, M. 2015. *Outils d'aide à l'étude architecturale des théâtres romains d'Afrique Approche comparative basée sur les nouvelles technologies de l'information et de la communication*. Sarrebruk, Presses académiques francophones.

Deconstructing Archaeological Palimpsests: Applicability of GIS Algorithms for the Automated Generation of Cross Sections

Miquel Roy Sunyer

miquel.roy@uab.cat

Centre d'Estudis del Patrimoni Arqueològic de la Prehistòria (CEPAP-UAB). Universitat Autònoma de Barcelona

Abstract: Archaeological interpretations are limited by how we manage data recovered during excavations. Cross sections are a common approach during the post-excavation phases since they help in the identification of geometries, vertical artefact dispersals, and stratigraphic relationships inside excavated volumes. These bi-dimensional scatter plots are obtained by projecting de X/Y vs. Z coordinates of artefacts along a given depth interval, but its generation becomes tedious and time-consuming if the process needs to be repeated many times and, consequently, the stratigraphic analysis usually remains incomplete.

To overcome these limitations, an ArcPy application (scripting module of ArcGIS10.X) has been developed, which automatically generates the cross sections of an entire archaeological dataset (i.e. an archaeological site) across specified intervals. The script generates both orthogonal and oblique cross sections. It has proved to be a useful tool with which common archaeo-stratigraphic issues arising during the excavation or in the lab can be addressed. This tool is also the starting point for further intra-site spatial analysis development such as 3D paleosurface reconstructions.

Keywords: Cross section, vertical plots, archaeological palimpsest, intra-site spatial analysis, stratigraphic sequences

Introduction

Data management is a crucial issue for theoretical and methodological development in archaeology. There have been many advances with the implementation of new techniques and instruments during the last years (Craig and Aldenderfer 2003; Mcpherron 2005; Fisher 2015). Problems persist, however, when analysing the resolution of archaeological sites and particularly in low- and medium-resolution archaeological palimpsests (Bailey 2007).

To overcome these limitations, since 2004 we have systematized the excavation process by incorporating computerized tools in the field and lab. A Visual Basic 6 software called ArqueoUAB has been developed that allows versatile manipulation of large amounts of data and storage in MySQL relational databases through a menu/tab-based design along with efficient data entry and analysis tools (Mora *et al.* 2010; Mora *et al.* 2014; Roda *et al.* 2014; Martínez-Moreno *et al*., in press). The use of this software is integrated in the whole excavation process (fieldwork and laboratory) that includes:

- item recovery with laser theodolite (XYZ positioning),
- Personal Digital Assistant (PDA) for contextual data recovery,
- storage in georeferenced relational databases,
- daily artefact labelling using Data Matrix codes (Martínez-Moreno *et al*. 2011),
- daily artefact analysis (morphometry, taphonomy, and typology), and
- daily data revision using GIS tools, helping in the decision-making process during the excavation (see Fig. 1).

During excavation seasons, an updated database of the archaeological site is obtained at the end of each day with all the artefacts being georeferenced and analysed; the datasets allow all types of queries based on their attributes.

This fieldwork methodology has been specifically designed to solve issues that have arisen in prehistoric sites (e.g. low- and mid-resolution Palaeolithic palimpsests) and provides several advantages:

1. fast and daily artefact processing,
2. reduction of errors generated in the excavation/lab,
3. workforce reduction/productivity increase,
4. almost real-time analysis of the excavated volumes, allowing the immediate correction of errors and corroboration/reformulation of hypotheses.

As a result, exceptionally complete databases are obtained from the point of view of spatial and alphanumeric data that can be accessed and exploited with most GIS software, providing endless possibilities for geo-processing and *intra-site* spatial analysis. The relevance of this methodology has led to its incorporation by other research teams (De La Torre *et al*. 2014).

Such methodological development is constantly being improved with the creation of new algorithms and refinement of the pre-existing ones. In this paper we present a tool derived from these advances, consisting of the automated generation

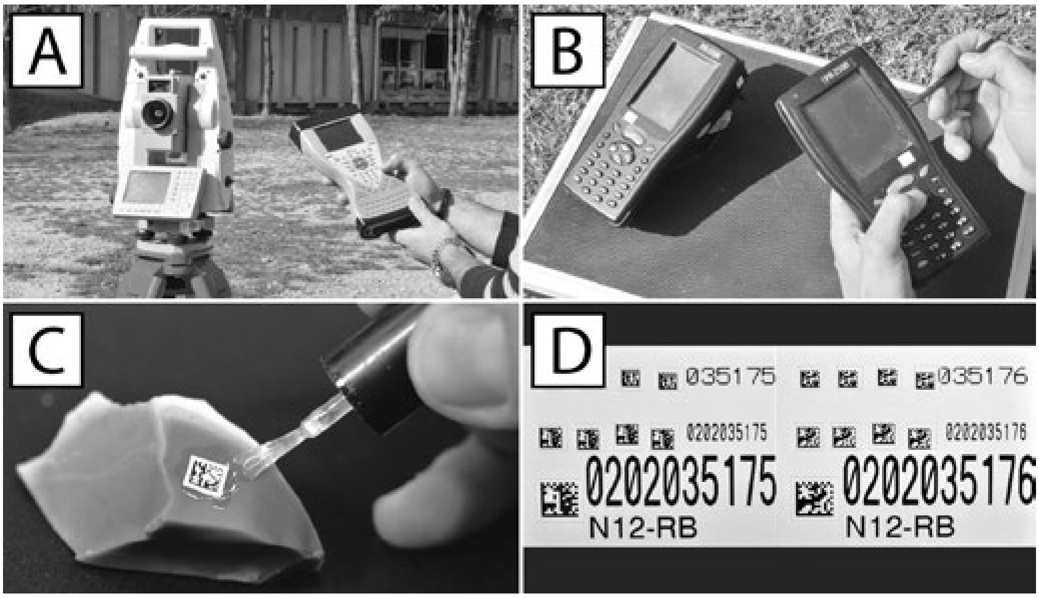

Fig. 1. Excavation methodology which implies both fieldwork and laboratory tasks. A: Laser theodolite; B: Personal Digital Assistant (PDA); C: Artefact labelling; D: Data Matrix codes.

of orthogonal and oblique cross sections of large excavated volumes using ArcGIS 10.0. The tool presented helps to analyse the archaeological levels, visualizing its geometry and providing a better understanding of site-formation processes, while helping in the decision making directed to solve specific problems during and before the excavation.

1 Cross sections in archaeology

There has been a popularization of the so-called Geographic Information System (GIS) in archaeological studies during the last years. Most of them are related with disciplines like landscape archaeology and palaeo-ecology which commonly deal with mid- and large-scale geographic spaces (Clarke 1977; Chapman 2006; Conolly and Lake 2006). On the other hand, there is a huge field of research that is implicit in every archaeological site, called ‘intra-site spatial analysis’ (Hietala 1984). The expansion of GIS into archaeology has affected this kind of analysis as well, providing new tools and methods to study spatial relationships between archaeological finds within sites.

Our fieldwork methodology, previously introduced, is consistent with intra-site spatial analysis techniques. Data are retrieved in the archaeological sites using millimetre-accuracy instruments (laser theodolite) and artefacts are recovered taking into account the geological context. At the same time artefacts are treated as isolated sedimentary particles. Consequently, human-related distributions can be properly studied in its spatial context.

Following this premise, one of our main interests has been to differentiate occupational phases along the archaeological sequences that we excavate (Middle and Upper Palaeolithic and Neolithic). This is done by differentiating both geological contexts and vertical dispersals of archaeological artefacts (represented as point-clouds) using the so-called ‘cross sections’.

The term ‘cross sections’ refers technically to the intersection of a 3D body with a plane, resulting in a 2D diagram that reflects internal structure of the sectioned body. In archaeology, this principle is applied in four main representations: litho-stratigraphic sequences, artefact profiles (e.g. ceramics), internal structure of buildings, and point-clouds of artefacts. The present paper is focused on the last of these approaches, where coordinates of artefacts are projected in profile views. Vertical plots of the excavated volumes are obtained that reflect spatio-temporal relationships between artefacts (points).

The motivation for such an approach is given by the need to monitor complex sedimentary sequences (not horizontal and discontinuous strata) obtained from large excavated surfaces (> 150 m^2 in some cases). These diagrams are important in the archaeological interpretation as they provide depositional models which allow us to understand of site formation processes and disaggregate basic notions in archaeology that have been recently addressed, such as ‘overlapping occupations’, ‘syn/diachrony’, ‘contemporaneity’, ‘archaeological level’, or ‘archaeological palimpsest’ (Martínez-Moreno *et al.* in press). Additionally, the vertical analysis of an archaeological level is a basic step in order to perform further spatial and non-spatial research in the horizontal plans, as it enables distinction among different diachronic occupational events separated by Z values that should not be mixed (although this is a point of view not always taken into account) (Mcpherron *et al*. 2005).

Vertical dispersals (point-clouds) must only be considered along a thickness or *depth interval* of the omitted horizontal coordinate. For instance, in an X/Z diagram, only artefacts occurring in a narrow range of Y coordinates (the omitted parameter) should be displayed (e.g. 20 cm along the Y axis). This concept has not been previously introduced although it is crucial for obtaining coherent diagrams and interpreting them. A depth interval that is too wide may lead to severe distortions of real geometries, such as the thickness of the archaeological units or fictitious accumulations of artefacts. On

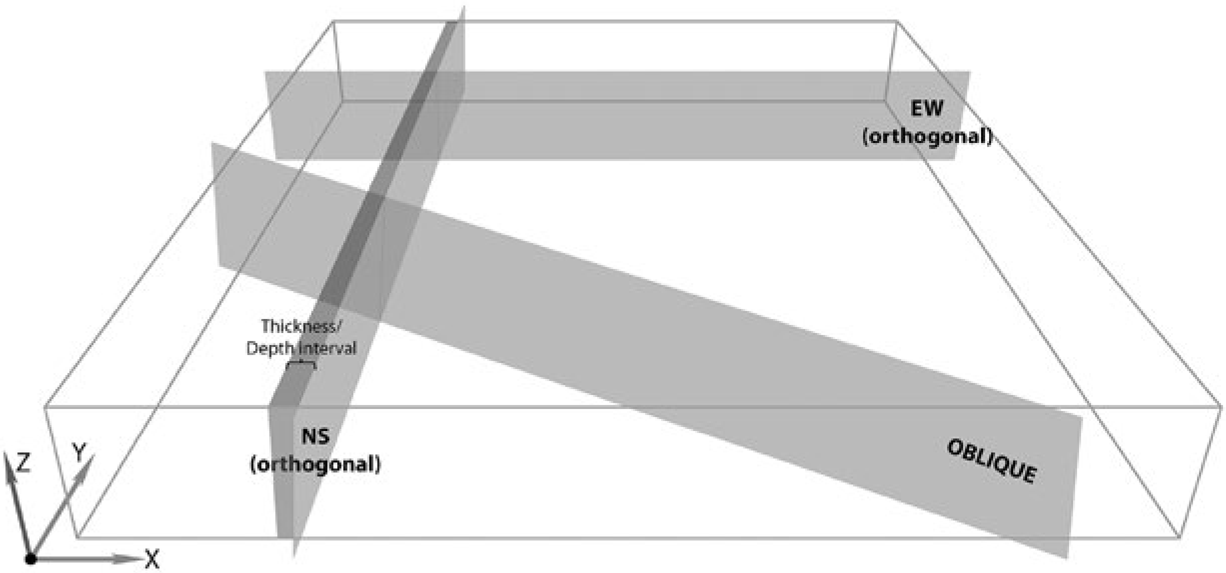

Fig. 2. Orthogonal and oblique cross-section types depending on its [their?] orientation with respect to a Cartesian coordinate system, and representation of thickness/depth interval.

the other hand, a depth interval that is too narrow may generate unrepresentative diagrams. The election of an appropriate depth interval depends on the geometry of archaeological units and the required level of detail.

Definitions explained above (cross section/vertical plot, depth interval/thickness) are not new in archaeology. Somehow, they have been applied in an implicit or indirect manner in many archaeo-stratigraphic approaches (Hietala 1984; Mcpherron *et al.,* 2005; Hester 2009; Sañudo *et al*. 2012; Gallotti *et al*. 2012; Machado *et al*. 2013). In spite of its practical potential, however, until now there has been no attempt to systematize and consolidate this knowledge. We think that the proper analysis of archaeo-stratigraphic sequences lies partly in the correct understanding of these methods. The following extends the concepts and practices usually employed, providing new terms/definitions and a consolidated view of how cross sections are obtained and treated.

In a Cartesian coordinate system, cross-section diagrams are obtained by projecting one of the horizontal coordinates (X or Y) versus the vertical dimension (Z). Two main kinds of cross sections can be obtained, depending on how these parameters are managed: orthogonal and oblique cross sections (Fig. 2).

1.1 Orthogonal cross sections

When cross sections are obtained by projecting the X-Z coordinates they may be called EW cross sections, as resulting vertical plots are oriented following the east–west direction of the Cartesian coordinate system. Analogously, when the Y-Z coordinates are projected, the resulting vertical plots may be called NS cross section, as they are oriented according to the north–south direction of the Cartesian coordinate system. Alternatively, taking the north-direction axis as reference, NS and EW cross sections may be called sagittal and transversal cross sections respectively. Both types — EW and NS plots — can be categorized as *orthogonal cross sections* because they are always parallel to one of the horizontal X/Y Cartesian axis (Fig. 2).

1.2 Oblique cross sections

Depending on the archaeological dataset, the geometry of archaeological units may not be properly reflected in orthogonal cross sections, hindering the correct interpretation of archaeo-stratigraphic sequences. In such cases it may be appropriate to obtain a cross section that is not parallel to any of the Cartesian axes (Fig. 2). These kinds of cross sections are known as *oblique cross sections*, as they maintain an angle different to 90º to both the X and Y axis. At this point, however, there is a dilemma because with the current software there no straightforward way to obtain an oblique cross section without, a) modifying the horizontal coordinates; or b) distorting the shape of the resulting diagram. Depending on which feature is preserved and which one is modified (a or b), two sub-kinds of oblique cross sections are defined (Fig. 3):

- *Ortho-oblique cross sections*: points of an oblique cross section are projected to one of the real Cartesian axes (X/Y). In this operation, an array of artefacts that is not orthogonal with the Cartesian axis is treated as if it was an ordinary orthogonal cross section (see Fig. 3 for details). These plots should be considered with caution due to inherent distortion effects which lead to a non-preservation of deep angles, shortening along the horizontal axis, and changes in the correlative position between artefacts. Coordinates, however, are maintained. Such a distortion effect is more pronounced when the angle of cross section with the orthogonal axis (X or Y) is higher. They should therefore only be used with low angles (e.g. < 10º).

- *Rotated cross sections*: Points are projected to an imaginary plane parallel to the section. These representations require a rotation of the whole point dataset through a specified angle around the Z-axis using a rotation matrix. This option

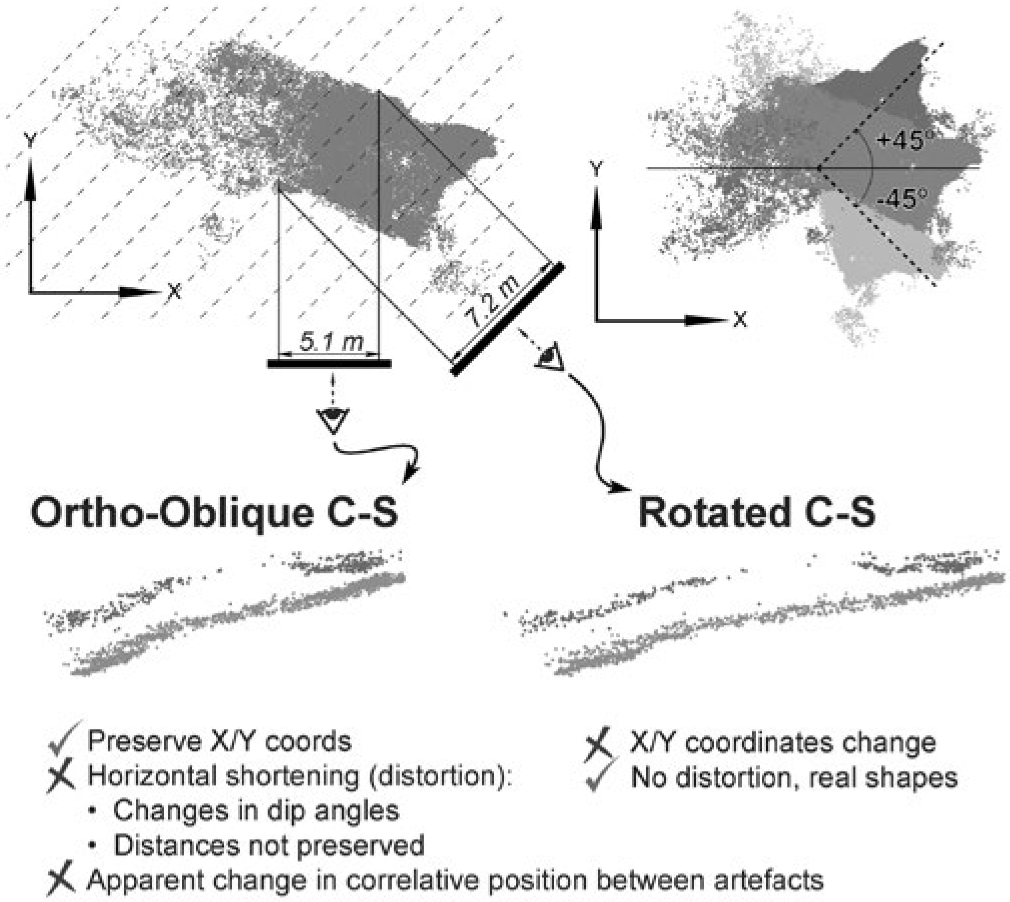

Fig. 3. Differences between oblique cross-section types (ortho-oblique cross sections and rotated cross sections). Note the distortion effects generated with the ortho-oblique cross sections.

provides real geometries as no distortions are applied. Consequently they maintain the real shapes and distances but, in return, X/Y coordinates are modified (Fig. 3):

Each point is recalculated as follows:

where θ is the angle by which cross sections must be parallel. Once the point dataset is rotated, cross sections are generated as if they were ordinary E-W plots, projecting the recalculated X coordinates against the unmodified Z values.

1.3 Automated cross-section generation: a tool for the analysis of archaeo-stratigraphic sequences

Functionalities of current GIS software facilitate the exploitation of spatial information from our archaeological databases using automated routines. Tools such as the ArcGIS's Model Builder or its scripting module — Python Window — and the open-source QGIS and gvSIG Model Builder solutions are quite viable options if specific processes need to be repeated continuously, saving valuable time during the excavation seasons (www.esri.com/software/arcgis, 2015).

We have developed an ArcPy tool (Python scripting module for ArcGIS 10.X) that automates the cross-section generation process creating orthogonal and oblique cross sections of the whole excavated volumes along user-specified depth intervals (ROY *et al*. 2015). This tool is presented as a *form* (Fig. 4) in which several parameters are specified. A minimum of six parameters need to be entered, which are the X/Y/Z point dataset, thickness or depth interval, an angle for oblique cross sections and the possibility of creating ortho-oblique or rotated cross sections, the scanning extent (an area delimited by X/Y vertices), and the symbology applied to the archaeological levels. Optionally, other parameters may be considered, such as the possibility of adding restrictions to the dataset (e.g. to specify several archaeological levels, exclude certain types of points, etc.), the addition of an overlay that highlights specific points (e.g. points retrieved during the last excavation day), or the horizontal reflection of the dataset (horizontal coordinates are turned into negative values in order to obtain an inverted view, a useful practice when working in the field).

Once the program is launched, it begins to section the specified extent in slides of the specified thickness. Each cross section is stored as an ESRI Shapefile or as a feature class in an ESRI File Geodatabase. For instance, a square extent of 50 m^2 containing 40,000 archaeological items is scanned to obtain automatically 72 orthogonal cross sections (36 EW and 36 NS) of 20 cm thickness, while the number of oblique cross sections depends

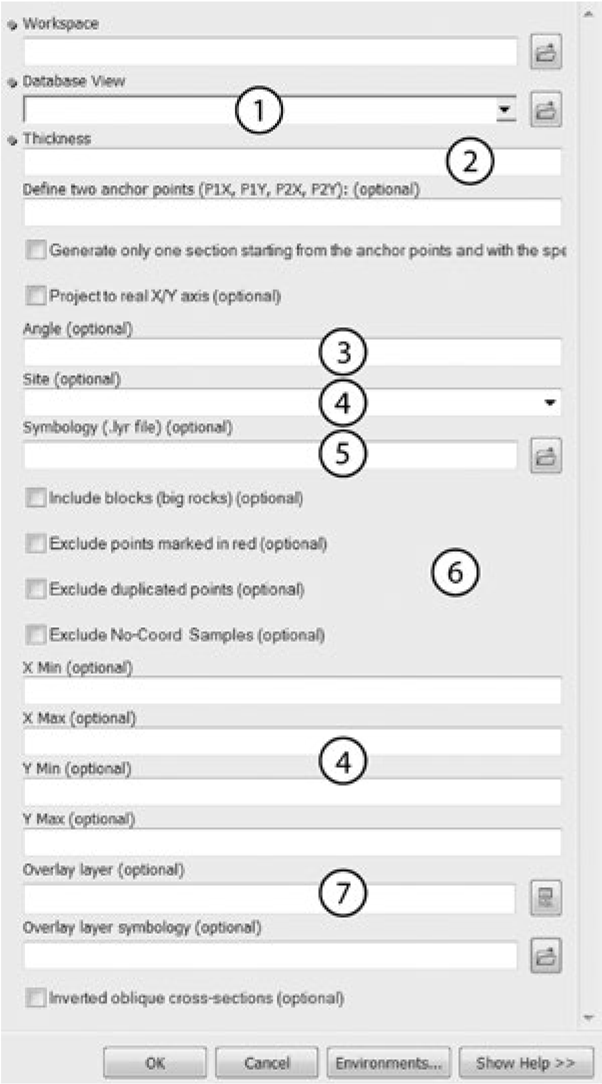

Fig. 4. Form used to launch the tool for the automated creation of cross sections. 1: XYZ point dataset; 2: Depth interval/thickness; 3: Angle (oblique cross sections; 4: Extent restriction; 5: Symbology; 6: Additional data restrictions; 7: Overlay layer.

on the angle considered (Fig. 5). The overall generation process for the previous example would not take more than 5–10 minutes (the time lapse depends on the machine used, the thickness of the slides, and the number of archaeological items).

Three ArcMap project documents (.mxd files) are generated (one for EW cross sections, one for NS cross sections, and one for oblique cross sections) which contain the generated cross sections. Each MXD file is a template where the vertical plots are found properly named as an ordered list of layers in the document's table of contents (TOC) (Fig. 6). A user-customized symbology has automatically been applied to all the cross sections, by which the archaeological levels can be differentiated. This is a major advantage as manual symbolization is a step that usually takes a long time. Active layers are displayed with the specified symbology. If overlays have been created in order to highlight specific points (e.g. artefacts retrieved during the last day of excavation), they are shown when a layer is activated. Other contextual information can be displayed in combination with the scatter plots (e.g. big stones, hearths, or full litho-stratigraphic sections). The tool prints out in the template the parameters that have been used to generate the cross sections, which are useful when using diagrams in the field (e.g. thickness, name of the archaeological site, type of points included/excluded in the diagrams, date of creation, name of the computer used, etc.).

Finally, each point in the cross sections has its own associated data in a table of attributes (piece identifier, archaeological level, XYZ position, type of object, raw materials attributes, technological attributes, morphometry — length, width, thickness and weight, recovery date) meaning that further queries and operations can be performed on each slide.

This tool has been developed to fit the excavation methodology described at the beginning of this paper. Hence, its implementation in the environments of other research teams requires a specific adaptation for each case. Similar architectures can be developed in most datasets, however, since these kinds of algorithms are based on four 'mandatory' parameters registered in most archaeological projects: X, Y, Z coordinates and archaeological level.

2 Further capabilities: Generation of realistic 3D models

The tool presented is also the starting point for the development of further analysis tools. We have ideated a methodology to recreate all kind of 3D surfaces of archaeological interest based on the cross sections, such as depositional and erosive surfaces or occupational palaeosurfaces.

The process for obtaining these 3D landscapes is synthesized in three steps that are represented in Figure 7: once the cross sections of an archaeological site are generated, stratigraphic contacts identified in every vertical plot are modelled as lines. Lines store attributes of the cross section, the type of stratigraphic contact, and an ID. In an intermediate step, the lines generated for each surface are automatically converted into an XYZ point grid treating line vertices as points. Finally the point grid is transformed into a 3D surface using the raster interpolation tools provided by multiple GIS software (e.g. the IDW interpolation tool included in the 3D Analyst extension of ArcGIS10.X).

Depositional models of complex stratigraphic sequences can be automatically generated and monitored using this technique. Although further research deserves to be done in order to obtain more detailed and accurate representations, today this methodology results in reconstructions of topographic features that are essential in the correct interpretation of site formation processes. For instance, in Figure 7, an erosive surface detected across an entire archaeological site is reconstructed using this technique. This erosive process partially destroyed the underlying Magdalenian floor, and the erosive void was filled with Mesolithic and Neolithic occupations. The point is that, due to excavation methodology, the unearthing process of this surface was conducted in multiple seasons in different parts of the site, destroying it in separated phases. Consequently, the total shape and extent of the erosive process had not been materially observed even in the field until this model was generated.

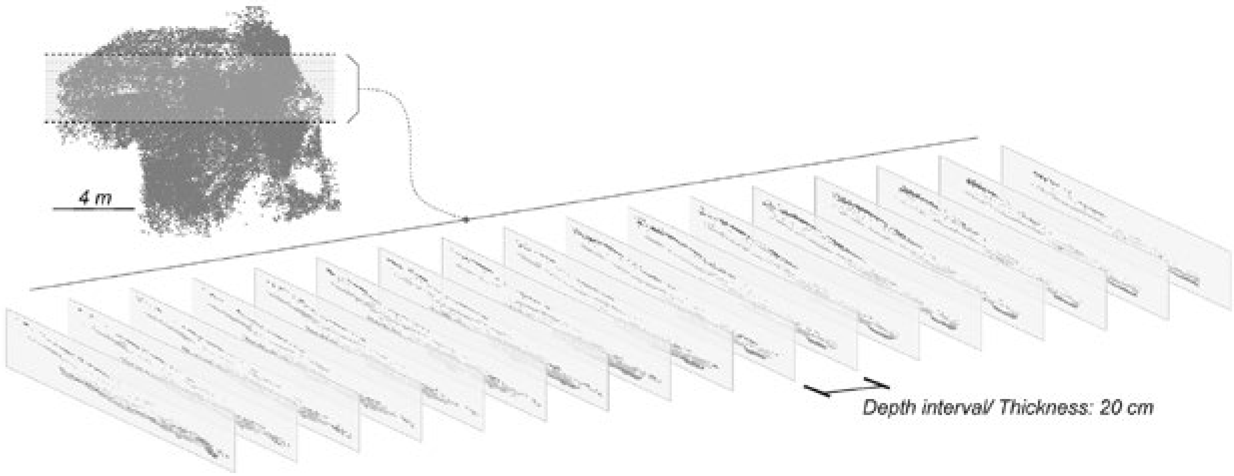

Fig. 5. Evolution of the archaeological levels from north to south at intervals of 20 cm (Cova Gran de Santa Linya archaeological site, Middle to Upper Palaeolithic transition levels, southern Pyrenees).

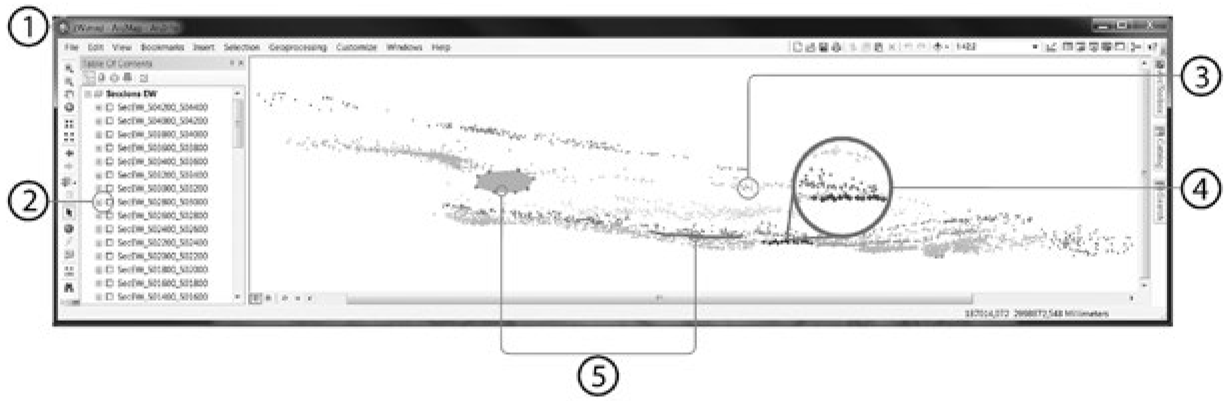

Fig. 6. Elements of MXD file templates with the generated cross section. 1: MXD project; 2: Ordered list of cross sections; 3: Active layers are displayed with the proper symbology; 4: Overlay layer used to highlight specific points (e.g. artefacts retrieved during the last day of excavation); 5: Contextual features shown in combination with the cross sections.

3 Conclusion

Systematization of excavation routines by our team (CEPAP-UAB) has turned into the incorporation of computerized tools in field and laboratory, which renders the global research process more efficient. With the implementation of innovative data recovery and management solutions, today we are exploring the archaeological record in an unprecedented way.

The presented tool has led to a significant improvement in the way that we approach the excavation of sedimentary sequences with a scarce archaeological visibility, and especially those contexts that can be defined as mid- and low-resolution archaeological palimpsests. The tool created allows a non-specialized user to browse easily across the entire excavated volumes and identify the stratigraphic relationships between elements (artefacts, rock falls, hearths, litho-stratigraphic units) from multiple points of view (EW and NS cross sections and oblique cross sections), which helps to avoid simplistic readings obtained from one or two scatter plots, enriching the archaeological interpretations. At the end of each day of excavation, an updated set of cross sections is obtained that makes it is easy to detect and correct typical human errors that have occurred in the field, and redefine hypotheses that need to be proved during the following days.

This tool is a good example of how archaeological interpretations can be improved while the excavation process becomes more efficient and reliable. The automated cross-section generation has allowed to reduce the time spent in obtaining essential diagrams for the excavation, enhancing its potential as a tool for the study of mid- and low-resolution palimpsests and for the identification of site formation processes and geometries usually ignored when working with a single conventional cross

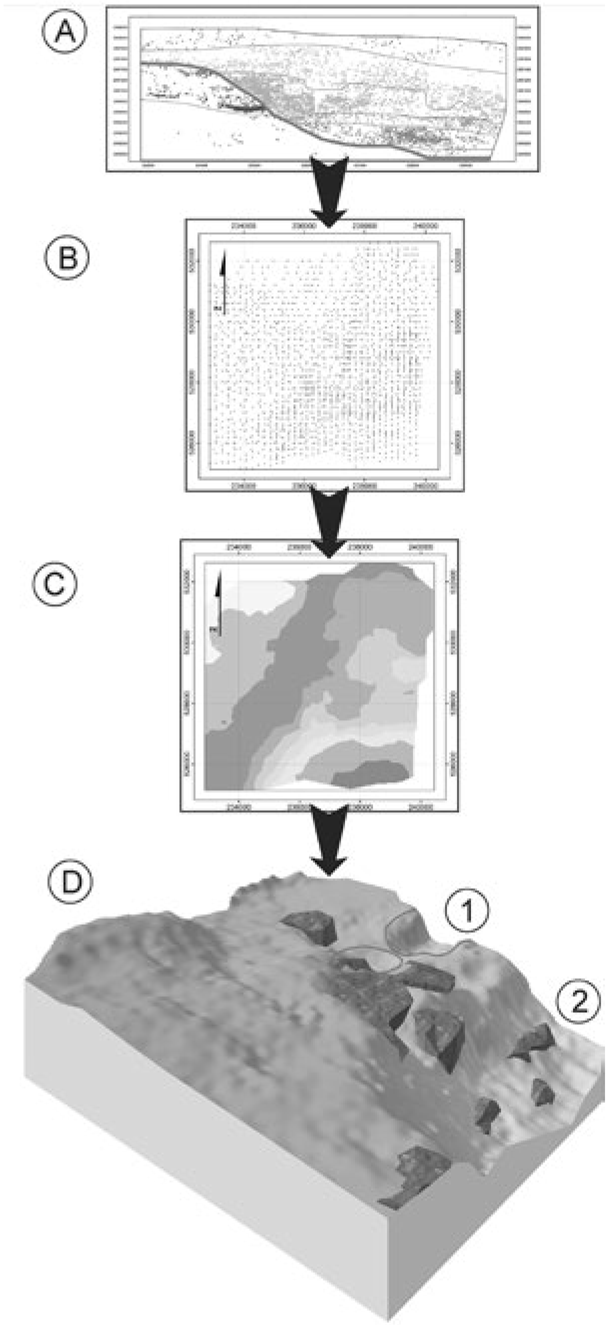

Fig. 7. 3D reconstruction of an erosive palaeosurface of the Cova Gran de Santa Linya site (southern Pyrenees, NE Spain) created from the cross sections. A: Stratigraphic contacts are modelled as lines in the cross sections; B: Lines are automatically converted into a XYZ point grid; C, D: 3D surfaces are obtained by interpolation methods. 1: Neolithic pits and hearths excavated in the Pleistocene floor; 2: Erosive void.

section or with 3D environments. Simultaneously, it is the basis for the development of new tools in the future that will lead to further improvements for research.

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Bibliography

Bailey, G. 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26: 198-223.

Chapman, H. 2006. Landscape Archaeology and GIS. Stroud, Tempus.

Clarke, D. 1977. *Spatial archaeology*. New York, Academic Press.

Conolly, J., Lake, M. 2006. *Geographical Information Systems in Archaeology*. New York, Cambridge University Press.

Craig, N., Aldenderfer, M. 2003. Preliminary stages in development of real-time digital data recording system for archaeological excavation using ArcView GIS 3.1. *Journal of GIS in Archaeology*.1: 13-22.

De La Torre, I., Arroyo, A., Proffitt, T., Martín, C., Theodoropoulou, A. 2014. Archaeological field techniques in Stone Age sites. Some case studies. *Treballs d'Arqueologia* 20: 21-40.

Fisher, E. C., Akkaynak, D., Harris, J. Herries, A. I. R., Jacobs, Z., Karkanas, P., Marean, C. W., Mcgrath, J. R. 2015. Technical considerations and methodology for creating high-resolution, color-corrected, and georectified photomosaics of stratigraphic sections at archaeological sites. *Journal of Archaeological Science* 57: 380-94.

Hester, T. R., Shafer, H., Feder, K. 2009. *Field methods in archaeology*. Left Coast Press.

Hietala, H. J. 1984. *Intrasite Spatial Analysis in Archaeology*. Cambridge, Cambridge University Press.

Martínez-Moreno, J., González-Marcén, P., Mora, R. 2011. Data matrix (DM) codes: A technological process for the management of the archaeological record. *Journal of Cultural Heritage* 12: 134-9.

Martínez-Moreno, J., Mora, R., Roy, M., Benito-Calvo, A. (in press). From site formation processes to human behaviour: Towards a constructive approach to depict palimpsests in Roca dels Bous. *Quaternary International*.

Mcpherron, S. 2005. Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32: 1003-14.

Mcpherron, S., Dibble, H. L., Goldberg, P. 2005. Z. *Geoarchaeology* 20: 243-62.

Mora, R., De La Torre, I., Martínez-Moreno, J. 2010. ArqueoUAB: A systematic archaeographic approach for the analysis of Palaeolithic sites. In L. Melero and P. Cano (eds.), *Computer Applications and Quantitative Methods in Archaeology. Fusion of Cultures. CAA. Granada, april 2010*. British Archaeological Reports International: 1-4.

Mora, R., Martínez-Moreno, J., Roda, X.; Roy, M., Vega, S. 2014. Métodos de excavación: del trabajo de campo a la interpretación arqueológica. *Treballs d'Arqueologia* 20: 7-20.

Roda, X., Samper, S., Mora, R., González, P., Martínez-Moreno, J. 2014. La aplicación de los códigos Data Matrix (DM) en el registro y la catalogación arqueológica. *Treballs d'Arqueologia* 20: 95-107.

Pompeii, the Domus of Stallius Eros: a Comparison Between Terrestrial and Aerial Low-cost Surveys

Angela Bosco
a.bosco14@studenti.unisa.it
Department of Cultural Heritage, University of Salerno, Italy

Marco Barbarino
Centro Interdipartimentale di Servizi di Archeologia, Università degli studi di Napoli L'Orientale, Napoli, Italy,

Rosario Valentini
Centro Interdipartimentale di Servizi di Archeologia, Università degli studi di Napoli L'Orientale, Napoli, Italy,

Andrea D'Andrea
Centro Interdipartimentale di Servizi di Archeologia, Università degli studi di Napoli L'Orientale, Napoli, Italy

Abstract: The European project 3DICONS enabled the acquisition of numerous architectural and archaeological assets. Different large models were acquired in Pompeii, in particular the work focused on lesser-known archaeological areas, but equally relevant for the analysis of different masonries and stratigraphical superimpositions. Among these areas, special attention has been given to the house of Stallius Eros (Regio I, Insula 6, 13–14), which contains a rich vertical stratigraphy covering a wide chronological period and offers interesting information about the development of this part of the ancient city. In order to provide a more complete and accurate digital replica, the use and integration of two photogrammetric approaches were used to evaluate the accuracy, efficacy, and velocity of the techniques. After surveying the domus using a total station, two interventions, by close-range and aerial photogrammetry, were carried out at two different times to generate a 3D high-resolution model of the ancient house.

Keywords: Pompeii, Close-range photogrammetry, Aerial and terrestrial surveys.

1 Archaeological context

In a report on the works carried out in Pompeii, Maiuri (1929) described with great accuracy the Domus of Stallius Eros (Regio 1, Insula 6, 13–14) excavated in 1926. He analysed the rooms by defining their probable function and created a map of the house, characterized by perimeter walls with different alignments compared to the adjacent houses. Unfortunately the archaeologist, and superintendent at the time, gave no information concerning the stratigraphy of the building.

The Domus of Stallius Eros was included in a group of 30 so-called 'atrium houses' in the framework of the project 'Pompeian Households: An On-line Companion' (Allison 2004). Regio I, with the exception of three large residential complexes—the House of Citharist (I, 4.25), the House of Menander (I, 10.4) and all of Criptoportico and Sacello Iliaco (I, 6, 2–4)—contains buildings of medium size and the best known and preserved manufacturing facilities in the city, in large part built between the second and first centuries B.C. (Pesando and Guidobaldi 2006).

The troubled life of the house of Stallius Eros is clearly visible in its walls. The oldest building techniques alternate with newer masonry, emphasizing changes of use in some rooms and numerous restorations in ancient times. The general layout of the house and the presence of some important constructive techniques among the oldest (*opus quadratum* and the so-called 'Opera a Telaio') in the perimeter walls, indicate a kind of 'frozen' structural domus of the Samnite period (Fig. 1).

According to Maiuri's hypothesis, the domus was completely ruined before the final eruption of Vesuvius. He concluded that the large pile of sand in the rooms around the front hall had rendered this house uninhabitable and indicated that it had been adapted as a private storage area for building materials.

Under the layer of pumice stone, caused by the eruption, there was a dark deposit (as described by Maiuri and only documented in photographs of the excavation taken at the time), representing the state of abandonment of the house before the eruption. According to the final report made by Maiuri after the excavations, room 3 was inaccessible at the time of the eruption. It had been closed for some time and made inaccessible, but Maiuri claimed he found building material in it from adjacent houses that were rebuilt. As in the hall, however, this room also contained finds that may have fallen from the top floor. The relationship between the inaccessibility of this room and the building material (Allison 2004) remains unresolved. The garden area (room 13) was decorated with Fourth Style garden scenes, consisting of various trees and other plants and sphinxes on pedestals, above a lattice socle interspersed with flowers; today the painting has almost completely disappeared.

After excavation in the 1920s, no other in-depth analysis has been undertaken in this area. In the last months, the study of the house has been included in the framework of the 'Grande Progetto Pompei', mainly within the framework of 'Piano della Conoscenza, which is largely based on a 3D survey of Pompeian monuments and on the analysis of the state of conservation of all private and public buildings.

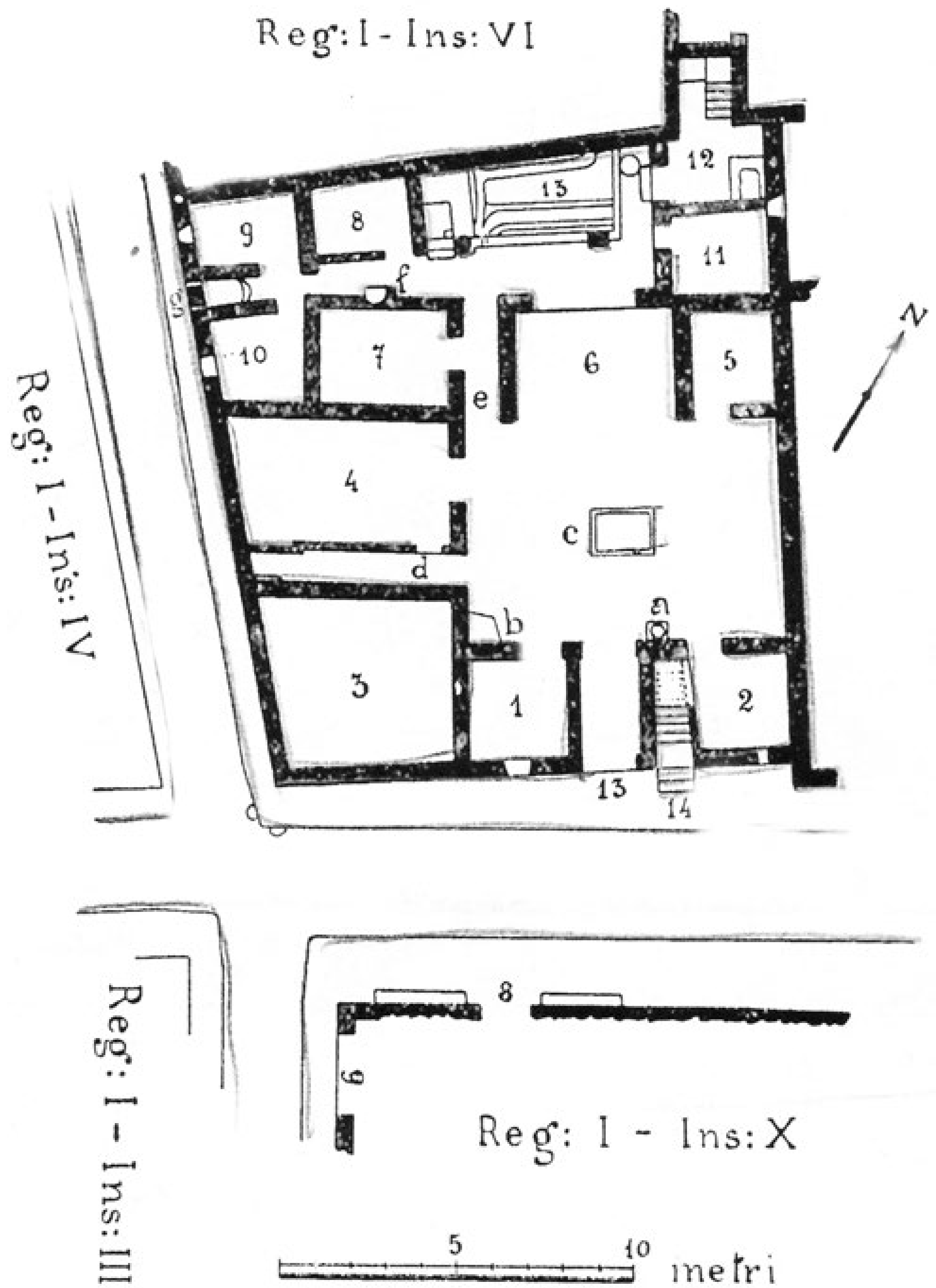

Fig. 1. General map of the house after the 1929 excavation.

2 The surveys

The survey operation was linked to the task of cleaning the domus organized by the University 'L'Orientale' of Naples, directed by F. Pesando, in June 2014. The work consisted in the removal of the modern surface stratum and in analysis of the wall stratigraphy, which is the only available data for the interpretation of the evolution of the layout and, therefore, of the house until the time of the eruption. The domus has a very high perimeter structure, in some parts reaching more than 6 m, and many rooms showing well-preserved internal walls.

In a previous paper (Bosco *et al*. 2015) we showed the survey of the domus by total station and the comparison of this updated map with two 3D models created by aerial and terrestrial close-range photogrammetry (Remondino 2006)

The surveys covered an area about 300 m^2. The 3D final replicas, obtained by close-range photogrammetry, were scaled according to ground control points measured by total station. For the terrestrial model five GCPs were used with a final error of 0.0039 m and 0.801 px. Five GCPs were used for the aerial survey. Due to the ground sample distance, the final error, as predicted, was also higher than the terrestrial survey: 0.370 m and 3.479 px.

Finally, all three surveys (by total station and close-range photogrammetry) were aligned and superimposed in order to evaluate possible differences and variances.

Detailed photo-plans of the walls of each room were extracted from the 3D replicas. This 3D documentation allowed a complete archaeological cataloguing of the walls and provided a basis for the accurate analysis of the structural and decorative decay. This work proved crucial as just after the archaeological campaign, the house was closed to the public and researchers for the reclamation of the area.

The paper focuses on the comparison between the models carried out by aerial and terrestrial close-range photogrammetry. In particular it shows the analysis produced by CloudCompare (www.cloudcompare.org) to test the reliability and accuracy of the two approaches considering the structural study of the building. For these reasons the paper deals with the verification of the accuracy of the two models in order to identify possible vertical decay as bulges and cracks.

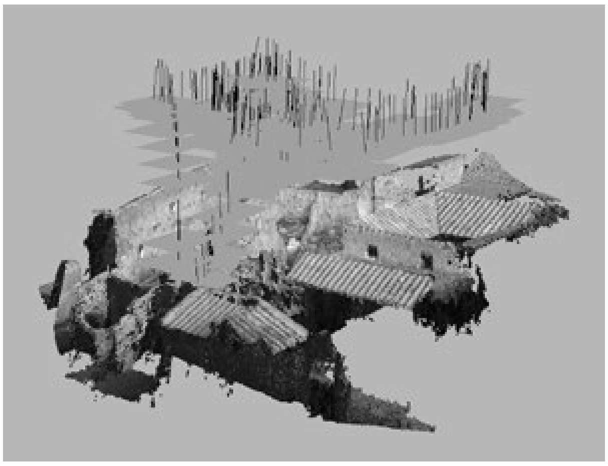

Fig. 2. Location and direction of the photos for the 3D model acquired by drone.

3 Data Acquisition and Post-Processing

About 1500 photos were taken for the terrestrial data acquisition with a SLR Nikon D90 (CMOS sensor APS-C 23.6x15.8 mm; max. resolution 4288 x 2848). The lens used was an AF-S DX Nikkor 18-55 mm 1:3.5-5.6G VR. The process took a few hours and the work of two operators. The distance between the operator and the surface to be scanned was not constant due to the irregular layout of the house, and the pictures were taken parallel to surfaces and around the internal structures at different heights by using a 5 m pole as a support for the camera. Moreover, a panoramic and a closer shot were taken in succession in order to obtain the largest image coverage possible and in the smallest detail at the same time.

After the terrestrial photo shoots, aerial photography by drone was undertaken. This survey method is practical and quick and for these reasons was considered useful for monitoring the progress of archaeological work (Chiabrando *et al*. 2012). The drone flight could only take place in the absence of visitors before the site opened and it was therefore carried out a few days after the terrestrial image-based photogrammetry.

This second survey was undertaken with a low-cost drone (quadricopter Apollo IdeaFly) equipped with a compact camera Canon PowerShot SX 260 (BSI-CMOS sensor 1/2.3" 6.17 x 4.55 mm; max. resolution 4000 x 3000). The camera was mounted on the drone in an upright position, without the aid of the gimbal, which is not adaptable to our camera model, in order to achieve better flight stability even though only vertical photos could be obtained. The flight took a total of about 8 minutes (with the use of two batteries) from a height of about 15 m from the top of the highest wall, and enabled the acquisition of numerous pictures in continuous shooting mode (about one per second). After careful selection to remove blurred and superfluous pictures, about 200 photos were judged useful for the final reconstruction (Fig. 2).

Agisoft Photoscan was used and the two surveys were processed independently according to a well-consolidated pipeline (Bitelli *et al*. 2006). After the alignment and sparse point cloud process, the dense point cloud models were further created and 'cleaned' in order to remove errors such as redundant points and blunders and processed to obtain high-detail surface models. The polygonal models needed repair, either manually or automatically, in order to fix some errors such as holes and incorrect faces and were later provided with high-detail photorealistic textures.

The photogrammetric survey from the ground has enabled the creation of a dense cloud model of about 98.000.000 points and a polygonal one of more than 225.000.000 faces which have been simplified in order to produce a lighter model. The decimation, performed by Geomagic Studio 2013, has provided a good compromise between keeping surface details and a reduction in the number of polygons.

The photographs from the drone produced a polygonal model of about 21.600.000 faces, which did not require a decimation procedure. Low light, due to the early morning hours, has also conditioned the data acquisition. Although less detailed, the aerial model shows the domus in its context (roofs, streets) providing a clear picture of urbanism.

4 Comparison

Because the data acquisition took place at two separate times using two cameras with diverse resolutions, the final models have very different properties. The integration of the two reconstructions in order to obtain a complete view of the context (thanks to the drone survey) and a detailed interior (thanks to the ground survey), provides much useful information for an archaeological interpretation of the house (D'Andrea, Barbarino 2012).

The two dense point clouds were aligned using CloudCompare and a cloud-cloud distance analysis using the Hausdorff distance algorithm was performed. This algorithm, based on the analysis of how far two subsets of a metric space are from each other, simply takes into account the distance from the nearest neighbour.

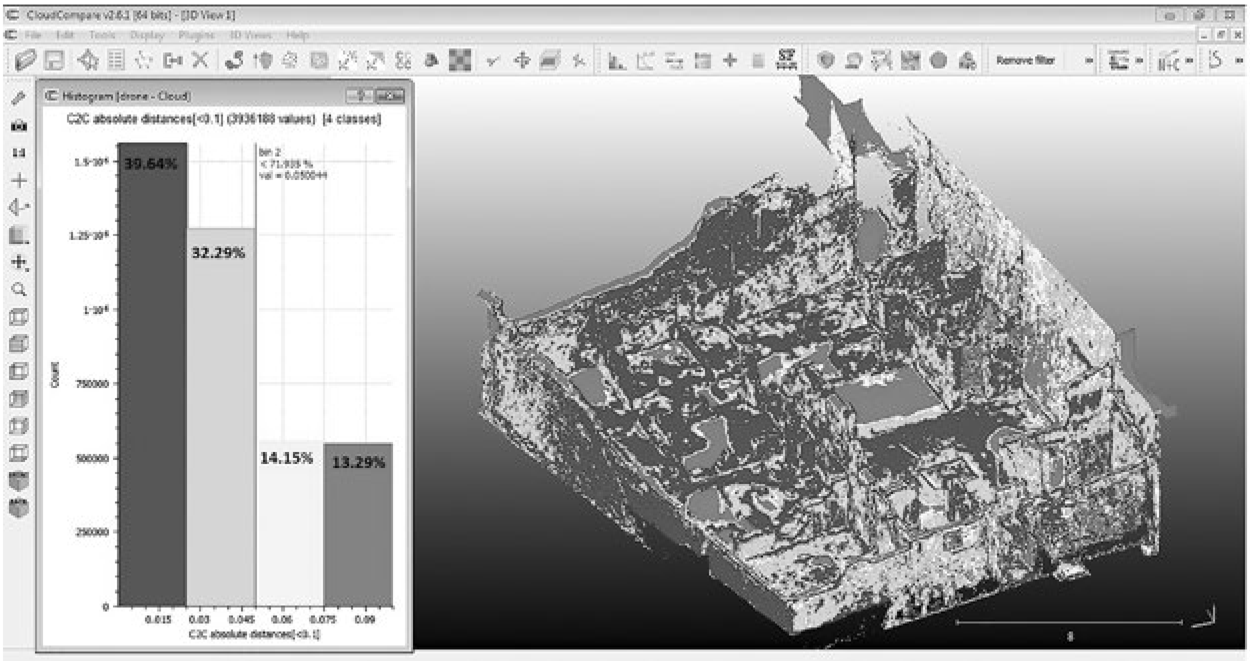

Fig. 3. Analysis of dense point clouds in CloudCompare.

Fig. 3 shows the final results of the overlapping of the two models. For greater understanding four classes have been chosen to identify the variances. The superimposition shows a good alignment: the la distance between the two models is lower than 5 cm in 72% of cases (blue and green colours). The variance in yellow, ranging between 5 and 7.5 cm (14.2%), seems to be localized mainly along the vertical lines of the highest wall where the drone was probably unable to capture the surfaces correctly. Finally the high percentage (about 13.3%) of deviations larger than 7.5 cm (in red) seems to coincide either with parts totally missing in one model (e.g. the crests of the walls) or with areas that were greatly altered during the time that elapsed between the two surveys (e.g. the *tablinum* was reburied and was not visible at the time of the aerial data acquisition).

In order to understand the reason for the presence of widely differing areas between the terrestrial and aerial survey, a specific analysis was performed for the highest wall in the eastern part of the house adjacent to house I, 6, 15. By applying the same analysis on a specific part of the model different results have been obtained (Fig. 4). In 40% of cases there is good overlapping while in 60% the distance is greater than 5 cm. One explanation of this wide variance is because the surface of the wall was barely captured by the drone camera, which can only shoot in an upright position (Fig. 5). Furthermore, as the data acquisition by drone was carried out in the morning before the opening of the archaeological area for safety reasons, the wall, which is particularly high, was still in a shaded area at the time of the flight (Fig. 6). With more sunlight we would probably have obtained better results in terms of the final overlapping. This is seen more clearly by looking at Figs. 5 and 6, where in the former image the surface of the wall is barely defined with many incomplete areas in comparison with the model obtained by terrestrial survey where the wall is complete and well represented.

5 Conclusions

The paper focused on the subject of low-cost digital survey in archaeology, by proposing an integration between two different approaches, terrestrial and aerial close-range photogrammetry. The Structure from Motion (SfM) techniques have been widely tested in archaeology with good and reliable results. The speed of data acquisition and automation in 3D data processing makes close-range photogrammetry a flexible and useful technique in the digital survey of archaeological sites, even those as complex and problematic as Pompeii.

The models obtained through terrestrial and aerial data acquisition show a good degree of overlapping, except for the areas that changed in appearance between the two acquisitions and the areas differently visible by the two approaches.

Considering the low cost of the whole operation and the environmental and timing difficulties, the final results are encouraging and satisfactory. Furthermore, there were logistical issues linked to the presence of visitors and tourists during the day and for these reasons the flight time of the drone was limited.

Even if the numerical analysis of the models has highlighted some limits in the accuracy of the digital models performed in the archaeological area of the Domus of Stallius Eros, the integration of the two approaches provides a more complete and useful model for archaeological research at Pompeii.

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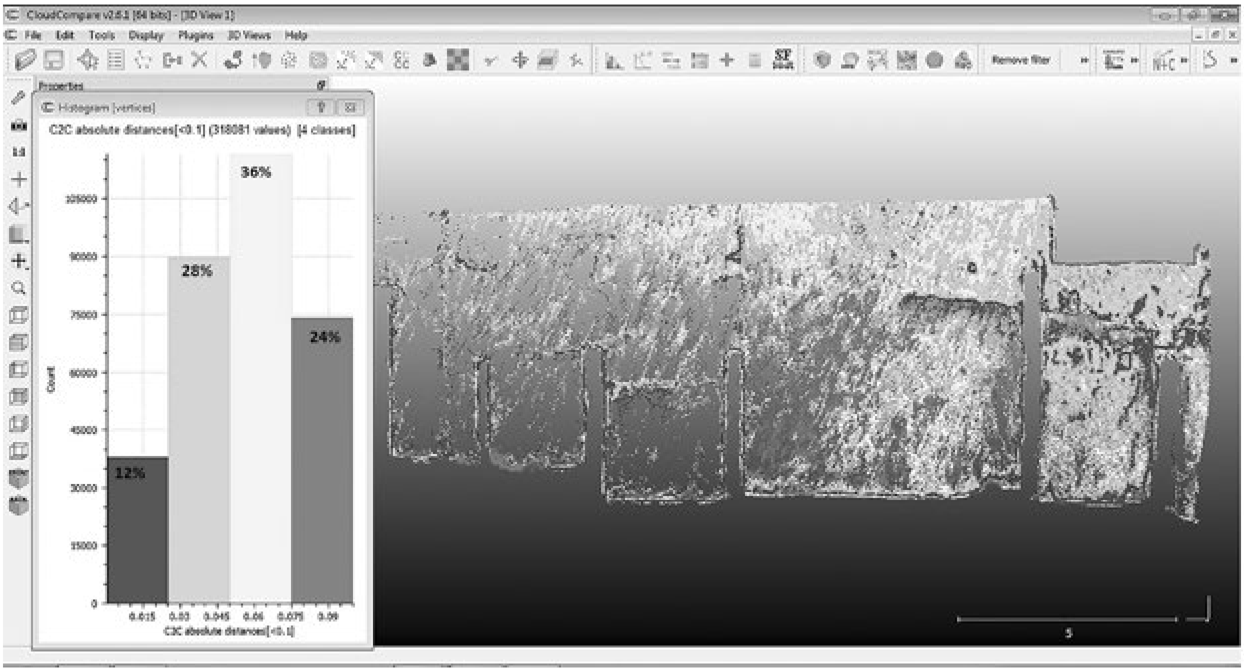

Fig. 4. Analysis of dense point clouds of the east wall.

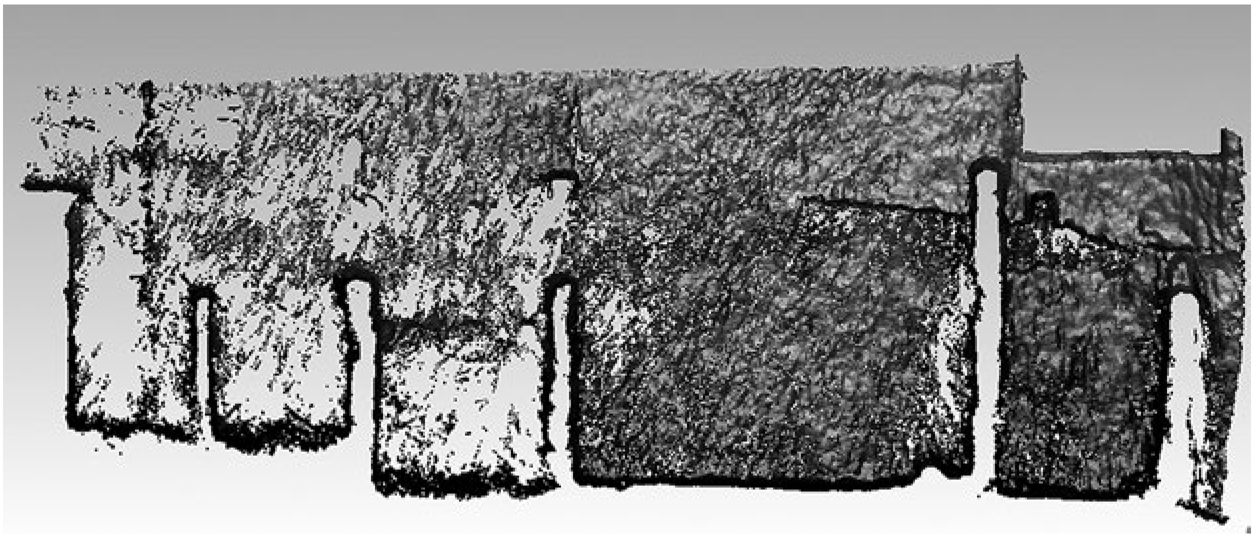

Fig. 5. Vertical surface of the east wall captured by drone.

encouraging this work and providing input to the research and Dr Marco Giglio for providing survey data acquired by the total station. The 3D model, images, and a video of the house of Stallius Eros are downloadable from www.europeana.eu/portal/search.html?query=3D+model+of+Stallius+Eros+Domus&rows=24 (accessed on 15 November 2015).

Bibliography

Allison, P. M. 2004. Pompeian Households: An On-line Companion. Available at: http://www.stoa.org/projects/ph/house?id=5 [Accessed: 30 june 2015]

Allison, P. M. 2004. *Pompeian Households. An Analysis of the Material Culture*. Cotsen Institute of Archaeology, UCLA, Monograph 42. Los Angeles, University of California.

Chiabrando F., Lingua, A., Maschio, P., Rinaudo, F., Spanò, A. 2012. Mezzi aerei non convenzionali a volo autonomo per il rilievo fotogrammetrico in ambito archeologico. In *Una giornata informale per i 70 anni del Prof. Carlo Monti* – 3 Maggio, Milano: 1-12.

Bitelli, G., Girelli, V., Remondino, F., Vittuari, L. 2006. Surface modelling of complex archaeological structures by digital close-range photogrammetry. In *Proceedings of 2nd International Conference on Remote Sensing in Archaeology*, Rome, Italy: 321-6.

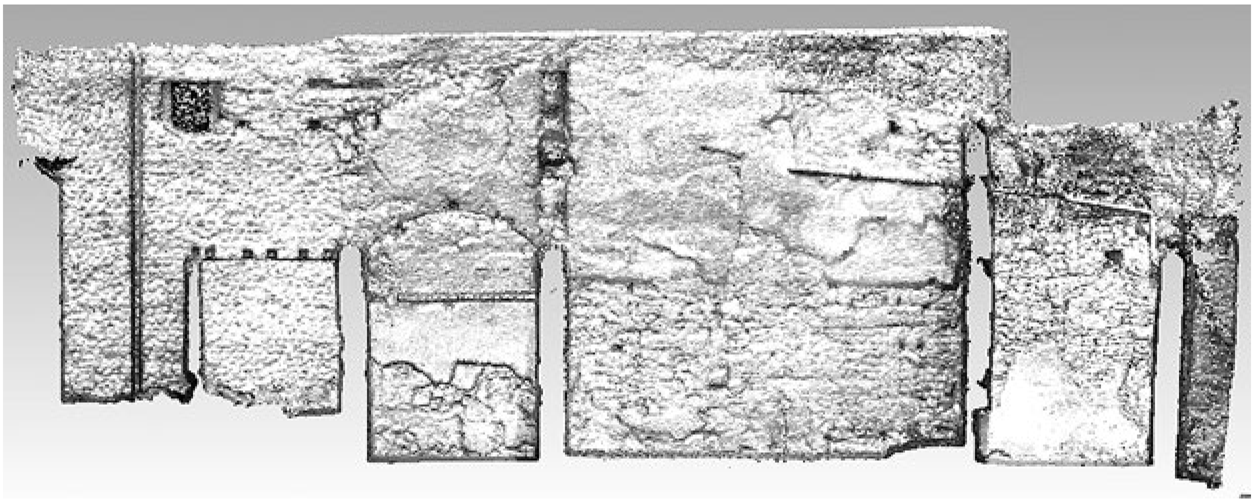

Fig. 6. Vertical surface of the east wall obtained by terrestrial data-capture.

Bosco, A., Barbarino, M., Valentini, R., D'Andrea, A. 2015. Low-cost surveys of the Domus of Stallius Eros in Pompeii. In *3D Virtual Reconstruction and Visualization of Complex Architectures, 25-27 february 2015, Avila, Spain*, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W4: 187-92. doi: 10.5194/isprsarchives-XL-5-W4-187-2015.

D'Andrea, A., Barbarino, M. 2012. Modellare lo scavo archeologico: esperienze e tecniche a confronto. In *Archeologia e Calcolatori* 23: 229-45.

Maiuri, A. 1929. Pompei - Relazione sui lavori di scavo dall'aprile 1926 al dicembre 1927. In *Notizie degli Scavi di Antichità*, 6, 5: 354-476.

Pesando, F., Guidobaldi, M. P. 2006. *Pompei, Oplontis, Ercolano, Stabiae*. Guide Archeologiche. Roma-Bari, Laterza.

Remondino, F., El-Hakim, S. 2006. Image-based 3D modelling: a review. In *Photogrammetric Record* 21, 115: 269–91.

Pottery Goes Digital. 3D Laser Scanning Technology and the Study of Archaeological Ceramics

Martina Revello Lami

m.revello-lami@uva.nl

ACASA Archaeology, University of Amsterdam;

Loes Opgenhaffen

loes@lopd.nl; l.opgenhaffen@uva.nl

ACASA Archaeology - University of Amsterdam; LOPD Graphic Solutions for Archaeology;

Ivan Kisjes

i.kisjes@uva.nl

ACASA Archaeology, University of Amsterdam,

Abstract: Most frequently brought into play for documentation purposes, 3D technologies are highly precise measurement tools, providing high quality three-dimensional archives of an object's surface. However, the possibilities offered by 3D technologies have not been fully explored in archaeological research so far. Pottery studies, in particular, have paid greater attention to develop sophisticated methods of visual recording and to build typologies, largely overlooking other applications. To bridge this gap, we will present the preliminary results of a pilot study carried out on experimental bodies of pottery, in which systematic ceramic analyses have been coupled with 3D technology. In so doing, we argue that the full potential of 3D technology applied to ceramics goes beyond accurate documentation. In receiving the complete account of surface topography, 3D models provide valuable information on the very process of making a pot, shedding light on manufacturing methods, technological choices and potters' motor habits.

Keywords: 3D scanning technology, Pottery analysis, Computational geometry, Shape analysis, Detection of manufacturing methods

Introduction: 3D technology beyond recording systems

Over the last fifteen years, the 3D recording of both structure and objects has received considerable scholarly and public attention, as the proliferation of literature on the subject may well demonstrate (Andreetto, Brusco, Cortelazzo 2004; Callieri, Ponchio, Cignoni, Scopigno 2006; Forte and Pietroni 2009; Stylianou 2009; Remondino, Barazzetti, Nex, Scaioni, Sarazzi 2011; Kampel and Sablatnig 2006; Meyer 2007; Pop and Bucksch 2007; Ter Haar, Cignoni *et al*. 2005; Limp, Payne, Simon, Winters, Cothren 2011). Initially, great emphasis has been placed on the description of methods and workflows, their weaknesses and strengths, giving full account of a range of deployment efforts. Only recently, the focus has shifted from the small to the wider picture in order to understand the implications, strategies, and consequences of the application of 3D imaging technology for reconstructing the past. From the acquisition of data to the creation of a digital archive, through digital object discovery, citation, analysis, study, and reuse, the complex process of 3D recording must be considered as part of a comprehensive and interconnected research infrastructure (or digital ecosystem; see Forte 2008; Limp, Payne, Simon, Winters, Cothren 2011). All the aspects belonging to 3D digital ecosystems need therefore to be approached as a whole and in an interdisciplinary manner, in order to assess most effectively the long-term value of these new techniques, as well as to address more consistent research questions.

1 Research questions and aims

It is exactly towards this direction that we have undertaken our research project, which has at its core the systematic integration of 3D recording methods within pottery analysis. One of the main aims of this ongoing project, carried out in joint forces by the 4D Research Lab and the Petrographic Lab of the University of Amsterdam, is to move beyond the current 3D documentation practices in order truly to explore where this technology can lead us. It is our belief that, although 3D documentation represents a valuable undertaking, it is too often an end in itself. Clearly, digital archives are powerful sources, 3D models are fun to play with as well as effective educational tools (Fig. 1), but more work needs to be done to embed 3D technology more firmly in our research practices and to evaluate what kind of archaeological questions we can answer with it.

As noted earlier, pottery studies have been mainly concerned with 3D techniques in order to accelerate the traditional practice of documenting potsherds. In particular, greater attention has been paid to the development of increasingly sophisticated methods for deducing from 3D outputs the most accurate artefacts profiles, with the ultimate aim of building automated typologies, but there is much more to be gained beyond this. Studies conducted on other types of artefacts, such as lithics, metals, or bone remains, have already started

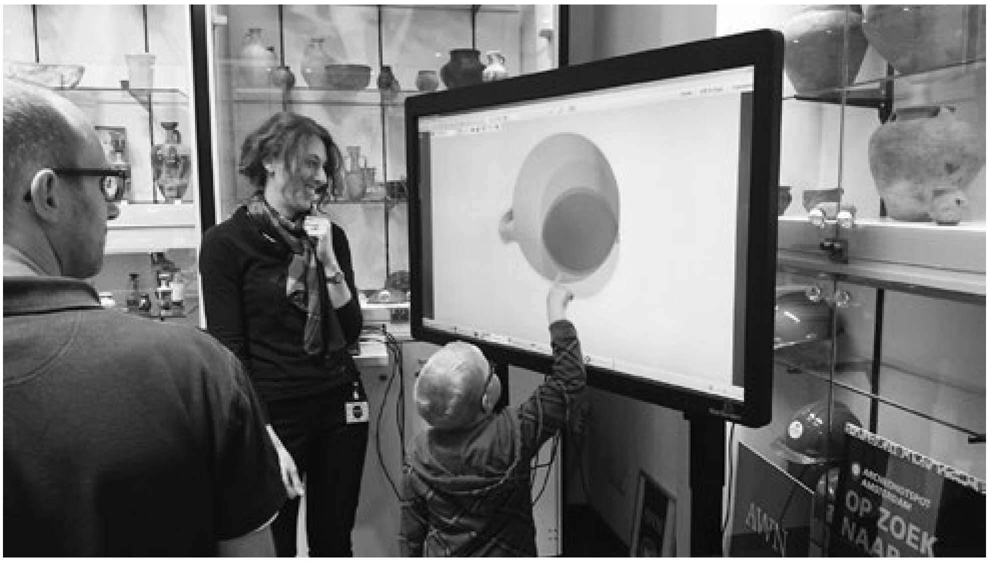

Fig. 1. The project 'Pottery goes digital' presented to the visitors of the Allard Pierson Museum (Amsterdam).

to explore different research paths, successfully applying 3D data for use-ware analysis or for studying post-depositional damage, proving that 3D techniques are not only highly precise recording tools, but are also valuable (though under-explored) research tools.

What does it mean to use 3D recording methods as a research tool when it comes to the ceramic record? Or, to take up Martin Millet's invitation (Millet 2015, CAA 2015 opening lecture), what type of questions can 3D data help to address? A survey of the current literature indicates the following as the most common applications of 3D data to pottery analysis:

- So far, studies on axial symmetry focusing on uniformity and deformation of wheel-thrown vessels and potsherds, have addressed the issue of ceramic variability and scale of production, opening an important line of inquiry into the *chaînes opératoires* that characterize specific manufacturing processes, workshops, or even the work of individual artisans (Gilboa, Karasik, Sharon, Smilansky 2004; Saragusti, Karasik, Sharon, Smilansky 2005; Karasik 2008; Gilboa, Tal, Shimshoni, Kolomenkin 2013).

- Following the same path, other works focusing on metrics associated with wall thickness, height, diameter, and estimated volume of pots provided greater depth to the discussion on ceramic variability. In fact, research applying 3D morphometric analysis to pottery may also include coil-built and handmade vessels, while studies focusing on axial symmetry are limited to wheel-thrown objects (Selden, Perttula, O'Brien 2014).

In this paper, we argue that the potential of incorporating 3D data within ceramic analysis is still largely untapped. In receiving the complete account of surface topography and texture, 3D technologies can lead to most accurate analysis of features such as grooves, spiral ridges, cracks, etc., which are of pivotal importance for assessing different shaping techniques, technological choices, as well as potters' motor habits. Remarkably, this is one of the most promising yet least explored application of 3D data to pottery analysis and will therefore be the focus of the remainder of this paper.

2 The analysis of surface macrotraces and the identification of pottery forming techniques

Since the pioneering works of Valentine Roux and Marie-Agnes Courty (Roux 1994; Courty and Roux 1995; Roux and Courty 1998), who have called into question the criteria traditionally used for identifying pottery-forming processes, ceramic analysts have spent much energy in the study of the surface macrotraces that enable us to distinguish better between different manufacturing techniques. For instance, the integration of ethnographic and experimental data with material science and macrotrace analysis on fine decorated proto-geometric Greek pottery clearly pointed out that most of the vessels previously considered as simply wheel-thrown were actually coil-built and finished only at a later stage with the aid of the wheel (Berg 2013; Ruckl and Jacobs, forthcoming). The combination of these two forming methods, also known as wheel coiling, can be considered as the intermediate ceramic technology between hand-building and wheel throwing (Fig. 2). Current research demonstrates that wheel-coiling was a common practice in many different geographical and chronological frameworks from 3rd-millennium Mesopotamia and India, to Middle Bronze Age Aegean and Mycenaean Greece, and has called for a reassessment of our ideas concerning the spread of the potter's wheel in the Mediterranean and beyond (Knappett 1999, 2004; Jeffra 2011, 2015; Berg 2013).

2.1 Tracing wheel-fashioning techniques

V. Roux and M.A. Courty distinguished four different methods of wheel-coiling depending on the stage at which the rotative kinetic energy (i.e. the wheel) is used for shaping the clay (Fig. 3). Based on their experimental material, they were also able to set a number of criteria for recognizing the four methods on ancient ceramics (Courty and Roux 1995; Roux

Fig. 2. Wheel coiling technique: rough-out made of assembled coils and then shaped and thinned with rotative kinetic energy (after Boileau 2009).

and Courty 1998). Without going into a detailed description of the different wheel-fashioning techniques, which would stray from the purpose of this paper, suffice to say that when dealing with ceramics, assessing manufacturing methods is a far more complex task than just choosing between hand-building or wheel-throwing. In particular, the identification of mixed techniques requires experienced ceramic analysts and closer macroscopic examination of surface features.

Despite substantial differences between wheel throwing and wheel coiling, the resulting appearance of the finished products may be quite similar. This similarity relates to features such as parallel horizontal striations and rilling, axial symmetry, and string-cut marks at the bases of ceramic vessels (Courty and Roux 1995). In particularly favourable conditions, however, the two techniques can be distinguished by closer examination of macroscopic surface features, such as coil-seams (often not parallel to the rilling), variation in wall thickness due to discontinuous pressure while shaping the pot at its initial stage — when it is assembled from coils — or significant undulations on compression zones due to the deformation of stiff coils. The presence and form of these traces will not only depend on the particular wheel-coiling method, but also on the skill of the potter (for a detailed description see Jeffra 2015).

2.2 Surface macrotraces in 2D

The recent work of S. Ruckl and L. Jacobs, who kindly shared their research with us as well as providing a large part of the material processed for this pilot study, well illustrates the importance of a correct interpretation of surface features for ascertaining pottery manufacturing techniques. In particular, Ruckl and Jacobs's analysis focuses on the identification of macrotraces related to the wheel-coiling technique, and uses as a case study protogeometric fine decorated pottery from Mitrou, Lefkandi, and Halos compared with experimental pots created in the Laboratory of Ceramic Studies in Leiden (Ruck & Jacobs, forthcoming). The latter body of pottery (the experimental material) lies at the core of our pilot project, providing an ideal opportunity to build a 3D reference collection of surface macrotraces based on pots for which the manufacturing technique is known, as they have been especially made for this purpose.

According to Ruckl and Jacobs's thorough analysis, the following are the most important surface features (or macrotraces) usually taken into account by specialists to ascertain different wheel-fashioning techniques, and on which we have focused our attention:

- Coils: the most evident features to identify coiling or wheel-coiling technique; in most cases imperfectly flattened coils largely retain their original shape and might be visible on the vessel's internal surface, often in the form of horizontal rilling (Fig. 4a).
- Coil seams: coil seams/joins can be observed on wall surfaces in the form of a narrow horizontal groove between two convex features, when two coils are not completely joined (Fig. 4b).
- Preferential horizontal breakage along the coil-joins: imperfectly joined coils may constitute fragile parts on wheel-coiled vessels, which will most probably break horizontally, along the two assembled elements (Fig. 4c).
- Compression undulations: usually due to the assembling of stiff coils, compression undulations are oblique irregularities in the form of restricted but prominent swellings (Fig. 4d).
- Overall, wheel-coiled vessels do show an irregular topography of interior surfaces (especially visible on the bases of large closed shapes), differential wall thickness on a horizontal plane, and small irregular cracks on the surface (Fig. 4e)

3 Surface macrotraces in 3D

3.1 Exploring 3D scanning methods

So far, we have seen two-dimensional representations of surface macrotraces re-elaborated by a professional photographer in order to make the features more evident, under the guidance of a ceramic specialist (Fig. 4). The result is effective, but is not metrically exact or easily achieved. For this reason we decided to run a test on the same experimental sherds in order

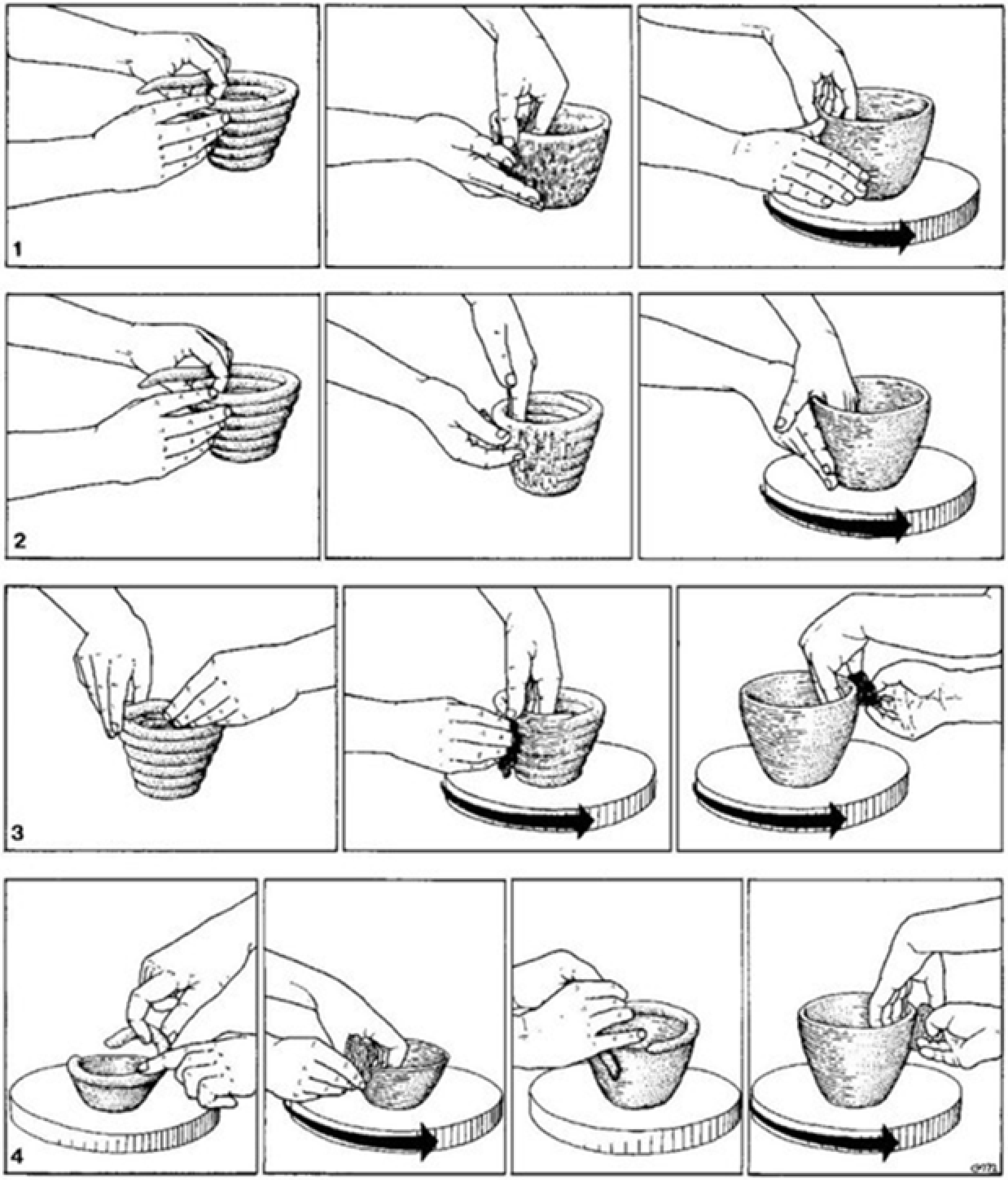

FIG. 3. FOUR WHEEL-FASHIONING METHODS (AFTER ROUX AND COURTY 1998: FIG. 1).

to evaluate to what extent 3D recording might ease the process of identifying and representing surface macrotraces and if so, whether it might also add information beyond the macroscopic level because frequently, wheel-coiled features are not visible to the naked eye. As an ultimate goal, we will try to establish whether the application of 3D technology might eventually lead to the development of an automated system for identifying ceramic forming processes and ancient manufacturing techniques.

The formulation of the above research questions has clearly determined the level of detail of our analysis. To set up the workflow, first we had to assess the techniques required and whether they were available at the 4D Research Lab. The 4D Lab has already extensively worked with the DAVID SLS-1, a low-cost structured light scanner. A few months ago, a relatively low-cost NextEngine Ultra HD laser scanner was added to the equipment at our disposal to explore further the possibilities of laser scanning. Lastly, the Lab has very recently

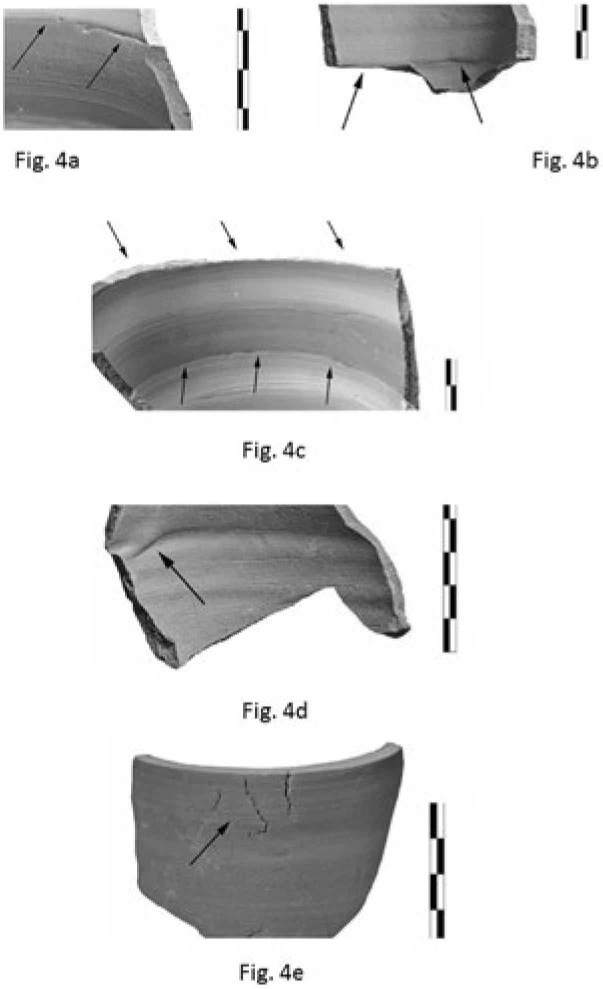

FIG. 4. SURFACE MACROTRACES, ARROWS INDICATE A) COILS; B) COILS-SEAMS; C) HORIZONTAL BREAKAGE; D) COMPRESSION UNDULATIONS; E) IRREGULAR CRACKS (COURTESY OF S. RUCKL AND L. JACOBS, AFTER RUCKL AND JACOBS, FORTHCOMING).

FIG. 5. BATCH OF MESHES CREATED WITH NEXTENGINE HD ULTRA LASER SCANNER.

purchased a white light scanner, the HDI Advance R3x White Light Scanner, but unfortunately, we could only run a couple of tests with it, and therefore it does not have a central role in our current project.

Having defined our working strategy, we selected the ceramic material to be recorded and started the actual acquisition process.

3.2 NextEngine Ultra HD laser scanner

The first scanning sessions were devoted to finding the most efficient method to scan potsherds with the NextEngine on the highest resolution in order to register the most detailed geometry. We also tested for the number of scans needed to cover effectively all the relevant fragments parts: as mentioned earlier, breaks are important markers for identifying manufacturing techniques and should therefore be recorded in detail. After a difficult start, thanks to the support of NextEngine we discovered that both the alignment issues of batches of sherds and the divergence in the z-axis, were due to calibration problems that could easily be solved by the machine itself. Subsequently we were able to scan five to seven sherds in one batch (Fig. 5), each batch needing eight to ten scans, which takes from 48 to 51 minutes. The scanner was set on 'extended' mode.

The accuracy is around 0.003 to 0.005 inches after alignment (Fig. 6). Each point-cloud of a sherd is then cleaned and fused to a mesh in ScanStudio (the scan-software of NextEngine), producing files of 85-260 MB per sherd, leaving little post-processing time in Meshlab. Lastly, we decimated 25% of the total original faces (or points) considerably reducing the size of the file and making the models more workable in the post-processing phase.

In any event, one should be aware that scanning multiple sherds in one batch might affect the automatic alignment. Occasionally, multiple scans of such fragmented material are too homogeneous in geometry for NextEngine to find good features to align. As a result, the operator needs, after reworking and cutting, to align ten to twelve scans manually, and much of this work has to be done on the basis of the texture layer. Another possible obstacle is that when more than two scans are recorded and overlap too much, the texturing results are a bit disappointing (although in our research, textures are not necessary). This entails further reworking/cutting time per scan to reduce the overlap, although multiple files should still overlap to some extent in order to proceed with the alignment. As a consequence, the overlapping parts — for instance sharp edges — can leave traces in the mesh, possibly misleading both specialists and software while analysing surface macrotraces.

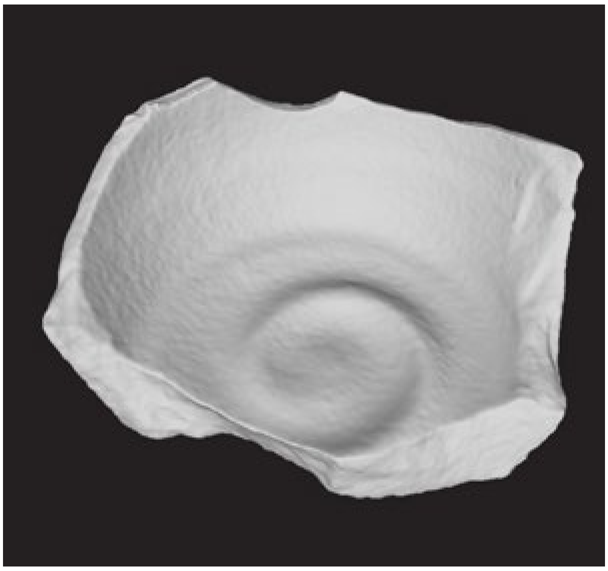

Fig. 6. Example of base fragment model created with NextEngine HD Ultra laser scanner.

3.3 David SLS-1

Given the previous experience in the 4D Lab with other projects, we initially decided not to use the DAVID SLS-1 scanner for this project. This is mainly because it takes some time to master both scanner and software (aside from the fact that it crashes frequently, provoking loss of data). Moreover, it is a rather time-consuming job to create good meshes useful for analysis. Therefore, we opted to concentrate our efforts on the NextEngine, which seemed more suitable for detecting surface macrotraces of potsherds. Given the ime constraints, however, we also mastered the DAVID scanner to operate simultaneously with the NextEngine, in order to accelerate the recording process of the ceramics. The DAVID was not able to scan in batches, not even with the aid of an automated rotary table. This resulted in scanning one sherd at a time, varying in time from 10 minutes to one hour, making it an average of 30 minutes per scan (i.e. per sherd; Fig. 7).

3.4 The ideal system?

As is clear from the above, at the beginning of our work we struggled to determine the best practice for scanning ceramic fragments for detailed pottery analysis, but not in vain. Now we can say with more certainty that the NextEngine is a valuable device only if the research questions do not require a high level of detail. The DAVID SLS-1 can meet this level of detail, but is only of value when the operator is highly experienced (and it requires a tremendous amount of time).

We ran a few test scans with the new high-end HDI Advance R3x White Light Scanner, which immediately showed that this type of machine is able to record the same sherds in less time, producing smaller files but with a higher accuracy. The White Light Scanner captured the same base fragment in 15 minutes and aligned them automatically, barely generating any noise. Scans are very clean, hardly requiring any post-processing, and provide the operator with a much smaller file of approximately

Fig. 7. Example of base fragment model created with David SLS-1 structured light scanner.

200 MB (Fig. 8). It must be said, however, that it takes a long time to calibrate the HDI (an average of 30 minutes), and when there are many differently sized potsherds it needs to be recalibrated. Moreover, the HDI is not designed for mass scanning of small pottery fragments in batches, leading to the conclusion that this is not the ideal device for such a type of analysis either.

To conclude, the NextEngine is a fairly accurate tool for purposes such as the (low-res) digitization of museum objects. As for the structured light scanning, the DAVID SLS-1 is in more or less the same price range, but may produce slightly greater accuracy, although if suffers from a greater time issue than the NextEngine (batches of sherds VS single sherd) and is far from user-friendly. The HDI R3x has the highest LOD and scans faster, but the calibration issue slows this down. Combined with the fact that it can only scan one sherd at a time (at least at this point in our research), this expensive device is not the best candidate either.

Therefore, in terms of (time-)efficiency and the type of research (i.e. LOD), the NextEngine UltraHD is the most suitable device to do the job.

4 Post-processing and digital analysis

4.1 Exploring algorithms for analysis with high-level software

Having developed the scanning strategy, we had to choose what software best suits the testing of scans in order to answer our research questions.

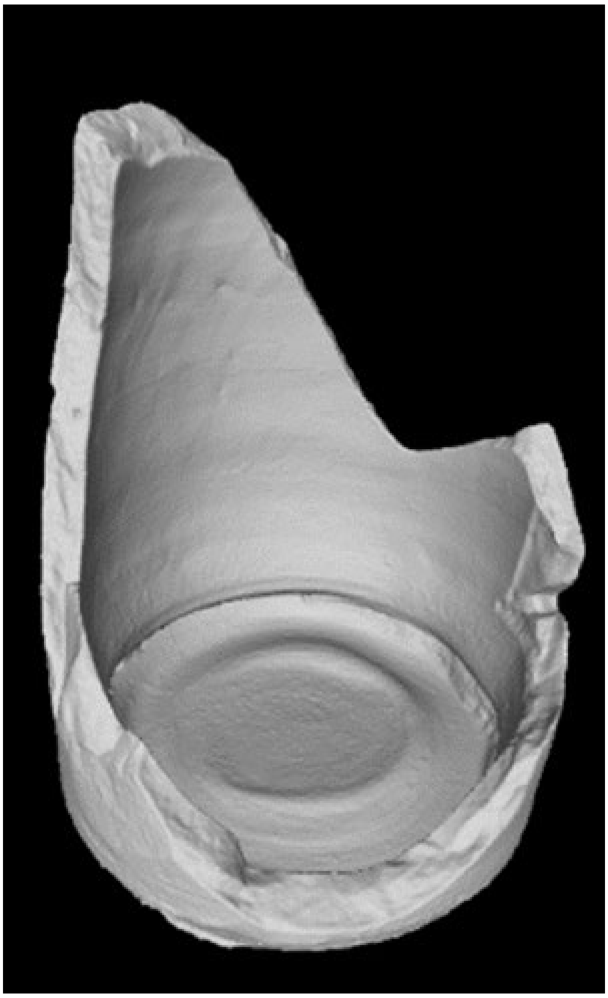

FIG. 8. EXAMPLE OF BASE FRAGMENT MODEL CREATED WITH HDI ADVANCE R3X WHITE LIGHT SCANNER.

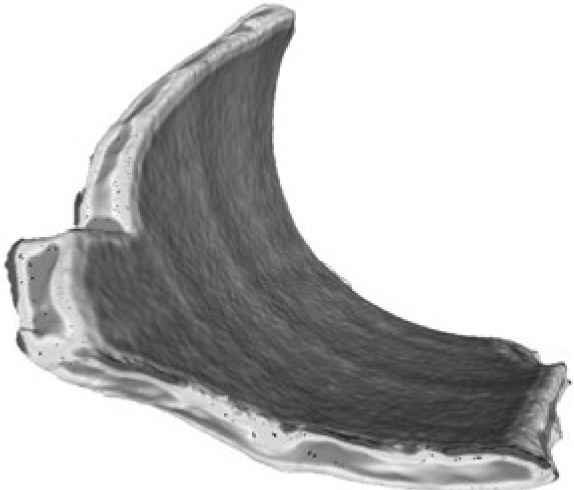

FIG. 9. COIL RIDGES HIGHLIGHTED AFTER FILTERING APSS CURVATURE IN PARAVIEW.

To explore which algorithms might prove useful for working out manufacturing techniques, we have been testing some algorithms integrated in existing software: the ever-popular Meshlab and some medical packages (3D Slicer: www.slicer.org/, Paraview: www.paraview.org/). We have also used programs such as Netfabb and Meshmixer to manipulate the meshes so that they are in workable condition for some of the software.

It worked to an extent: the ridges separating coils could be detected (Fig. 9). We could also isolate some of the voids caused by coiling (Fig. 10 but hardly visible) by searching for contours after computing the vectors perpendicular to the surface.

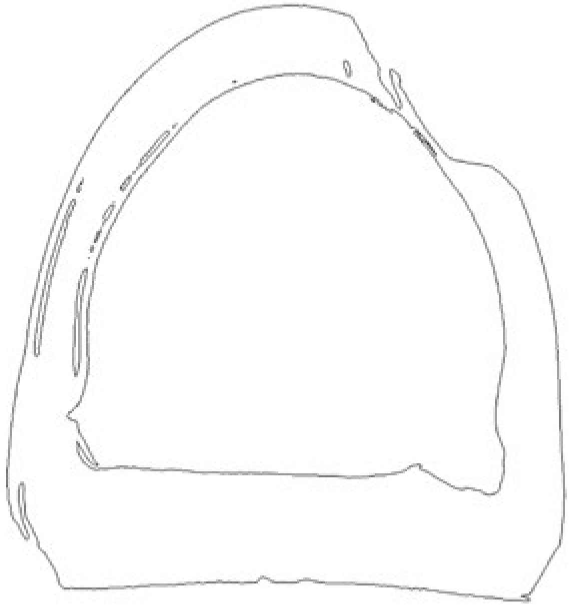

FIG. 10. VOIDS HIGHLIGHTED AFTER EDGE DETECTION IN PARAVIEW.

We also tried the various curvature algorithms native to Meshlab, to find patterns matching broken-off coils and coil ridges in pot walls. The NextEngine scanner produced some dirty meshes, but after a little light smoothing, the curvature algorithms (APSS in this case; see Guennebaud and Gross 2007 and Guennebaud *et al*. 2008) clearly show the coil ridges on the ceramic surface and also produce characteristic patterns where there are broken coils on the breaks of the sherd (Fig. 11).

Surface normals also seemed a promising way to find characteristic cracks and ridges, tapered edges and dislocated coils computationally, but the problem is that sherd meshes do not have a standard orientation, so the X, Y, and Z normals cannot provide a consistent enough direction to be used to identify the phenomenon in question. This is still a problem as we have not yet found a way to detect in a consistent way the ‘up’ side of undiagnostic sherds (e.g. wall fragments not featuring diagnostic elements such as rim, neck, shoulder, base,

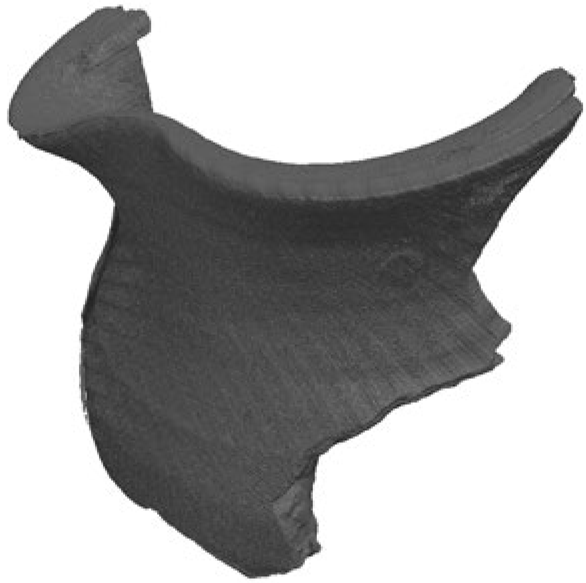

Fig. 11. Z component of the surface normals highlighted in Paraview.

etc.) without manual marking. As some of the characteristics depend on fragment orientation, this is quite problematic; nonetheless, the normals should provide enough information (especially taking the local context into account) to extract valuable data (Fig. 12).

Another way to define relevant ridges and cuts was to simply smooth the mesh and calculate the distance of the smoothed mesh to the original (per closest vertex; Fig. 13).

Some of the algorithms available in these software packages (e.g. fibre bundle detection, skin separation, skeleton detection) seemed encouraging for detecting specific manufacturing markers, but in practice did not produce results for our dataset. We suspect that minor modifications to those algorithms would make them useful to us.

In the end this software turned out to be too uncustomizable (in the case of Meshlab and 3D Slicer) or too cumbersome to script (in the case of Paraview) to set up a pipeline of algorithms that can really isolate manufacturing markers. We therefore switched to the Visualization Toolkit (www.vtk.org), an open-source library with an API in Tcl/Tk, Java, and Python. We chose the Python interface to be able to also make use of the NumPy (http://www.numpy.org) and SciPy (http://www.scipy.org) scientific computing libraries and to have access to the Image Segmentation and Registration Toolkit (www.itk.org). Before proceeding, one word of caution for those thinking about venturing this way: while most programs provide a Python console that has access to a VTK library, the Python API of VTK is not very well documented and does not describe all of the methods that VTK offers in C. Moreover, some of the methods that the C interface offers are limited in Python

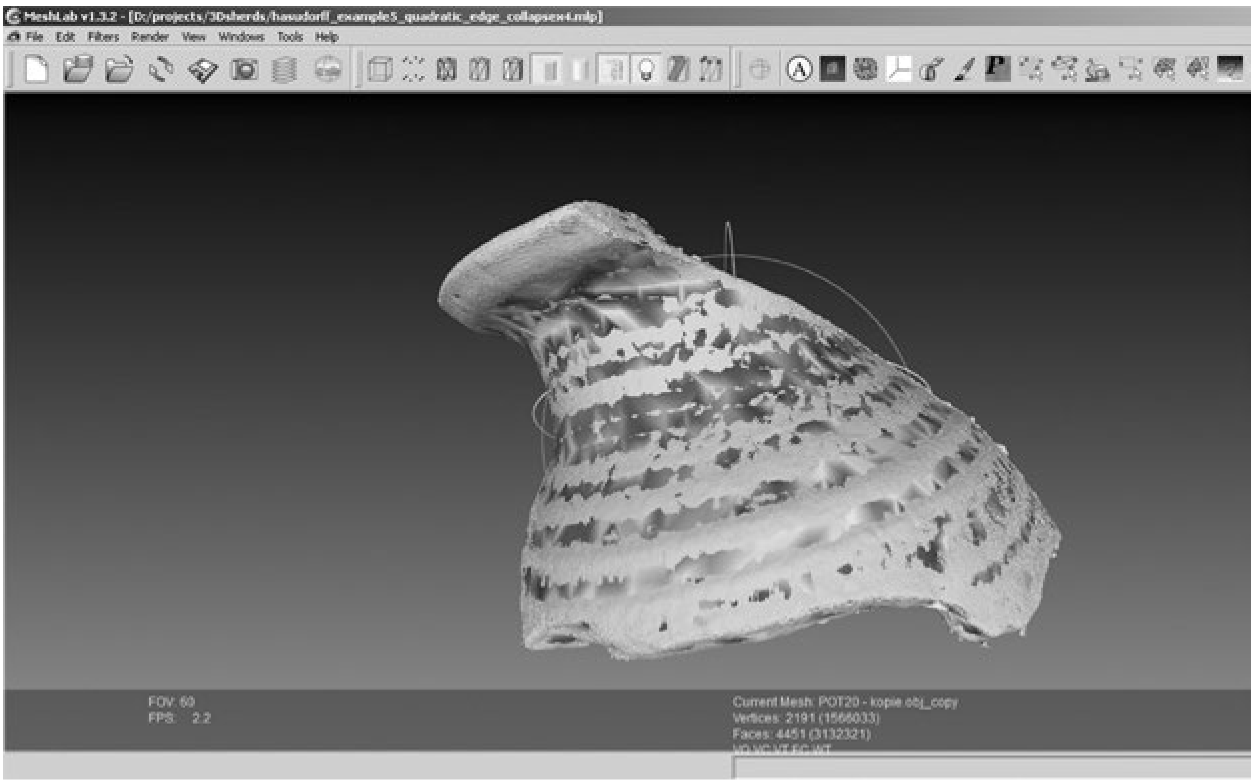

Fig. 12. Smoothing/decimating and comparing (MeshLab).

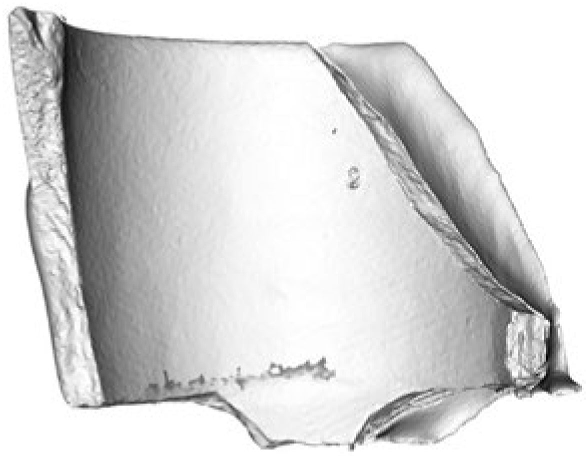

FIG. 13. SMOOTHING MESHES TO HIGHLIGHT RIDGES AND CUTS (MESHLAB).

in the argument set you can pass to it, limiting functionality. Thus, it is better to just use C++ in order to have both good documentation and a full interface. This is the path we have chosen.

4.2 Setting up lower-level algorithm pipelines

We wrote a set of Python scripts, one for each typical manufacturing marker, using Gaussian curvature computation, surface normals, various smoothing and decimation algorithms, thresholding, connected component detection, and Boolean mesh operations. For each type of coiling feature we set up a pipeline of algorithms in a specific order using a combination of the above algorithms and special parameters relevant to the properties of the feature we were looking for (e.g. the metric size of the feature).

The most effective pipeline so far for detecting larger macro-traces of coils turned out to be first to simplify the mesh by either smoothing or decimating using quadratic edge collapse and then calculating the distance between the original and the resulting meshes, followed by either a threshold or a binary subtraction. This gave us a representation of the sherds' surface features. The choice of simplification technique is very important — how the model is simplified determines how the surface features are warped, which of course has a great effect on what is detected. The various smoothing algorithms currently native to VTK turned out not to be ideal for surface feature detection, but by adjusting the arguments to the functions we could make them work for these macro-traces.

Curvature and surface normal filters are best suited to find coil features on breaks. A small modification to the VTK curvature and surface normals algorithms (increasing the Kernel radius) would make things easier, as our earlier experiments in Meshlab had shown us, but with the right parameters we were able to detect the coil markers anyway.

Automatic orientation of the sherds in space is a problem for detecting horizontal breakage. After a few experiments, we believe that the best way to find the orientation of a sherd in space is to use the principal axes (Sylvester 1852). That makes an orientation at least reproducible. Even if it is impossible to find which way is 'up' for a sherd just by calculating the principal axes, it is always possible to calculate the 'flat lying' position of a fragment, making it possible to highlight important features such as wall thickness discontinuities.

After identifying the markers on the test set of sherds, we described the geometry of the detected areas as a set of very simple shape descriptors (i.e. numbers that describe the shape of the feature), in order to compare them to the expected shapes of the manufacturing indicators. Such statistical morphological descriptors seemed a promising way to find, for example, the variability of wall thickness of a sherd, aside from the mentioned problem of sherd position, but the imaging and mathematical libraries we found currently lack the support for three-dimensional shape descriptors. We have therefore implemented a few of our own. We limited ourselves to a small set of very simple descriptors, most of which turned out not to be (directly) useful in filtering pottery production technique markers from false positives.

The shape descriptor that proved most useful — from the few we tried — was the standard deviation of the set of distances of the cell centroids of the geometry to the centre of mass of the geometry as a whole. A kernel density estimation (see for instance Parzen 1962) of the surface areas of the detected parts seems to show a bit of clustering, even in our small test dataset. This is not surprising as this descriptor readily distinguishes elongated from roundish geometries, helpful for finding (oblong) cracks, coils, and voids from (roundish) fingerprints, lumps, and sherd surface hollows.

5 Concluding remarks

However preliminary our foray into the graphics analysis of pottery manufacturing techniques has been, we can conclude that it is a promising road to pursue. The few simple methods we have applied show enough potential to continue in this direction. The next stage of our research is to focus on the application of the recording and post-processing methods

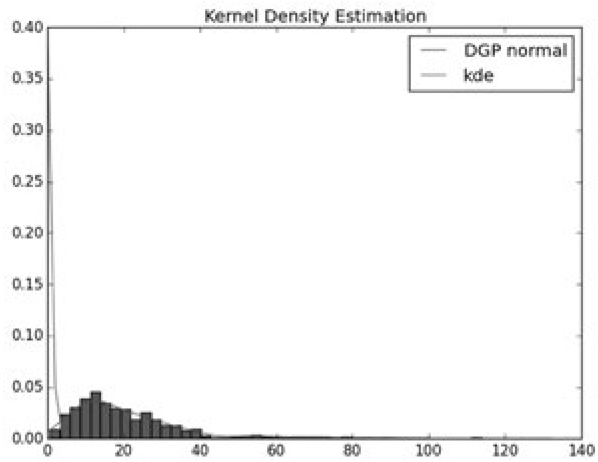

FIG. 14. SHAPE DESCRIPTORS AND KERNEL DENSITY ESTIMATION OF THE SURFACE AREAS OF DETECTED PARTS.

illustrated in this work to consistent bodies of archaeological ceramics. We are convinced that further elaboration and specification of the algorithms to suit our needs will result in a solid expert system that should be able to discern even mixed manufacturing techniques, providing a powerful analytical tool to both pottery specialists and non-specialists. The scanning of the fragments has already proved its value for several analysts who could access the material without physical contact. This adds a whole new dimension to the study of ancient manufacturing techniques.

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Bibliography

Andreetto, M., Brusco, N., Cortelazzo, G. M. 2004. Automatic 3D modeling of textured cultural heritage objects. Image Processing, IEEE Transactions on, 13, 3: 354-69.

Berg, I. 2013. The Potter's Wheel in Mycenaean Greece: A Re-assessment. Φιλική Συναυλία: Studies in G. Graziadio, R. Guglielmino, V. Lenuzza, S. Vitale (eds.), *Mediterranean Archaeology for Mario Benzi*, British Archaeological Reports International Seriers 2460: 113-22. Oxford.

Boileau, M. C. 2009. Le façonnage au tour en Syrie urbaine du IIIe millénaire: une technique réservée à des objets de valeur ?. *The Arkeotek Journal* 3, 3.

Callieri, M., Ponchio, F., Cignoni, P., Scopigno, R. 2006. Easy Access to Huge 3D Models of Works of Art. In D. Fellner (ed.), *Fourth Eurographics Italian Chapter 2006 (Graz, Austria 2006),* Graz University of Technology, Eurographics Association: 29-36.

Courty, M. A., Roux V. 1995. Identification of Wheel Throwing on the Basis of Ceramic Surface Features and Microfabrics. Journal of Archaeological Science 22: 17–50.

Forte, M. 2008. Cyber-archaeology: an eco-approach to the virtual reconstruction of the past. In T. A. Mikropoulos and N. M. Papachristos (eds.), *Proceedings of International Symposium on Information and Communication Technologies in Cultural Heritage, Ioannina, Greece*: 91-106. Ioannina, University of Ioannina.

Forte, M., Pietroni, E. 2009. 3D collaborative environments in archaeology: Experiencing the reconstruction of the past. *International Journal of Architectural Computing*, 7, 1: 57-76.

Gilboa, A., Karasik, A., Sharon, I., Smilansky, U. 2004. Towards computerized typology and classification of ceramics. Journal of Archaeological Science 31, 6: 681-94.

Gilboa, A., Tal, A., Shimshoni, I., Kolomenkin, M. 2013. Computer-based, automatic recording and illustration of complex archaeological artifacts. *Journal of Archaeological Science* 40, 2: 1329-39.

Grosman L., Sharon G., Goldman-Neuman T., Smikt O., Smilansky U. 2011. Studying post depositional damage on Acheulian bifaces using 3-D scanning. *Journal of human evolution* 60: 398-406.

Guennebaud, G., Gross, M. 2007. Algebraic point set surfaces. In *ACM Transactions on Graphics, Siggraph 2007 Proceedings* 26, 3: 23.1-9. New York, ACM.

Guennebaud, G., Germann, M., Gross, M. 2008. Dynamic sampling and rendering of algebraic point set surfaces. In *Proceedings of Eurographics (Crete, Greece, 14-18 april 2008), Computer Graphics Forum* 27, 2: 653-62.

Jeffra, C. D. 2011. The Archaeological Study of Innovation: An Experimental Approach to the Pottery Wheel in Bronze Age Crete and Cyprus, Unpublished PhD thesis, University of Exeter.

Jeffra C. D. 2015. Experimenting wheel-coiling methods. *The Arkeotek Journal* 2, www.arkeotekjournal.org.

Kampel, M., Sablatnig, R. 2006. 3D data retrieval of archaeological pottery. In H. Z. Z. Pan, H. Thwaites, A. C. Addison, M. Forte (eds.), *Interactive Technologies and Sociotechnical Systems, Proceedings of the 12th International Conference VSMM 2006*, Lecture Notes in Computer Science, 4270: 387-95.

Knappett, C. 1999. Tradition and Innovation in Pottery Forming Technology: Wheel Throwing at Middle Minoan Knossos. *Annual of the British School at Athens* 94: 101–29.

Limp, F., Payne, A., Simon, K., Winters, S., Cothren, J. 2011. Developing a 3-D digital heritage ecosystem: From object to representation and the role of a virtual museum in the 21st century. Internet Archaeology, 30. http://dx.doi.org/10.11141/ia.30.1

Meyer, E. 2007. Acquisition 3D, documentation et le restitution en archéologie. Proposition d'un modèle de Système d'Information dédié au patrimoine, Unpublished PhD thesis, Université Henri Poincaré-Nancy I.

Parzen, E. 1962. On estimation of a probability density function and mode. *The annals of mathematical statistics* 33, 3: 1065-76.

Pop, G., Bucksch, A. 2007. Combining modern techniques for urban 3D modelling. In *Geoscience and Remote Sensing Symposium, IGARSS 2007*. IEEE International: 2067-70. IEEE.

Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., Sarazzi, D. 2011. UAV photogrammetry for mapping and 3d modeling–current status and future perspectives. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 38, 1/C22. ISPRS Conference UAV-g, Zurich, Switzerland.

Roux, V. 1994. La technique du tournage: Définition et reconnaissance par les macrotraces. In *Terre cuite et société: La céramique, document technique, économique, culturel. Actes des rencontres, 21–22–23 octobre 1993*: 45–58. Juan-les-Pins, APDCA.

Roux, V., Courty M. A. 1998. Identification of Wheel-Fashioning: Technological Analysis of 4th–3rd millennium BC Oriental Ceramics, Journal of Archaeological Science 25: 747–63.

Ruckl, S., Jacobs L. F. H. C. (forthcoming). With a Little Help from My Wheel: Wheel-coiled Pottery in Protogeometric Greece. *Journal of the American School of Classical Studies at Athens*, Hesperia.

Saragusti, I., Karasik, A., Sharon, I., Smilansky, U. 2005. Quantitative analysis of shape attributes based on contours and section profiles in artifact analysis. *Journal of Archaeological Science*, 32, 6: 841-53.

Selden, J., Perttula, T., O'Brien, M. 2014. Advances in Documentation, Digital Curation, Virtual Exhibition, and a Test of 3D Geometric Morphometrics: A Case Study of the Vanderpool Vessels from the Ancestral Caddo Territory. *Advances in Archaeological Practice*, 2, 2: 64-79.

Sylvester, J. J. 1852. A demonstration of the theorem that every homogeneous quadratic polynomial is reducible by real orthogonal substitutions to the form of a sun of positive and negative squares. In *Philosophical Magazine*, 4, 23: 138-42.

Ter Haar, F. B., Cignoni, P., Min, P., Veltkamp, R. C. 2005. A comparison of systems and tools for 3D. Proceedings of 3D Digital Imaging and Modeling: Applications of Heritage, Industry, Medicine and Land. Padova, Italy.

ARIADNE Visual Media Service: Easy Web Publishing of Advanced Visual Media

Federico Ponchio
federico.ponchio@isti.cnr.it

Marco Potenziani
marco.potenziani@isti.cnr.it

Matteo Dellepiane
matteo.dellepiane@isti.cnr.it

Marco Callieri
marco.callieri@isti.cnr.it

Roberto Scopigno
roberto.scopigno@isti.cnr.it

CNR-ISTI, Visual Computing Lab, Pisa, Italy

Abstract: This paper describes the design and development of a service for 'visual media' files. In the first phase of the ARIADNE project we reviewed the status of visual media resources (2D, RTI, 3D) in the archaeology domain, but there was possibility of publishing visual media resources on the web. To fill this gap we have designed a service aimed at providing easy and unsupervised publication on the web. The service provides a very easy interface (a simple web form) that allows the user to upload the visual media file; the data is then transformed in a web-compliant format, supporting multi-resolution encoding, compression, and progressive transmission. At the end of the data-processing phase the user receives an email containing the URL of the published asset (or, in case he/she wants to store the file locally, a .zip file). Specific browsers for the three types of media have also been developed, based on 3DHOP technology.

Keywords: Visual media, Web publishing and visualization, HTML, WebGL, 3D models

Introduction

One of the major goals of the EC INFRA 'ARIADNE' project[1] is to design, implement, and deliver a number of digital services for the archaeological community, which will be integrated in the ARIADNE web portal. A sub-focus in the ARIADNE project is to provide support for the management of 'visual media'. The concept of visual media can be broadly described as any type of visual representation of archaeological findings or assets, i.e. conventional 2D images (including high-resolution and high-dynamic range, HDR), special images (such as relightable images or panoramic images), 3D models, and videos. The term 'visual data', therefore, encompasses any media that helps archaeologists to represent, document, and communicate the artworks under investigation or study in a better way.

Visual media are not new instruments of work for archaeologists—drawings and images have been used for centuries—and they are part of common working practice. The new issue is how to make proficient use of those media when different digital incarnations are made available with the progress of ICT technology. A number of new, low-cost and commodity opportunities for the easy acquisition of digital visual representations are now available and largely used in the field. Specific to the archaeological domain is the very wide extent of archaeological data, which include representations of small finds (a few centimetres in size) and of an entire archaeological site (hundreds of metres). What is still cumbersome is how to open up those data to the external world (both experts and lay people), and how to publish them in a simple and efficient way. An ARIADNE workshop held in Pisa in October 2013 demonstrated that knowledge and experience with media production technologies was fairly good (with many ARIADNE partners already using 3D scanning and enhanced digital documentation); on the other hand, a critical issue highlighted at the workshop was the lack of tools and experiences for sharing and publishing these visual media on the web, either as independent resources or as part of structured archives (Scopigno *et al.* 2013). Publishing visual media on the web is not easy when someone has rich data and does not want to downgrade them to a size/resolution of insufficient quality. Current sampling technologies allow the production of very complex and high-resolution models (up to Giga-pixels or Giga-vertices). These models allow the faithful representation of even small parts or subtle details of the object of interest,

[1] EC INFRA 'ARIADNE: Advanced Research Infrastructure for Archaeological Dataset Networking in Europe' project, 7th FW; www.ariadne-infrastructure.eu/

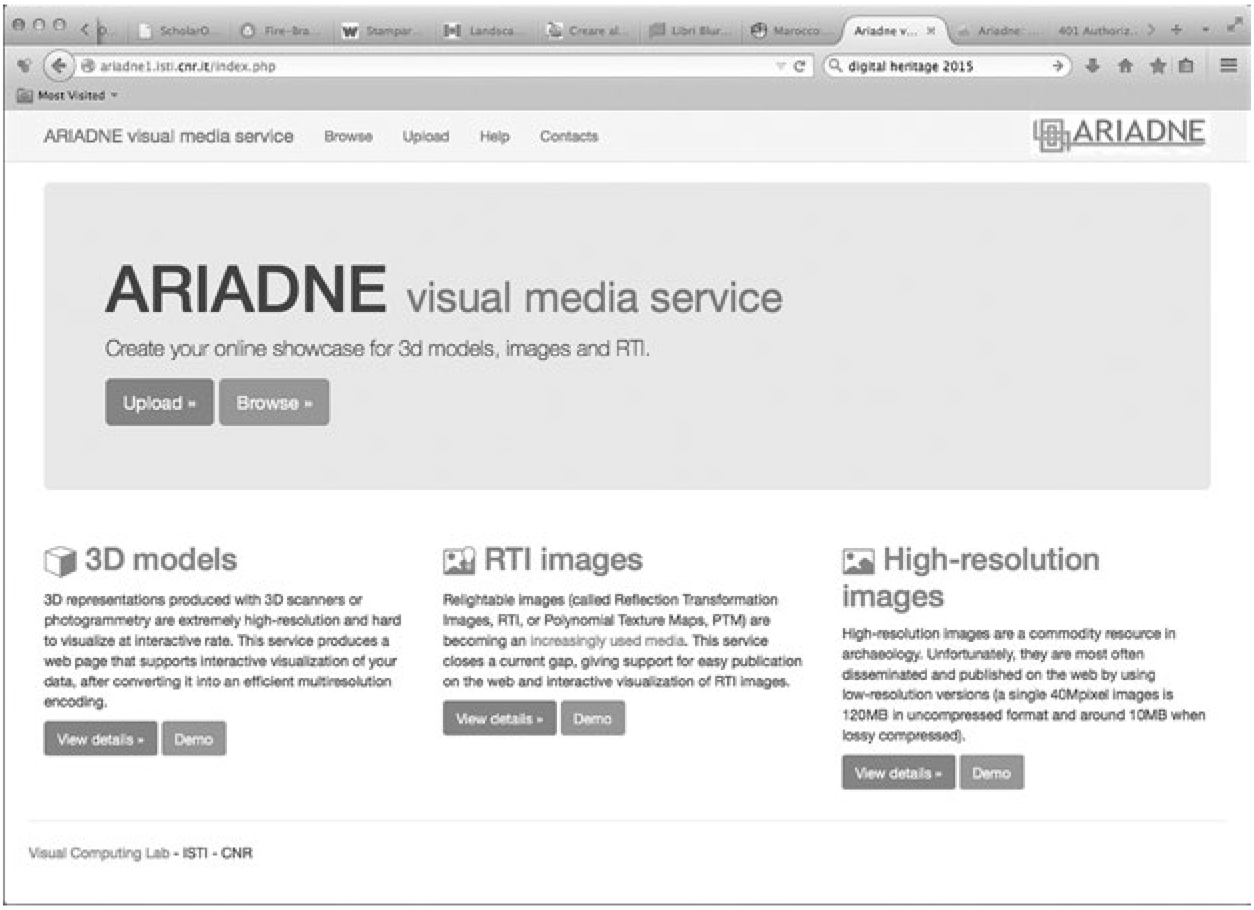

Fig. 1. The ARIADNE Visual Media Service homepage (http://visual.ariadne-infrastructure.eu/).

and the extensive use of sub-sampling or compression (in the case of images) or geometry simplification (in the case of 3D models) is usually not adequate for CH applications. Publishing data on the web invites the question of which format should be used, possibly producing acceptable transmission times, and what type of visualization features should be provided. A very successful web approach has been the one taken by YouTube, providing a simple interface for video data upload and making available to the user all the processing needed to convert and post the data on the web. Sketchfab (https://sketchfab.com/) has taken a similar approach but only for 3D models. The goal at the design stage (2014) of the Ariadne infrastructure was to provide a service similar to the one provided by YouTube (easy publication and presentation on the web of complex media assets), but focusing on media types which did not have an available service: high-resolution 2D images, RTI (Reflection Transformation Images, i.e. dynamically relightable images), and high-resolution 3D models.

The ARIADNE Visual Media Service approach is to build an automatic service able to transform any media file uploaded by ARIADNE partners into a format that will allow easy and efficient access and remote visualization on the web. The service is based on a simple web interface and currently supports the three types of visual media defined above.

These types of media are still not very common on the web, because their visualization may require the download of an entire file (long transmission times discourage users), and possibly select/install dedicated software (viewers). Moreover, the owner of high-quality data may prefer not to allow visitors freely to download them, in order to protect the ownership of the data.

Conversely, our approach is to design a service that allows inexperienced users to upload any visual media file of interest and (after some processing) receive the URL where the specific data has been stored and can be accessed for efficient visualization. Efficiency of visual presentation is gained by the design of proper GUI (viewers) and also by endorsing efficient data representation schemes. With this setup, even inexperienced users can easily create an efficient webpage to display complex 2D or 3D content. Alternatively, for more experienced users, these basic web pages may be the starting point for the development of more complex visualization, or for the integration of this visualization in existing websites, taking advantage of the features of the 3DHOP platform (www.3dhop.net). Finally, the data structures for remote visualization (multi-resolution for 3D models, image pyramids for images, and RTI web encoding) protect the original data, as the direct download of a multimedia file in single plain format is not straightforward.

We will describe in the next section the types of data that we currently manage in our server; the technical design and the algorithmic solution used are described in Section 4.

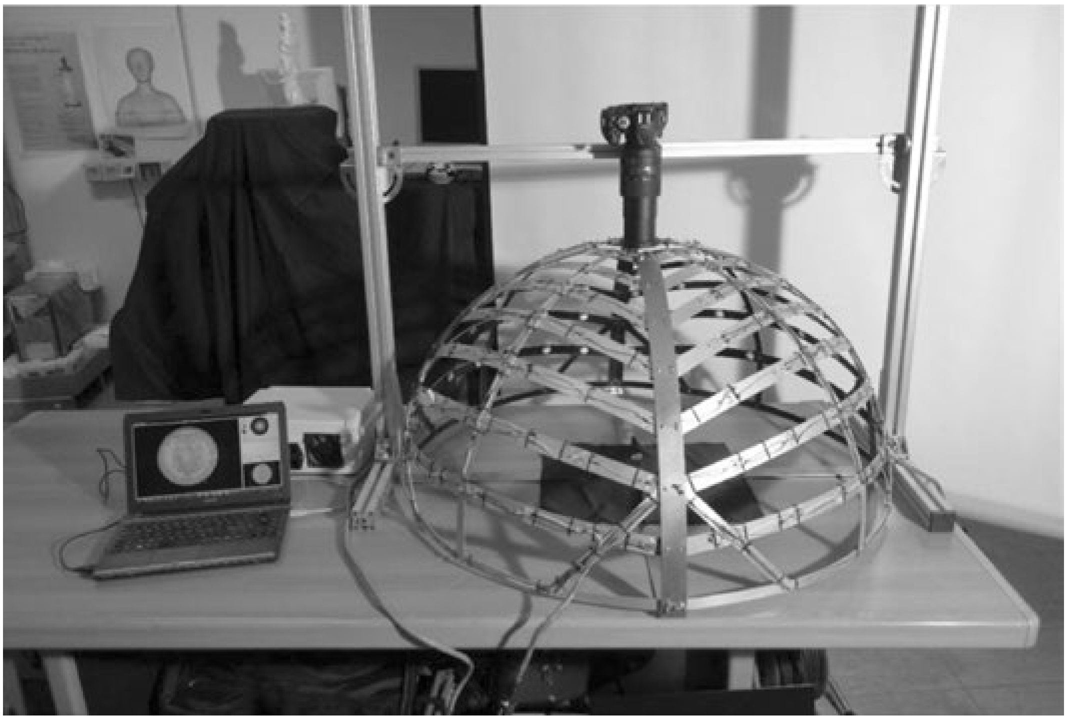

FIG. 2. THE RTI ACQUISITION DEVICE DEVELOPED BY CNR-ISTI.

1 Which type of visual media to support?

1.1 High-resolution Images

Images are the more common visual media, and they have been part of archaeological datasets from the very beginning, originally by means of an analogue, printed version and more recently by means of digital supports (either original digital images or scanned from old prints/slides). These data are what form most digital archives and collections.

While images are a medium that was fully integrated with the web and html from the very beginning, there are a few aspects that lack a standard solution for archival and visualization purposes. Most of the images produced nowadays are high-resolution. High-resolution images are now a commodity resource, with the remarkable evolution of digital photography (as one example, a recent off-the-shelf Smartphone now has a 41 MPix camera) and the wide availability of tools that allow aligning and stitching image patchworks, enabling users to reach huge image resolutions.

When high- or huge-resolution images are available, visualization on the web can be difficult, due to the amount of data that have to be transmitted before the web browser is able to present something visually. This is because standard web browsers must receive the entire file before visualizing it. Another important and critical issue is the need to protect the data.

A possible solution to avoid the problem of waiting for the entire image transmission before being able to provide a visual feedback is the approach adopted by map viewers. For example, Google Maps (http://maps.google.com) handles its huge maps by encoding them in a sequence of decreasing resolutions. Each image of this sequence is split into square tiles of fixed size (usually 256 pixels per side) to allow for the data management at high granularity. The client in the browser 'composes' on the fly the portion of the image selected by the user using the most suitable tiles, according to the size of the portion being viewed. This approach is based on simple multi-resolution encoding that has been demonstrated to be very efficient for visualizing this type of data. A similar approach can be employed to visualize high-resolution images, based on tiling and hierarchical representation schemes.

1.2 Reflection transformation Images (RTI)

Relightable images (usually called Reflection Transformation Images, RTI) are becoming an increasingly used technology to acquire detailed and interactive documentation on quasi-planar objects (Malzbender *et al*. 2001; Palma *et al*. 2010). This is particularly useful for objects characterized by complex light reflection attributes. The advantage of this representation is the possibility of changing the light direction over the image in real time (i.e. at visualization time), and the availability of using enhanced visualization modes in order to examine fine details of the object's surface.

RTI images have been successfully applied in a number of applications, such as coin collections, cuneiform tablets, inscriptions, carvings, bas-reliefs, paintings, and jewellery. Moreover, RTI images offer the possibility of obtained a digital representation of artworks made of certain materials, which cannot be easily obtained through the usual 3D scanning technologies (highly reflective materials, semi-transparent objects, etc.).

Typically, this type of image is generated from a set of photographs taken with a fixed camera (positioned on a tripod or an acquisition gantry) under varying lighting conditions (see Fig. 2 where an acquisition gantry is holding the camera and providing a set of LED lights in the inside surface of a wire dome). RTI encodes the acquired data in a compact way, using view-dependent per-pixel reflectance functions, which allows the generation of a relighted image using any light direction in the upper hemisphere around the object location. Per-pixel reflectance functions vary between different RTI types. For PTM (Polynomial Texture Maps) the function is a biquadratic polynomial (6 coefficients are required to define it). For more advanced RTI, hemi-spherical harmonics are usually employed (9 coefficients are used). In the latter type of RTI, the image is subdivided into nine layers, one layer for each HSH coefficient, where the i-th layer contains the i-th coefficient of the three RGB colour channels. Then for each layer a multi-resolution quad-tree is created and a tile for each node of the tree is saved in JPG format. To visualize a specific pixel, the nine JPG images that contain its HSH coefficients must be loaded.

As regards the acquisition of this type of image, CNR-ISTI has built an automatic acquisition device (a dome) that allows tens of objects to be acquired in a single day, and produce the RTI images in an automatic way (see Fig. 2). The dome is composed of four aluminium shells that can be easily assembled and disassembled to simplify transportation. It has 116 cold white LEDs (6 Watt, 750 lumen) used to change the lighting conditions and an overhead high-resolution reflex camera (Nikon D5200, 24Mpixel). The dome is computer-controlled to enable a completely automatic acquisition by synchronizing the switching on of each LED with the camera shutter.

The interactive visualization of RTI images can be supported both locally, using freely available tools (e.g. see the desktop RTI Viewer distributed by CHI at http://culturalheritageimaging.org/What_We_Offer/Downloads/View/), and on the web, using a WebGL component (Palma *et al*. 2012). As previously stated for high-resolution images, because RTI images are often at large resolution, this visualization component has to adopt a similar tile-based hierarchical approach.

1.3 3D models

3D representations have also become quite common in archaeology. Two classes of models are produced:

- *Sampled models*, usually produced with active 3D scanning (laser-based systems or systems using structured light) or by adopting recent photogrammetry approaches (production of 3D models from sets of 2D images);

- *Modelled representations* produced using the user-driven modelling systems designed for 3D modelling and computer animation applications (Blender, Maya, etc.).

In the context of professional archaeological applications, sampled models are more common, since those models offer much more control on the *accuracy* of the representation than hand-modelled representations. The latter, conversely, are more common in the applications oriented towards the larger public (e.g. to produce videos or virtual reconstructions).

Presentation on the web of complex 3D models is still a very difficult task to achieve; here with the term ‘complex’ we mean models composed of millions of samples, like those usually obtained by 3D scanning. This is mainly due to two reasons: it is hard to transmit/render such data interactively on commodity platforms; and publishing 3D material on the web is still a task that few developers can undertake. On the other hand, 3D models should not be confined to the single archaeologist’s archive and should be shared with the community, to increase knowledge and stimulate further study.

Publication of 3D models on the web has already been accomplished in several projects; we cite here the work done in 3DCOFORM by Fraunhofer IGD (Limper *et al*. 2013; 2014), who has implemented a web-based archive of 3D-scanned models based on WebGL technology (Khronos Group 2009). But this approach does not yet include an automatic publishing service.

There is a pressing need for platforms supporting easy and free publication of 3D models on the web. SketchFab (https://sketchfab.com/), a recent commercial solution, appeared while we were designing and implementing our system. SketchFab is an excellent system, supporting automatic publishing and a simple and easy to use interface, but focusing on professional use in the CH domain, it lacks flexibility (it only supports 3D models, only provides one layout, users cannot change anything) and does not provide a support for multi-resolution encoding and progressive transmission (thus making the transmission and visualization of very large models very difficult). SketchFab, therefore, requires the 3D model to be fully downloaded on the remote client before it can visualize it.

2 Visual Media Service design

The ARIADNE Media Service aims to provide support for the easy publication and presentation on the web of complex visual media assets. The idea is to build an automatic service able to transform any media file uploaded by an ARIADNE or any external user into a format that will allow easy and efficient access and remote visualization on the web. The goal is to provide a service where the user does not need any knowledge of the issues related to visual media publication on the web, or to the handling of different file types and compression/multi-resolution technologies. Interaction with the service must be very simple and should provide easy-to-use results.

The service is based on a simple web interface and currently supports the three types of visual media mentioned above: high-resolution images, RTI images, and high-resolution 3D models. These types of media are still not very easily found on the web because their visualization may need to download heavy files and possibly select/install dedicated software.

Our approach with the ARIADNE Visual Media Service is to provide a platform that makes it very simple to publish and share those media; at the same time, we also offer some (limited) protection over the data, since we do not send the remote browser the entire file in plain format. The adoption of a multi-resolution and compressed encoding makes stealing the file slightly more complicated than the usual save-as option provided by clicking on the right button in a standard web context.

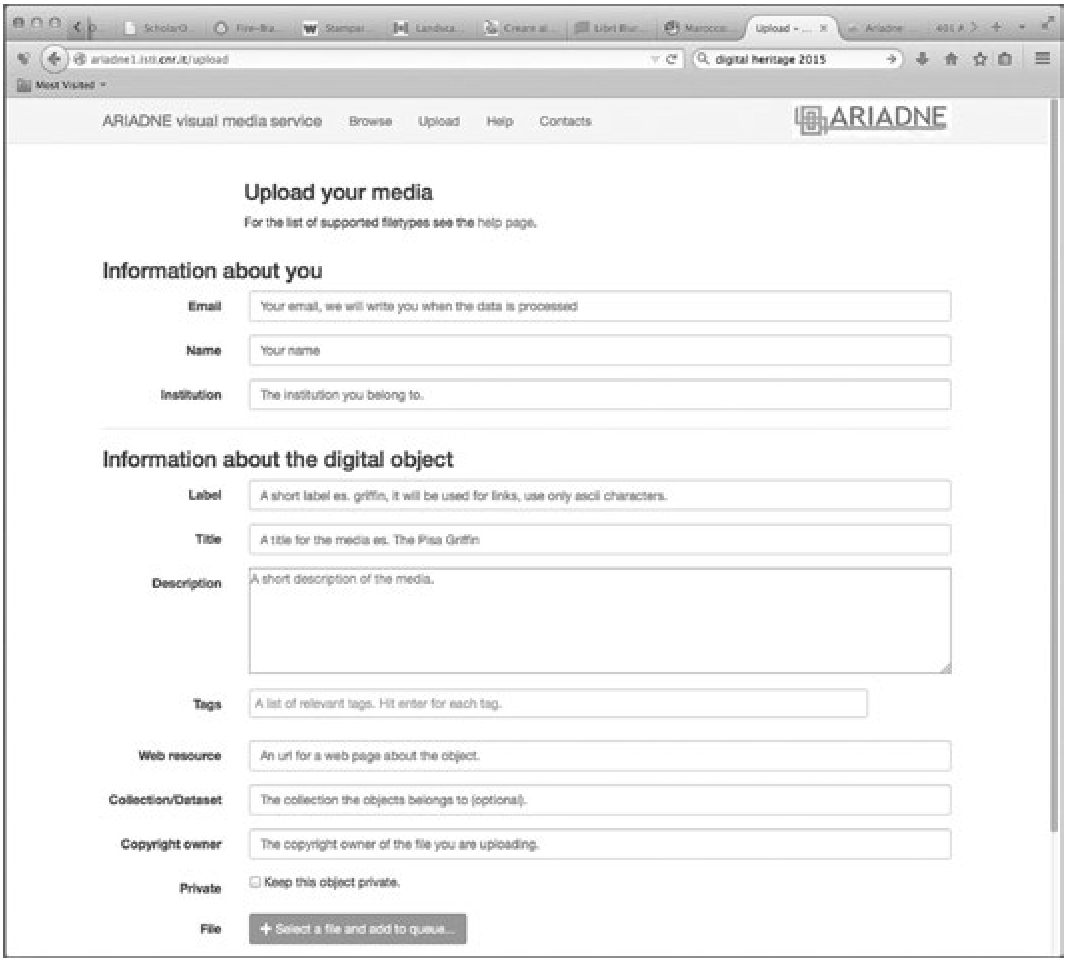

Fig. 3. The ARIADNE Visual Media Service upload web page (http://visual.ariadne-infrastructure.eu/upload).

We will first describe how to use the service, then give some details on the technology and algorithms used.

After accessing the service, the user finds a simple web form (http://visual.ariadne-infrastructure.eu/upload) that allows him/her to upload his/her own data (3D model, hi-res image, or RTI) and provide some basic information about the file and the represented artwork. The service processes the input data automatically and creates an online page. At the end of the processing and format conversion phase, the user receives an email containing a link to the visualization page (hosted on the Ariadne web-service and open to any external user) and to an admin page, where the associated data can be modified. It is also possible to download the created page (html code + processed 3D Model or 2D image) in order to store and integrate the content on a user's local server or archive. The user may also keep the image private, in which case it will be accessible only if the user provides a direct link.

High-resolution images are transformed into a multi-resolution format, supporting progressive streaming. The service transforms each image in a web-compliant format: similar to Google maps, the high-resolution image will be regularly divided into tiles and a hierarchy of images at different resolutions will be produced from these tiles; a rendering webpage is then created where it will be possible to navigate the image in a WebGL frame (see an example of the *image browser* in Fig. 4).

RTI images are managed in a similar way to hi-res images, even if the encoding for web streaming is a bit more complex, and WebGL rendering also takes care of the input and calculation of the variable-lighting (see an example of the RTI image browser in Fig. 5). The way we process and encode RTI images to provide web-based visualization is described in detail in Palma *et al.* (2012).

In the case of *3D models*, the geometry is processed, converting the 3D model into a multi-resolution format. We adopt the *Nexus* format, http://vcg.isti.cnr.it/nexus (Ponchio *et al*. 2015). This multi-resolution structure is streaming-friendly, and is used to create a visualization web page using the *3DHOP* web presentation tool, based on WebGL (Khronos 2009). An example of the browser for 3D models is presented in Fig. 6.

3DHOP (*3D Heritage On-Line Presenter*, www.3dhop.net) is a set of templates and components for the development of a Virtual Museum or effective presentations on the Web of digital 3D assets (Potenziani *et al*. 2015). Its main features include: easy presentation of different types of multimedia

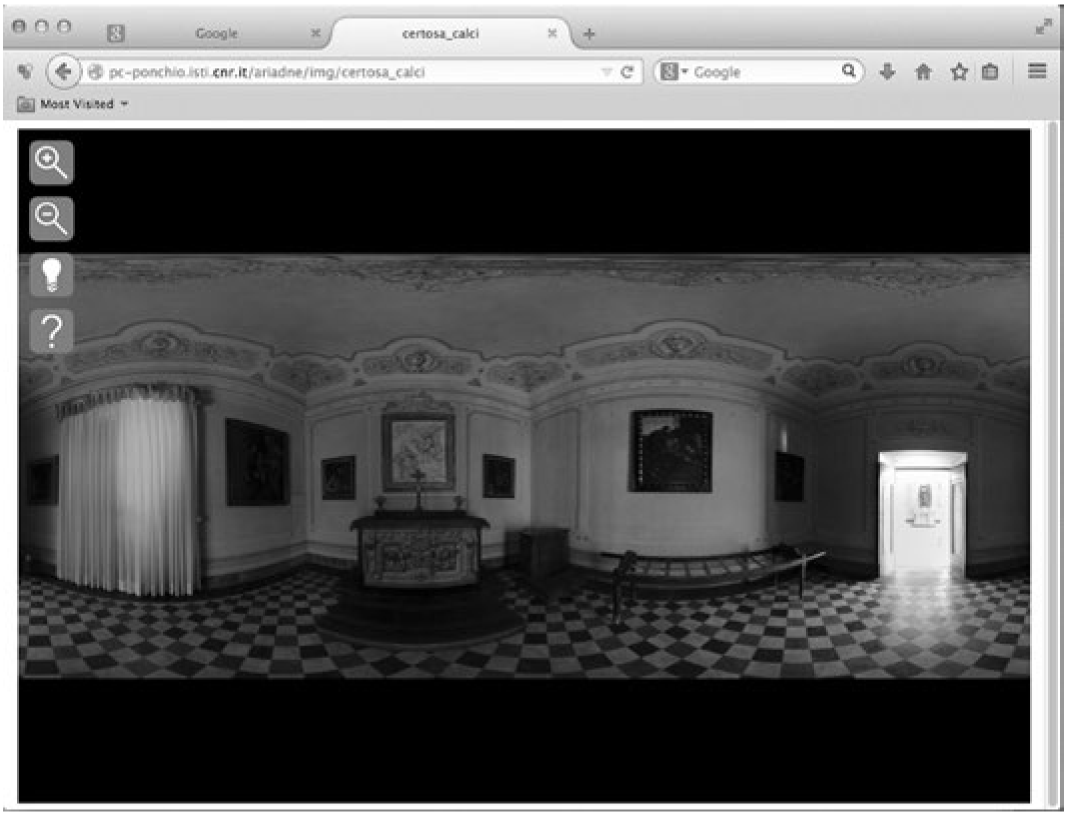

Fig. 4. A visualization page automatically generated by the Visual Media Service, for browsing a 2D high-resolution image.

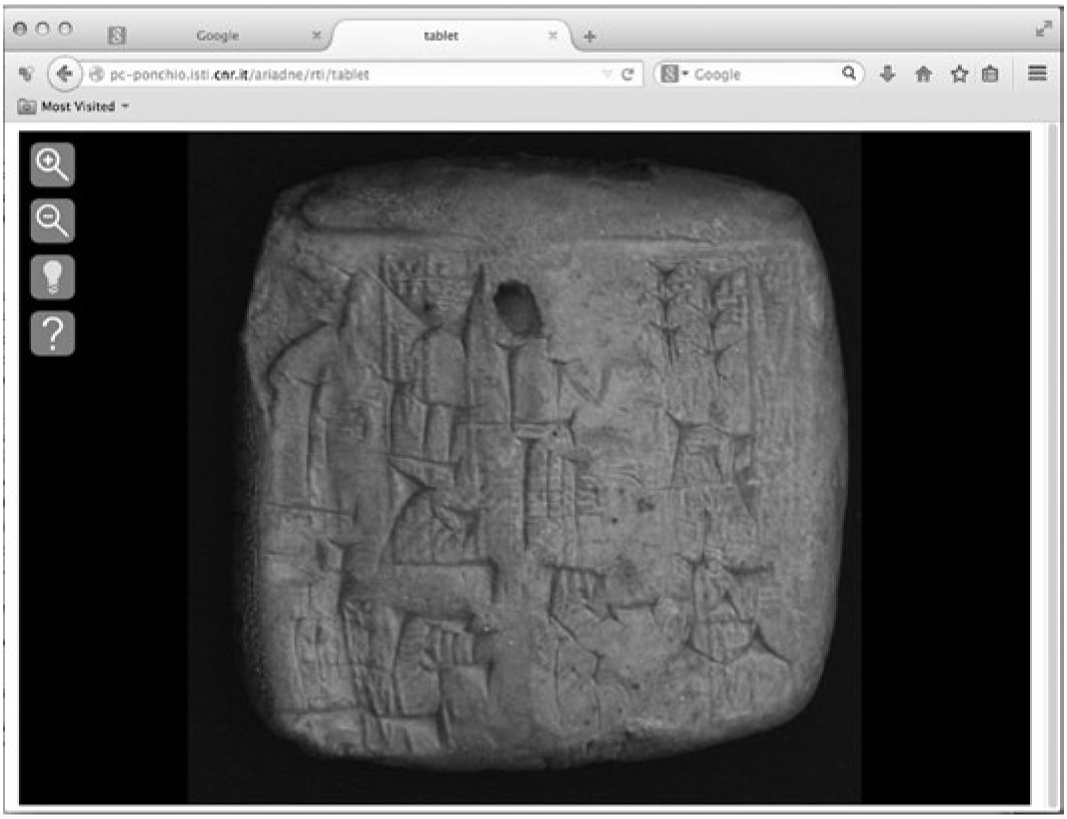

Fig. 5. The visualization page automatically generated by the Visual Media Service for browsing an RTI image.

FIG. 6. THE VISUALIZATION PAGE AUTOMATICALLY GENERATED BY THE VISUAL MEDIA SERVICE FOR BROWSING A 3D MODEL.

content, sophisticated customization capabilities for the Web presentation, seamless integration with the rest of the Web page allowing integration of different multimedia data. 3DHOP is designed to be easy to learn and easy to use. Its modular structure allows users with different levels of expertise to use it effectively, even when the user has very little or no knowledge of Computer Graphics and Web Programming. The framework also provides terrain visualization, different navigation/ interaction modes, and picking and camera controls. Many of these components are designed to answer the needs that are often encountered in the development of Cultural Heritage applications (for example, it is particularly easy to build a web page showing a collection of objects).

The visualization of high-resolution 3D models is based on a WebGL and Javascript implementation of the *Nexus* multi-resolution framework: the model to be visualized is pre-processed and converted into a collection of small fragments of a few thousand triangles, at different resolutions. These fragments can be assembled together to approximate the original surface. Depending on the perspective, an optimal set of fragments is selected to minimize the rendering error, given an ideal number of triangles to be rendered for each frame. Thus, only the fragments effectively viewed by the users are required to be sent through the web for each frame.

This approach is optimal for a number of reasons:

- It minimizes the CPU usage, as the assembling algorithm is quite simple. This is especially important since the client side is running in Javascript.
- Using a collection of fragments naturally supports an out-of-core approach, which allows us to start rendering as soon as data is incoming, and tile-based data processing to minimize the effects of network latency.
- It is possible to optimize the rendering quality for each given bandwidth value.
- Automatic pre-fetching is implemented to hide latency as much as possible.
- There is no need for special server support: data transmission just requires the basic http protocol. In other words the browser itself handles both the data streaming and rendering tasks.

With this setup, inexperienced users can easily create an efficient webpage to display complex 2D or 3D content. Alternatively, for more experienced users, these basic web pages may be the starting point for the development of a more complex visualization layout, or for the integration of this visualization in existing websites, taking advantage of the features of the 3DHOP platform (www.3dhop.net). Finally,

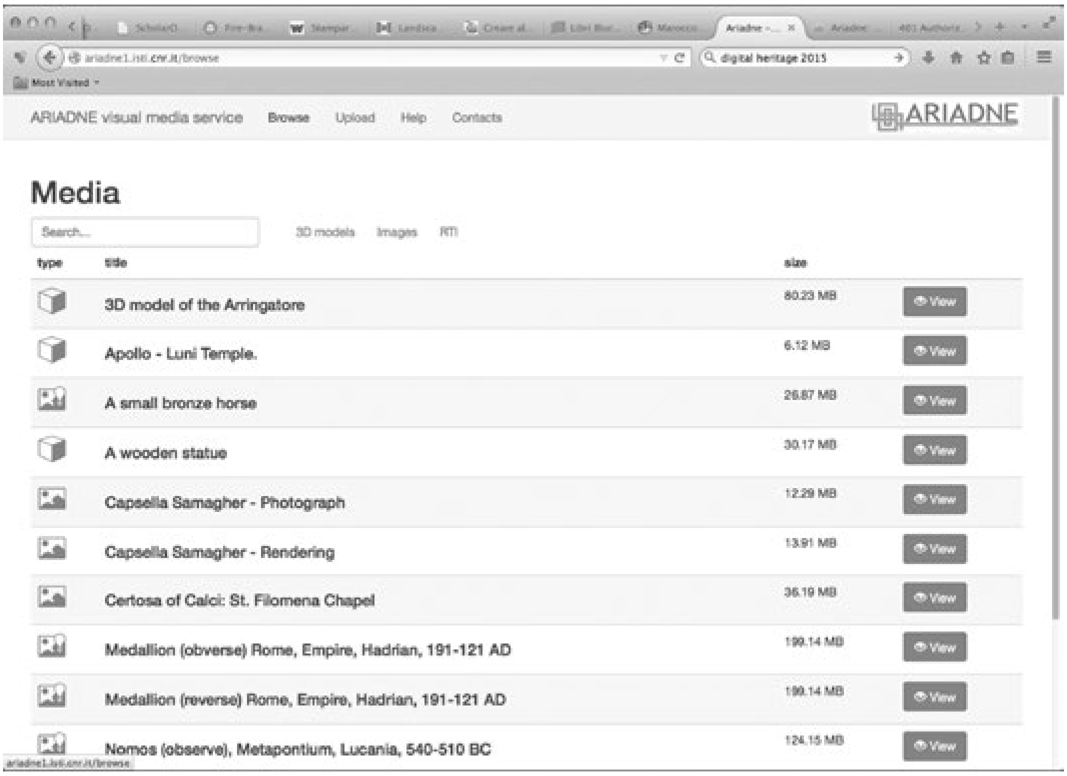

Fig. 7. The ARIADNE Visual Media Service browsing web page, that provides access and a search of the uploaded Visual Media data (http://visual.ariadne-infrastructure.eu/browse).

the data structures for remote visualization (multi-resolution for 3D models, image pyramids for images, and RTI web encoding) protect the original data, since direct download of the multimedia encoding in a single plain file is not possible.

In Section 3.3 we mentioned SketchFab as the current main competitor for our Visual Media Service. We have to underline that SketchFab focuses only on 3D models, while the Visual Media Service also supports other media types. To cross-compare the efficiency in data transmission and visualization, we did a test comparing the speed of SketchFab and other web-based browsers with the performances of the 3DHOP platform; this is reported in Potenziani *et al*. (2015). The results obtained on large models are largely in favour of our multi-resolution-enabled approach.

3 Conclusions

The Ariadne Media Service represents a first step toward a full integration of visual media in the context of archaeological datasets. Initial testing started on selected datasets provided by ADS, Discovery Programme, and other partners of the ARIADNE project. The results of a first preliminary user evaluation have been quite positive so far. A more detailed and structured user evaluation will be made in the fourth and final year of the ARIADNE project and results will be published soon.

Concerning future extensions, we are planning to upgrade the current version with a new one supporting:

- Increased flexibility: the uploading form will allow the selection either of a default browser layout or the specification (by means of simple check boxes) of the browser features. It will be possible to customize the browser layout and features, following the flexible tools provided by the underlining 3DHOP platform.

- The management of other media, such as High Dynamic Range images (HDR). We will allow the direct publication of the original HDR data and the automatic conversion on the fly to LDR format (driving the HDR to LDR to fulfil an optimal conversion focusing on a specific image area selected by the user).

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Bibliography

Khronos Group, Webgl - OpenGL es 2.0 for the web. 2009, http://www.khronos.org/webgl/

Limper, M., Wagner, S., Stein, C., Jung, Y., Stork, A. 2013. Fast delivery of 3d web content: A case study. In *Proceedings of the 18th International Conference on 3D Web Technology. Web3D '13*: 11–7. New York, ACM.

Limper, M., Thoener, M., Behr, J., Fellner, D. W. 2014. SRC - a streamable format for generalized web-based 3 data transmission. In N. F. Polys, A. Chesnais, E. Gobbetti, J. Doellner (eds.), *The 19th International Conference on Web3D Technology, Web3D '14*, *Vancouver, Canada, 8-10 august 2014*: 35-43. New York, ACM.

Malzbender, T., Gelb, D., Wolters, H. 2001. Polynomial texture maps. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01)*: 519-28. New York, ACM.

Palma, G., Corsini, M., Cignoni, P., Scopigno, R., Mudge, M. 2010. Dynamic Shading Enhancement for Reflectance Transformation Imaging. In: *ACM Journal of Computing and Cultural Heritage*, 3, 2, n. 6. ACM.

Palma, G., Siotto, E., Proesman, M., Baldassarri, M., Baracchini, C., Batino, S., Scopigno, R. 2012 Telling The Story Of Ancient Coins By Means Of Interactive RTI Images Visualization. In *CAA 2012 Proceedings of the 40th Conference in Computer Application And Quantitative Methods in Archaeology*, Southampton, UK, 26-30 march 2012: 177-85.

Ponchio, F., Dellepiane, M. 2015. Fast decompression for web-based view-dependent 3D rendering". In *Proceedings of the 20th International Conference on 3D Web Technology*, Heraklion, Crete, Greece, 18-21 June 2015: 199-207. New York, ACM.

Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Scopigno, R. 2015. 3DHOP: 3D Heritage Online Presenter. In *Computer & Graphics* 52: 129-41. Elsevier. doi: 10.1016/j.cag.2015.07.001

Scopigno, R., Dellepiane, M. 2013. Ariadne infrastructure for Multimedia data: Matching technologies and user needs. Report of the first meeting of the *ARIADNE SIG on 3D & Visualization,* 7-8 october 2013.

Mapping Archaeological Databases to CIDOC CRM

Martin Doerr[(1)]
martin@ics.forth.gr

Maria Theodoridou[(1)]
maria@ics.forth.gr

Edeltraud Aspöck[(2)]
edeltraud.aspoeck@oeaw.ac.at

Anja Masur[(2)]
anja.masur@oeaw.ac.at

[1] Institute of Computer Science, Foundation for Research and Technology - Hellas (FORTH), www.ics.forth.gr/isl
[2] ÖAW – Österreichische Akademie der Wissenschaften, http://www.orea.oeaw.ac.at/

Abstract: The exponential growth of the web and the availability of large numbers of digital datasets revealed the need for integrated access to heterogeneous and autonomous data sources. In the Cultural Heritage domain, ARIADNE supports transparent integration by means of an advanced metadata schema, based on CIDOC CRM, and adapted to the needs of archaeology.

In this paper we present the mappings of two archaeological databases to the ARIADNE Reference Model. The mapping of dFMRÖ, a relational database of pre-Roman and Roman Imperial period coins, presents an interesting use case of relational database mapping where there is need to address and separate both categorical and factual information. The mapping of Gräberfeld Franzhausen-Kokoron, a database of 400 Late Bronze Age cremation graves, serves as a test case for a common representation of archaeological records and survey data. The importance of conceptually separating past from present archaeological activities and interpretations will be demonstrated.

Keywords: Mapping technology, Information access, Semantic search, Archaeological databases, Cultural heritage information, CIDOC CRM

Introduction

The exponential growth of the web and the availability of large numbers of digital datasets revealed the need for integrated access to heterogeneous and autonomous data sources. In the Cultural Heritage domain, ARIADNE (www.ariadne-infrastructure.eu/), an FP7-INFRASTRUCTURES-2012-1 EU project (Grant agreement no: 313193), brings together and integrates existing archaeological research data infrastructures so that researchers can use the various distributed datasets and new and powerful technologies as an integral component of the archaeological research methodology. The primary role of the CIDOC CRM (ISO 21127:2006, www.cidoc-crm.org/) is to enable information exchange and integration between heterogeneous sources of cultural heritage information. CIDOC CRM was chosen as a good starting point for defining ARIADNE's Reference Model, a coherent global ontology that is based on CIDOC CRM and an extension suite that allows deep integration of scientific and cultural-historical evidence and facts. The ARIADNE Reference Model represents a view on the archaeologically relevant parts of the CIDOC CRM and compatible extensions of it that have either been modified, enhanced, or developed from scratch in the ARIADNE project and are all subsequently submitted for review and approval by CIDOC CRM SIG and CIDOC.

There is an ongoing effort in ARIADNE systematically to provide sample mappings for the most relevant types of archaeological datasets and in this context several mapping activities were initiated trying to convert existing schemata of archaeological data to CIDOC CRM and its extensions, which comprise the ARM.

In this paper we will present the collaborative work between domain experts (OEAW) and IT experts (FORTH) defining mappings of two archaeological databases to CIDOC CRM and its extensions. The mapping of dFMRÖ (digitale Fundmünzen der Römischen Zeit in Österreich), a relational database of pre-Roman and Roman Imperial period coins found in Austria and Romania, presents an interesting use case of relational database mapping where there is a need to address and separate both categorical and factual information. We introduce two specialized relations in order to support categorical production, similar to relations used in the FRBR model (www.cidoc-crm.org/frbr_inro.html). The mapping of Gräberfeld Franzhausen-Kokoron, a database of 400 Late Bronze Age cremation graves from Franzhausen-Kokoron, Austria, with about 3800 records, serves as a test case for exploiting the scientific investigation methods for archaeology and the use of CRMarchaeo and CRMsci, the extensions of CIDOC CRM to support archaeological excavations (Masur *et al*. 2014) and scientific observation, measurements, and processed data.

The paper is organized as follows: Section 1 presents the ARIADNE Reference Model; Section 2 describes briefly the tool and language that we used to define the mappings; Section

3 presents the mapping of the dFMRÖ, a relational database of pre-Roman and Roman Imperial period coins found in Austria and Romania while Section 4 presents the mapping of Gräberfeld Franzhausen-Kokoron, a database of 400 Late Bronze Age cremation graves from Franzhausen-Kokoron, Austria.

1 The ARIADNE Reference Model

ARIADNE aims to bring together and integrate the existing archaeological research data infrastructures so that researchers can use the various distributed datasets and new and powerful technologies as an integral component of the archaeological research methodology. An immense number of archaeological digital datasets and encoded facts are placed on the web, in digital repositories and other information systems every day. They are the accumulated outcome of the research of individuals, teams, and institutions but they form a vast and fragmented corpus and their potential is constrained by difficult access and non-homogeneous perspectives. It is therefore important to build infrastructure and web services that will enable exploration, data-mining, semantic integration, and experimentation across all these rich resources.

The ARIADNE Research Infrastructure Project for Archaeology aims to go beyond the current Digital Library paradigm with simplistic catalogues and search facilities, by laying the foundation for the integration of rich, structured information from all heterogeneous sources that may be relevant for answering a research question. The first aim is a uniform, consistent representation of data that have a potential bearing on questions beyond their local context of creation and use, so that directly and very indirectly related facts can be filtered out effectively from the mass in order to support further interpretation by the researcher.

Only semantic web technologies and formal ontologies allow such a consistent representation and effective management of billions of statements. The respective technology is advancing very rapidly, and the challenge of the day is therefore not to adapt data models to the possibly still limited performance of current platforms, but to develop a global, extensible schema in the form of a formal ontology that enables integration without loss of meaning, rather than ‘core fields’ and ‘application profiles’. In the end, this appears to be a more demanding task than the development of efficient platforms. Moreover, the creation and maintenance of data in an adequate form exceeds the cost of the development of platforms by some order of magnitude. Therefore manually restructuring data at each technological step should be replaced by transforming data into comprehensive structures with expected long-term validity, inter-operability, and extensibility. This is a task of highly interdisciplinary ontological engineering.

In order to address the complexity of archaeological data integration, ARIADNE’s main challenge was to develop a global, extensible schema in the form of a formal ontology that will enable integration without loss of meaning. CIDOC CRM was chosen as the backbone of the ARIADNE Reference Model. CIDOC CRM (ISO21127) is a formal ontology intended to facilitate the integration, mediation, and interchange of heterogeneous cultural heritage information. It was developed by interdisciplinary teams of experts, coming from fields such as computer science, archaeology, museum documentation, history of arts, natural history, library science, physics, and philosophy, under the aegis of the International Committee for Documentation (CIDOC) of the International Council of Museums (ICOM). It started bottom up, by reengineering and integrating the semantic contents of more and more database schemata and documentation structures from all kinds of museum disciplines, archives and, recently, libraries as empirical base. CIDOC CRM contains the most basic relationships to describe what happened in the past on a human scale, i.e. people and things meeting in space-time, parts and wholes, use, influence, and reference. More detailed kinds of discourse required extensions.

The ARIADNE Reference Model represents a view on the archaeologically relevant parts of the CIDOC CRM and compatible extensions of it that have either been modified, enhanced, or developed from scratch in the ARIADNE project and are all subsequently submitted for review and approval by CIDOC CRM SIG and CIDOC. The ARIADNE RM, presented in Figure 1, comprises the following extensions:

- **CRMinf** (CRMinf 2015) is a formal ontology produced by Stephen Stead, Paveprime Ltd, and collaborators and is intended to be used as a global schema for integrating metadata about argumentation and inference-making in descriptive and empirical sciences such as biodiversity, geology, geography, archaeology, cultural heritage conservation, research IT environments, and research data libraries. The Argumentation Model is reducing the IAM model in Doerr, Kritsotaki and Boutsika (2011) and embedding it in the CRMsci.

- **CRMsci** (CRMsci 2014): the Scientific Observation Model is a formal ontology intended to be used as a global schema for integrating metadata about scientific observation, measurements, and processed data in descriptive and empirical sciences. It has been developed from the bottom up from specific metadata examples from biodiversity, geology, archaeology, cultural heritage, conservation, and clinical studies in the context of the projects ACGT (http://acgt.ercim.eu/), InGeoCloudS (www.ingeoclouds.eu/), iMarine (www.i-marine.eu/), and ARIADNE.

- **CRMgeo** (Doerr, Hiebel 2013): a spatiotemporal model that provides an ‘articulation’ (linkage) between the standards of the geospatial and the Cultural Heritage community in particular between GeoSPARQL and CIDOC CRM. It has been developed in the context of Marie Curie Actions—Intra-European Fellowships (IEF) Funding scheme (under project number 299998) and ARIADNE.

- **CRMdig** (CRMdig 2014): a model for provenance metadata is an ontology to encode metadata about the steps and methods of production (‘provenance’) of digitization products and synthetic digital representations such as 2D, 3D, or even animated models created by various technologies. It has been developed in the context of projects CASPAR (www.casparpreserves.eu/) and 3D-COFORM (www.3d-coform.eu/).

- **CRMba** (Ronzino 2015): the Buildings Archaeology is an ontology developed for investigating historic and prehistoric buildings, the relations between building

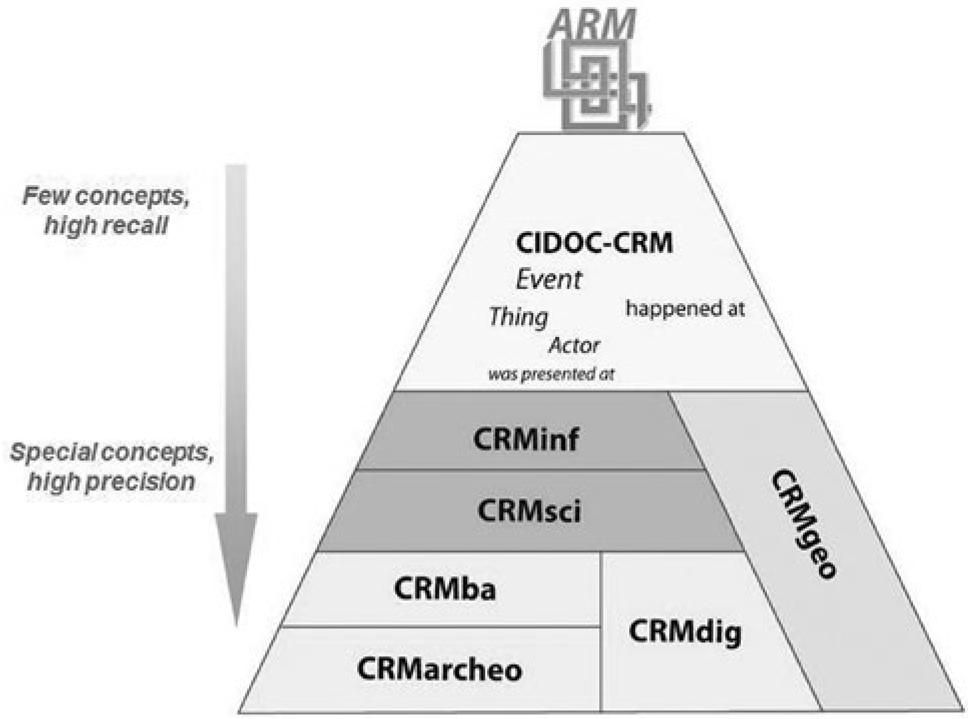

FIG. 1. ARIADNE REFERENCE MODEL (ARIADNE RM).

components, functional spaces, topological relations, and construction phases through time and space.

- **CRMarchaeo** (CRMarchaeo 2014): the Excavation Model is an ontology to encode metadata about the archaeological excavation process developed in the context of project ARIADNE.

2 The mapping process

The process of mapping the schema of an archaeological database to a common coherent global ontology is not trivial and needs support from appropriate tools (Oldman *et al*. 2014). First we need a sufficient mapping specification to support the transformation of each distinct schema of an archaeological dataset (source schema) into the ARIADNE RM (target schema). It is crucial that during the transformation, the information encoded in the source database is not lost and the initial 'meaning' is preserved as much as possible. In several cases, that we will present in more detail in the following sections, information in the source database is implicit and hidden in forms, user interface fields, or in the worst case in the head of a curator, the domain expert. This implies that the transformation process cannot be undertaken solely by technical people. It requires close collaboration between the domain experts who possess the domain knowledge and the IT experts who possess the technical knowledge of the semantic web.

In ARIADNE, the mapping workflow presented in Figure 2 follows the Synergy Reference Model which is an initiative of the CIDOC CRM Special Interest Group (www.cidoc-crm.org/who_we_are.html). Mapping is facilitated by 3M (3M 2015), a Mapping Memory Manager that includes a mapping editor, a mapping specification, and a mapping memory to accumulate knowledge and experience. The mapping specification is based on X3ML (X3ML 2014), an XML-based declarative language aiming to support the cognitive process of a mapping definition. It describes schema mappings in both human and machine-readable form and supports the close collaboration of domain and IT experts. X3ML separates schema matching — performed mainly by domain experts — from URI generation and terminology mapping – performed mainly by IT experts. In the use cases described in the following sections, schema matching was performed by the domain experts (OEAW) assisted by IT experts (FORTH) using the 3M editor. The URI generation was performed by IT experts. The experience gained during these mappings contributed significantly to the evolution of the tools and the X3ML mapping mechanism proved adequate for the domain experts to understand, define, and verify the semantics of mapping specifications.

3 Mapping dFMRÖ (digitale Fundmünzen der Römischen Zeit in Österreich)

Digitale Fundmünzen der Römischen Zeit in Österreich (Digital Coin finds of the Roman Period in Austria) is an online MySQL database of the Numismatic Research Group of the Austrian Academy of Sciences (dFMRÖ 2007). Since the 1990s it has documented coin finds from the Celtic and Roman periods that have been published in various printed volumes of the FMRÖ (Fundmünzen der Römischen Zeit in Österreich/Coin finds of the Roman Period in Austria) from the 1970s up to 2007. Starting with a Microsoft Access database, it was set

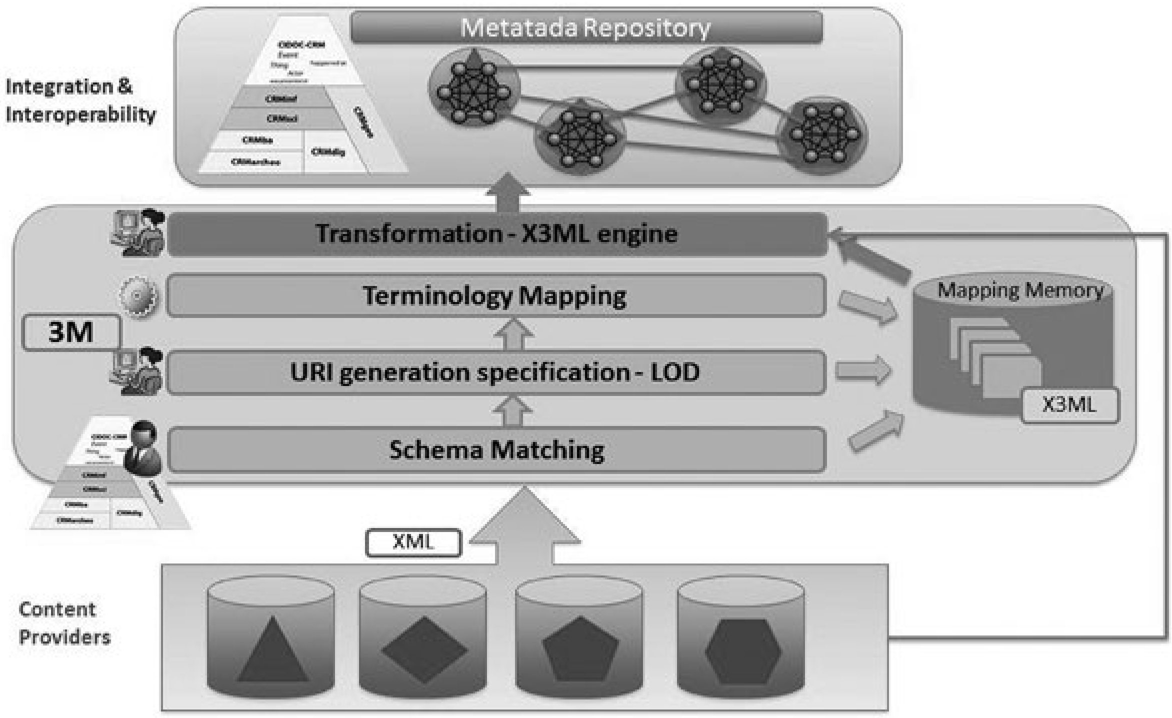

Fig. 2. Mapping workflow.

up in its current form in 2007 and hosts about 76,000 finds. All coins were found in Austria or, as a result of previous project cooperation, in Romania. The coins represent an important part of the Austrian cultural heritage.

The relational schema of dFMRÖ was chosen as an interesting first mapping use-case since it represents a large class of well-defined traditional databases. Is consists of a main COIN table and nine auxiliary tables linked together with simple joins as can be seen in Figure 3. The database contains data describing the objects/coins such as measurements, metal, preservation, etc. and contextual data, e.g. find spot, archaeological context, and dating (Fig. 4).

The goal is to interpret the relational schema as a semantic model (*domain – property – range*) and we achieved it through the transformation of the tables and fields of the relational schema of dFMRÖ into equivalent ARIADNE RM paths. Our mapping starts with the specification of the domain mapping, which specifies that the records of the main dFMRÖ table (COIN) correspond to instances of the entity E22 Man-Made Object of CIDOC CRM; two approaches are possible:

1. Introducing a specialization of E22 Man-Made Object and enhancing the ARIADNE RM: Exx COIN *subclass of* E22 Man-Made Object

2. Defining the Type of E22 Man-Made Object: E22 Man-Made Object. *P2 has type:* E55 Type = 'Coin'

The introduction of a new class should comply with the 'Minimality' modelling principle of CIDOC CRM (CIDOC CRM, 2015): 'A class is not declared unless it is required as the domain or range of a property not appropriate to its superclass, or it is a key concept in the practical scope.'

Field names stand for a relationship (*property*) and the kind of contents (*range*) while the field contents stand for entity instances. In the simplest case an equivalent proposition can be defined as a one-to-one mapping like the one in Figure 5. In this example the field ID is the source property mapped to the target property *P1 is identified by* and also the source range mapped to the target range E42 Identifier. It was decided that local identifiers in relational database tables would be mapped explicitly only if these identifiers are visible in the user interface and used in other documents as well. Alternatively, the local database identifiers are used only for generating URIs for the record instance — here the coin instance — and the identifier fields are not mapped at all.

In most cases it is not possible to have a one-to-one mapping. Instead, one field of the source maps to a complex path in the target. Figure 6 demonstrates one such case. In the dFMRÖ COIN table, the field WEIGHT that contains the weight value for each coin instance cannot be mapped to a single CIDOC CRM class. In CIDOC CRM, the class E54 Dimension (*which comprises quantifiable properties that can be measured by some calibrated means and can be approximated by values)* has three properties:

- *P90 has value* has as range a literal that is the actual weight value.

- *P91 has unit* has as range an E58 Measurement Unit which in the case of dFMRÖ is grams, information that is not

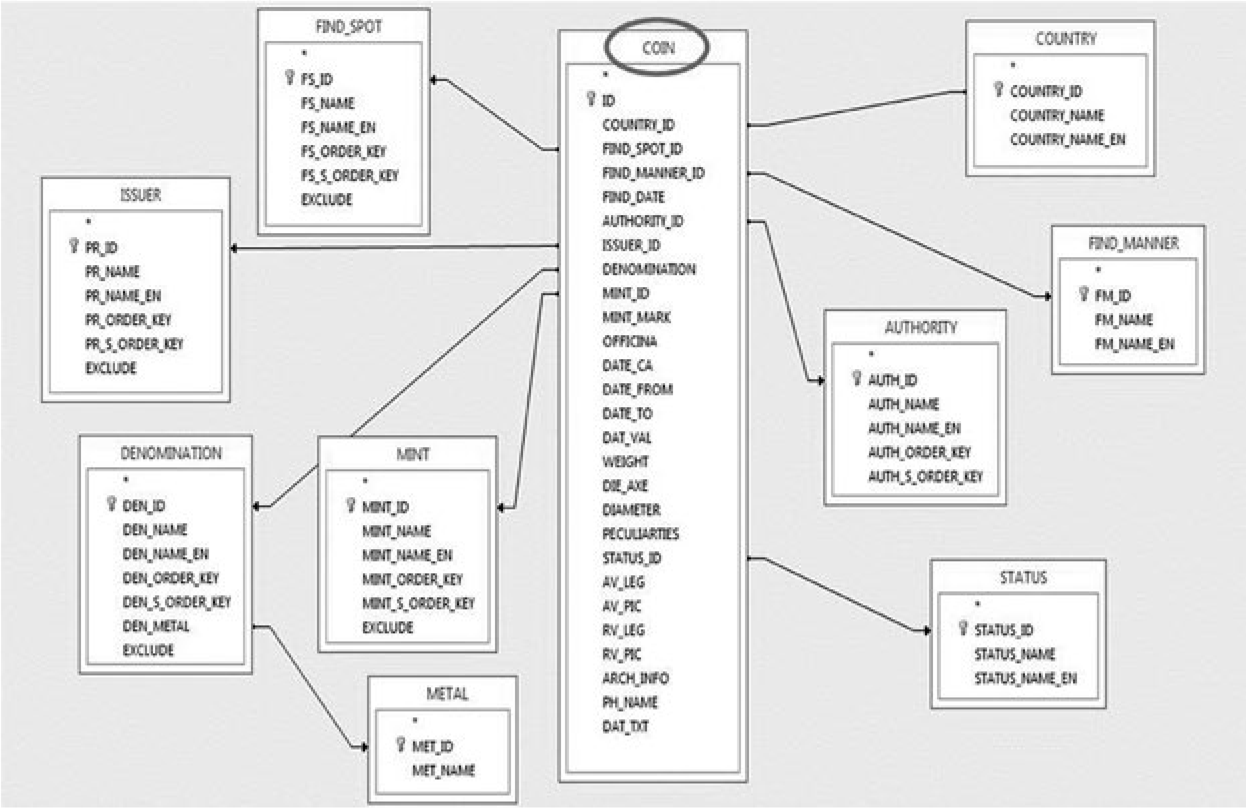

FIG. 3. THE RELATIONAL SCHEMA OF DFMRÖ.

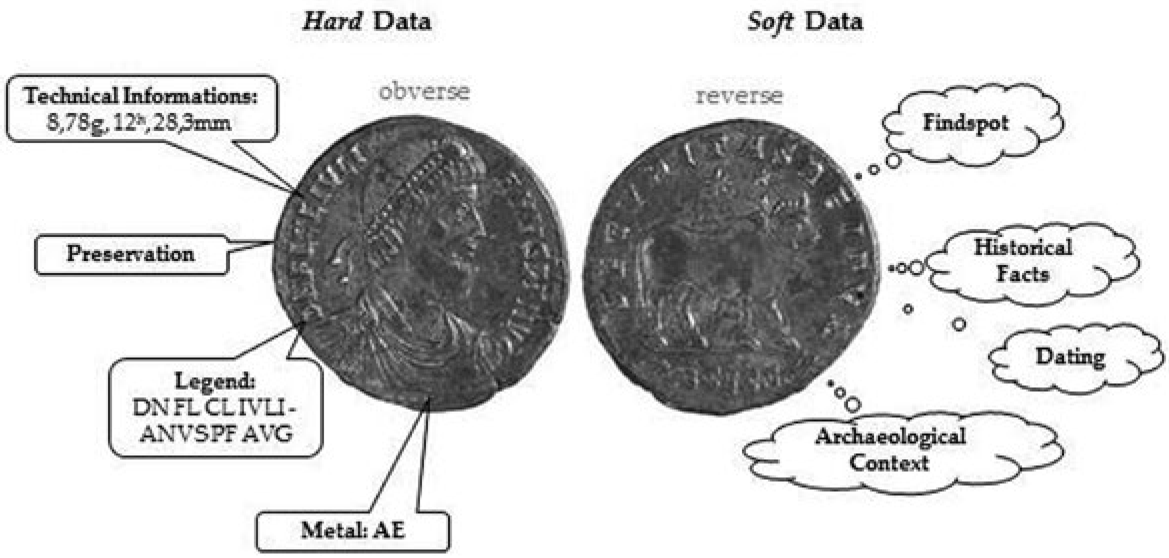

FIG. 4. COINS — AN ARCHAEOLOGICAL SOURCE.

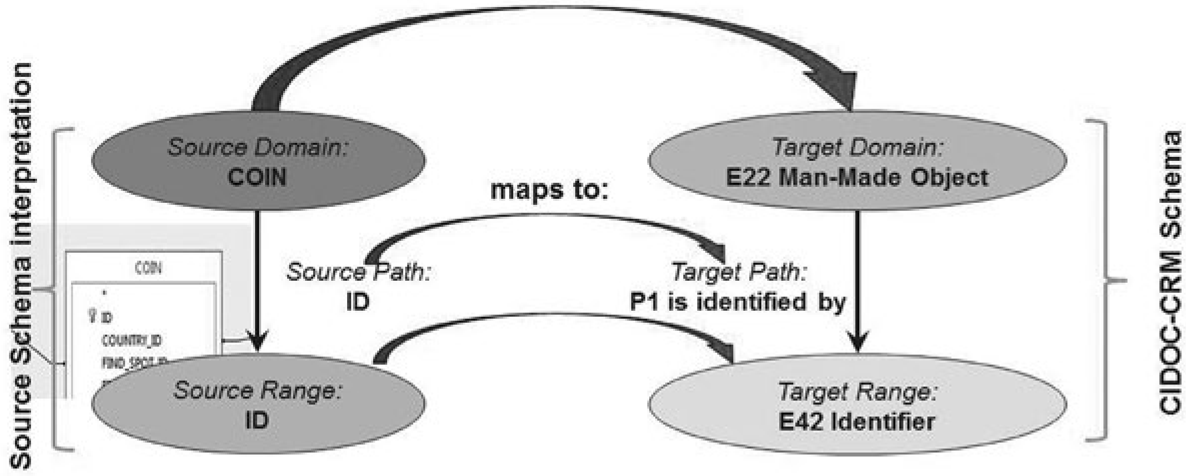

FIG. 5. CREATING AN EQUIVALENT PROPOSITION.

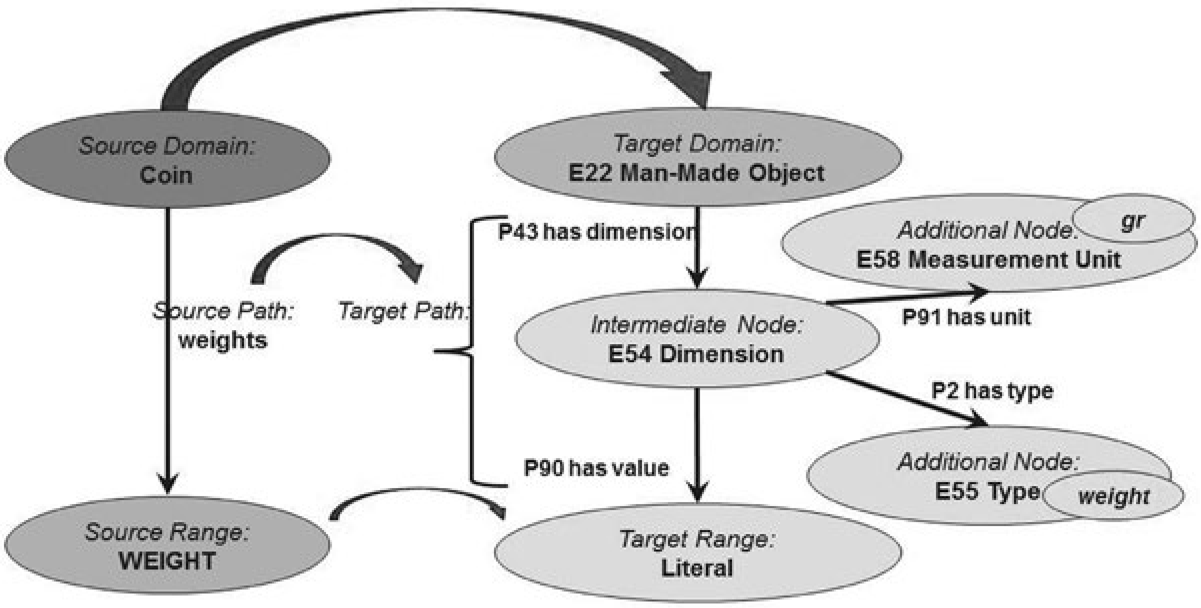

FIG. 6. INTRODUCING INTERMEDIATE NODES AND CONSTANT EXPRESSIONS.

encoded in the relational database but is built into the User Interface of dFMRÖ.

- *P2 has type* has as range an E55 Type that takes the constant value of 'weight'.

The simple source path 'COIN has weight ' maps to the complex path

E22 Man-Made Object. *P43 has dimension*: E54 Dimension. *P90 has value*: Literal

E54 Dimension. *P91 has unit*: E58 Measurement Unit = 'gr'

E54 Dimension. *P2 has type*: E55 Type = 'weight'

E54 Dimension is an intermediate node in the X3ML terminology while E58 Measurement Unit and E55 Type are two constant expressions. The intermediate node and constant expression constructs of X3ML provide flexibility during the mapping and allow the encoding of implicit, 'hidden' information of the source. In the current implementation of

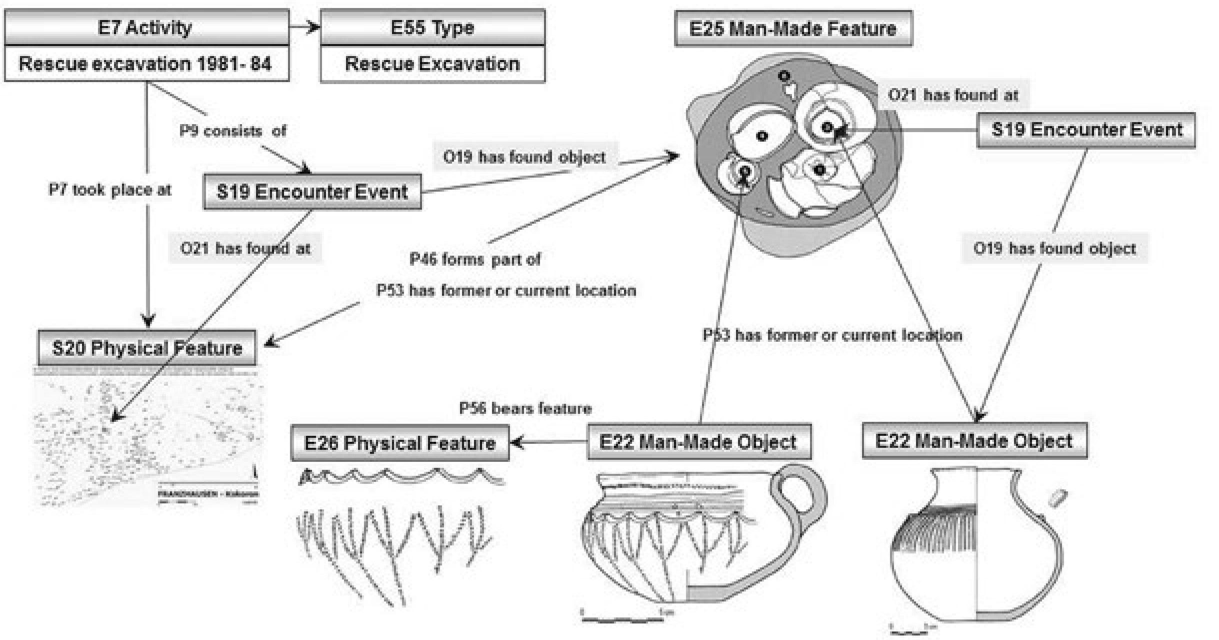

Fig. 7. Part of the FK Cemetery semantic graph.

X3ML, the source schema is specified as xpaths and a dedicated construct allows the specification of relational joins.

dFMRÖ contains factual data describing a specific coin such as the find spot and categorical data describing a category of coins such as historical information (Fig. 4). In order to distinguish these two types of information we extended our model with the property PC1 and produced things of type that supports categorical production similar to FRBRoo R26 producing things of type (FRBRoo 2015). During the mapping process it was identified that the concept 'issuing a coin' in the coin database is not yet adequately covered by CIDOC CRM. 'Issuer' is an accidental role that does not characterize an actor independently from particular contexts or activity. Therefore the Actor does not have the type 'Issuer' but the activity has the type 'Issuing':

The join of the source table COIN, field ISSUER_ID to the table ISSUER, field PR_ID (ISSUER_ID == PR_ID) maps to the complex path

E22 Man-Made Object. *P108i was produced by*: E12 Production

E12 Production. *P17 was motivated by*: E7 Activity.*P14 carried out by*: E39 Actor

E7. Activity. *P2 has type*: E55 Type = 'Issuing'

We propose the specialization *'gave order'* of *P17 was motivated by* in order to cover the 'issuing a coin' concept.

The detailed mapping of dFMRÖ is available at dFMRÖ (2015).

4 Mapping Gräberfeld Franzhausen-Kokoron

The Gräberfeld Franzhausen-Kokoron database contains information on 403 cremation graves from the late Bronze Age Urnfield Culture (1050–800 BC; Lochner, Hellerschmid 2010). The graves were excavated between 1981 and 1984 and in 1991 in the small market town of Franzhausen in eastern Austria. Graves typically contained urns with burnt human remains, unburnt animal bones and, frequently, copper alloy objects (pins, fibulas, arm- and neck-rings, razors, and knives) were found.

A Microsoft Access relational database was created in 2006 to catalogue and analyse the graves. In 2010 the database was published online with an interactive cemetery plan interface for viewing the records of each grave (Lochner, Hellerschmid 2010). The database provides information on the archaeological features (grave pits, position of urns, etc.) and finds (e.g. pottery and bronze objects) as well as results from analysis of human remains (age at death, sex) and animal remains.

Figure 7 presents a part of the semantic graph that is created with the mapping to the ARIADNE RM. The two rescue excavations are mapped to two E7 Activities. Each of these activities consists of several S19 Encounter Events (CRMsci 2015), which correspond to finds within each grave (E25 Man-Made Feature) and each object (e.g. vessels, E22 Man-Made Object) found inside the graves. The information about the vessel decoration (E26 Physical Feature) is linked to the vessel through the *P56 bears feature* property. The relational database makes extensive use of compound keys (see Figure 8) and the simple join construct of X3ML is not sufficient. A special construct will be implemented in order to support compound keys.

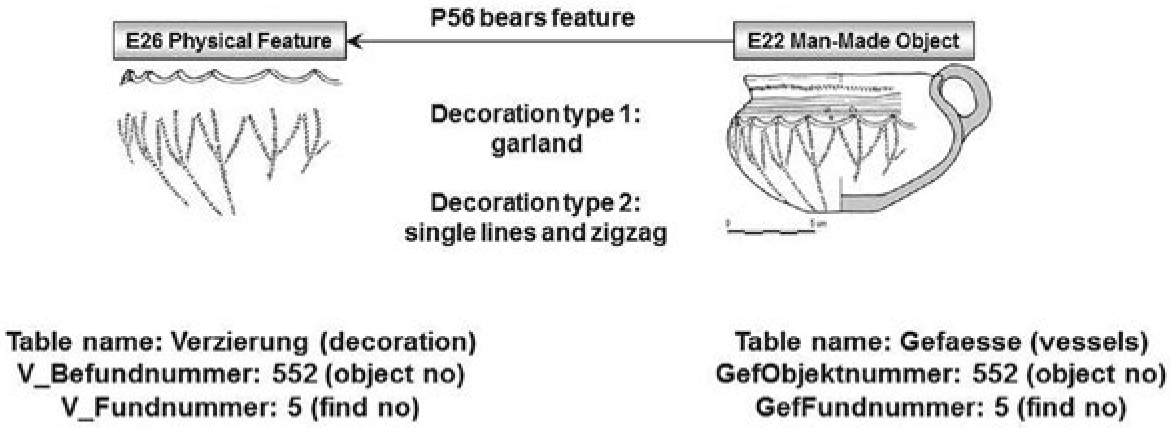

Fig. 8. Join with compound keys.

The mapping exercise identified limitations of the original database that can be resolved or improved in the future with the use of ARIADNE RM. Information about the excavations is not recorded explicitly but semantics are built into the User Interface, the queries or the values of the identifiers. For example *Befundnummer*, which is a field that identifies the find, is a three-digit number (*nnn*) if the find belongs to the 1981–84 excavation and a five-digit number (*nnn91*) if the find belongs to the 1991 excavation. The mapping under condition construct of X3ML allows the extraction of this hidden excavation information from the Franzhausen-Kokoron database and the creation of the appropriate S19 Encounter Events, which are parts of the respective rescue excavations (E7 Activity). These events can play the role of hooks for adding information in the future about the excavations, resulting in knowledge revision and augmentation. Current limitations of preservation, migration, and extensibility of the database can potentially be solved. A thorough analysis of the goals of excavations (what was the archaeological question?) can maximize the interpretation capability after excavation and allow the comparison of previous excavations on the same site or space. Revision of knowledge based on existing data is feasible by adding information about excavations. Statistical analysis of the data is also facilitated and it is possible to identify patterns in the data, e.g. age at death related to the location of the graves. Last but not least, the mapping to a common coherent ontology such as the ARIADNE RM will allow future integration with other relevant databases; something that was impossible in the current state of the database.

5 Conclusions

In this paper we presented the mappings of two indicative archaeological databases to the ARIADNE Reference Model, a global ontology based on CIDOC CRM, and an extension suite that allows deep integration of scientific and cultural-historical evidence and data. The mapping process was assisted by the 3M editor and the X3ML mapping definition language and was achieved by the close cooperation of the domain experts with the IT experts.

We have demonstrated that different databases about quite specific archaeological content can successfully be integrated under the much more generic ARIADNE Reference Model without loss of specificity of meaning. We have further demonstrated that the X3ML mapping mechanism is adequate for the domain experts to understand, define, and verify the semantics of mapping specifications.

This is a major step forward towards realizing large-scale, high-quality information integration of scientifically relevant data under a rich schema, as valuable resources for the researcher, in contrast to the core-data approaches of major aggregators, such as Europeana, and some other research infrastructure projects.

Mapping archaeological databases to CIDOC CRM and its extensions can (a) serve as a guide for good-practice data structures; (b) be used to create a semantic web of cultural knowledge; (c) compare and/or enhance knowledge from other similar databases; (d) support preservation, migration, and extensibility; and (e) enable all kinds of comprehensive statistical studies.

Future work in ARIADNE includes the mapping of other relevant databases, the creation of the integrated semantic repository, and the compilation of a list of interesting archaeological questions that can be used to validate the repository.

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Bibliography

CIDOC CRM 2015. *Current Official Version of the CIDOC CRM. Definition of the CIDOC Conceptual Reference Model*. *The version 6.1 of the reference document*. Available at: http://www.cidoc-crm.org/docs/cidoc_crm_version_6.1.pdf [Accessed: 23 june 2015]

CRMarchaeo 2014. *CRMarchaeo: the Excavation Model, version 1.2.1*. Available at: http://www.ics.forth.gr/isl/CRMext/CRMarchaeo/docs/CRMarchaeo1.2.1.pdf.

RDFS encoding available from: http://www.ics.forth.gr/isl/CRMext/CRMarchaeo.rdfs [Accessed: 23th june 2015]

CRMdig 2014. *CRMdig: an Extension of CIDOC-CRM to support provenance metadata, version 3.2*. Available at: http://www.ics.forth.gr/isl/CRMext/CRMdig/docs/CRMdig3.2.pdf. RDFS encoding available from: http://www.ics.forth.gr/isl/CRMext/CRMdig.rdfs [Accessed: 23th june 2015]

CRMinf. (2015) *CRMinf: the Argumentation Model, version 0.7*. Available at: http://www.ics.forth.gr/isl/CRMext/CRMinf/docs/CRMinf-0.7.pdf [Accessed: 23th june 2015]

CRMsci 2014. *CRMsci: the Scientific Observation Model, version 1.2.2*. Available at: http://www.ics.forth.gr/isl/CRMext/CRMsci/docs/CRMsci1.2.2.pdf.

RDFS encoding available at: http://www.ics.forth.gr/isl/CRMext/CRMsci.rdfs [Accessed: 23th june 2015]

dFMRÖ 2007. dFMRÖ – digitale Fundmünzen der Römischen Zeit in Österreich. Available at: http://www.oeaw.ac.at/antike/index.php?id=358 [Accessed: 23th june 2015]

dFMRÖ 2015. dFMRÖ mapping to CIDOC CRM. Available at: http://139.91.183.3/3MEditor/Index?type=Mapping&id=Mapping209&lang=en [Accessed: 17th november 2015]

Doerr, M., Kritsotaki, A., Boutsika, A. 2011. Factual argumentation - a core model for assertions making. *Journal on Computing and Cultural Heritage* 3, 3. New York, ACM.

Doerr, M., Hiebel, G. 2013. CRMgeo: Linking the CIDOC CRM to GeoSPARQL through a Spatiotemporal Refinement. Technical Report: ICS-FORTH/TR-435, April 2013. Available at: http://www.ics.forth.gr/isl/CRMext/CRMgeo/docs/TR435-CRMgeo.pdf RDFS encoding available at: http://www.ics.forth.gr/isl/CRMext/CRMgeo.rdfs [Accessed: 23th june 2015]

FRBRoo 2015. *FRBR object-oriented definition and mapping from FRBR$_{ER}$, FRAD and FRSAD(version 2.1)* Available at http://www.cidoc-crm.org/docs/frbr_oo/frbr_docs/FRBRoo_V2.1_2015February.docx [Accessed: 23th june 2015]

Ronzino, P. 2015. *CIDOC CRMBA. A CRM extension for buildings archaeology information modeling,* Unpublished PhD Thesis, The Cyprus Institute, Nicosia

Lochner, M., Hellerschmid, I. 2010. *Ein Gräberfeld der jüngeren Urnenfelderkultur aus Franzhausen-Kokoron (UFK)*. Katalog und Abbildungen, Version 02/epub, doi:10.1553/KatalogUFK. Available at: epub.oeaw.ac.at/franzhausen-kokoron [Accessed: 25th june 2015]

Masur, A., May, K., Hiebel, G., Aspöck, E. 2014. Comparing and mapping archaeological excavation data from different recording systems for integration using ontologies. *CHNT Proceedings*, Stadtarchäologie, Museen der Stadt Wien (Hrsg.), CHNT Proceedings 2013. Available at: http://www.chnt.at/wp-content/uploads/Masur_etal_2014.pdf [Accessed: 25th june 2015]

Oldman, D., Doerr, M., De Jong, G., Norton, B., Wikman, T. 2014. Realizing Lessons of the Last 20 Years: A Manifesto for Data Provisioning & Aggregation Services for the Digital Humanities. *D-Lib Magazine* 20 (7/8) (July/August), doi:10.1045/july2014-oldman. Available at: http://www.dlib.org/dlib/july14/oldman/07oldman.html [Accessed: 23th June 2015]

X3ML (2014) *The X3ML engine*. Available at: https://github.com/delving/x3ml [Accessed: 23th june 2015]

3M (2015) *The Mapping Memory Manager*. Available at: http://www.ics.forth.gr/isl/3M [Accessed: 23th june 2015]

Scientific Datasets in Archaeological Research

Nikolaos A. Kazakis
nikkazak@ceti.gr

Nestor C. Tsirliganis
tnestor@ceti.gr

Laboratory of Archaeometry and Physicochemical Measurements, Athena
– Research and Innovation Center in Information, Communication and Knowledge Technologies, Xanthi, Greece

Abstract: Recent trends in archaeological research dictate the incorporation of various analytical methods for the dating, chemical, mineralogical, morphological, physicochemical, etc. characterization of ancient objects, which corroborate the archaeologists' observations. Each investigation method provides different feedback with relatively discrete application when used individually, but once single studies are combined, the amalgamation of all should contribute to the completion of the archaeological puzzle, answering various explicit (e.g. age, place) and implicit (temporal evolution, connection between places) raised questions.

As a result, numerous scientific data (of various formats and types) and metadata are produced creating large and complex scientific datasets. The use of common terminology and definitions to describe these data, along with the establishment of a formal standardized structure that provides a common and extensible semantic framework on which any cultural heritage information can be mapped, would assure the credibility and durability of scientific datasets in archaeological research.

The present work provides an overview of the types and formats of scientific data and metadata produced in archaeological research through a detailed presentation of the common practices used in pottery provenance studies.

Keywords: Scientific data, Metadata, Provenance, Ceramics, Chemical analysis

Introduction

Archaeology aims towards the understanding of humankind. A further objective is the recreation of the material culture, the reconstruction of the cultural past, and the understanding of the life ways of peoples through the material remains of past societies. These can considerably contribute to the better knowledge of the social, political, economic, and cultural structure and evolution of ancient societies as well as their interactions within sites or regions (e.g. Rice 1987; Tite 2008).

In this endeavour in recent years, archaeology interacts increasingly with natural sciences and informatics to take advantage of the possibilities they offer and reduce the subjective element. The combined information from the various scientific disciplines allows the investigation of theories and interpretations that shed light on the human past and environment.

Numerous 'components' of archaeological research, such as studies on dating, provenance, and dietary habits lean heavily on the natural sciences and involve the use of advanced scientific methods applied on the archaeological finds. All the information extracted from the materials using such methods produce a plethora of scientific data and metadata, which do not merely serve as tools for answering individual archaeological questions, but also allow the complete scientific documentation of the artefacts and the creation of large scientific reference datasets.

These datasets include data of various formats and types, while their metadata (e.g. experimental method, date of measurement, etc.) are essential for their evaluation and constructive use, especially when comparisons are attempted.

The present work provides an overview of the specifications of the scientific data and metadata produced in archaeological research and their importance from a scientific point of view. This is accomplished through the detailed presentation of the common practices in pottery provenance studies, which can be considered as the most representative example of scientific data production in the archaeological research, because of the large number of methods that can be involved and the variety of the obtained data.

1 Approaches in archaeological research

Traditionally, the study of ancient artefacts was mainly focused on meticulous macroscopic observations by the archaeologists. More specifically, conclusions were derived from their typology, decoration, iconography, and chronology, based exclusively on stylistic considerations and aesthetic evaluation of the artefacts as well as their use, role, and function. This was also complemented in some cases by available historical archive studies. In addition, evaluation of their characteristics could also shed light on the places (e.g. Attic or Corinthian pottery in ancient Greece) and the techniques of production (black-figure style), distribution, trade routes, organization, and contacts of the societies that created and exchanged them.

In the late 1950s, the term 'archaeometry' was first introduced by Prof. C.F.C. Hawkes to refer to the use of methods and techniques emanating from the natural sciences (physics, chemistry, mathematics, geology, geophysics, biology) and their application to archaeology as well as to art objects in order to provide solutions for specific questions and problems (Harding 1994). The term today is expanded to include computer technologies and their contribution to the study of cultural heritage and is increasingly referred to as 'heritage science', which actually represents a modern and more sophisticated approach in archaeological research.

It is evident and widely accepted that physical properties and composition are significant descriptive characteristics of both raw materials and the finished products (e.g. Buko 1984). In the same respect, the manufacture techniques can characterize the appearance and functional capabilities of the finished object. As a result, various methods, simple or complex, destructive or non-destructive, qualitative or quantitative, can be employed to study these features and provide information about the past of the archaeological finds. Any advanced method employed for such a purpose is valid for describing an artefact by objective, precise, and replicable standards, free from aesthetic or subjective judgements common to art-historical appraisals. In parallel, they allow the definition of units of measurement or comparisons that are standardized and independent of the context of observation. Thus, for a pot that could be described as 'soft and poorly fired' for one cultural region and 'hard and well fired' for another, a measured hardness of 5.0 in the Mohs' scale, and a firing temperature between 800^{o}C and 900^{o}C eliminates the ambiguity of the qualitative terms. It must be stressed that the most important aspect of all these methods is that they yield a database, which can be used to relate material properties to human behaviour and technology.

To this respect, very determinant was the role of digital technologies, developed in the second half of the 20th century, which significantly contributed to the organization of accumulated knowledge and set up new methodologies for analysing the physicochemical properties of archaeological objects. At the same time, cultural databases, 3D digitization and reconstruction, and virtual reality are used in order to make material remains more accessible and better understandable to both scholars and the general public. Last but not least, the Geographical Information System (GIS) was also introduced to archaeological studies from the late 20th century onwards. The distribution of artefacts through place and time can provide important information for issues such as trade routes, contacts, use and function, etc.

Accordingly, heritage science can be regarded as the 'forensics' in cultural investigations, since it seeks information in retrospect when trying to answer four primary questions: who, where, when, and how. This is achieved through the amalgamation of several natural sciences and the production of numerous scientific data, which can stem from:

- measurements of physicochemical parameters and properties of materials/environment
- analyses of the composition of materials
- study of the structure of the materials
- assessment of physicochemical processes in materials/environment
- spatial data
- statistical data

2 Case study — pottery provenance studies

In order to elaborate on the issues mentioned above and develop the identity and complexity of scientific data in archaeological research, the procedure followed during a pottery provenance study is described in detail, as it constitutes the best example of the synergy of various sciences in archaeological studies (chemistry, physics, geology, petrography, mathematics, informatics, etc.).

The provenance of ceramics, that is, seeking an answer to the question of where the artefacts were produced, is a vital issue in archaeological studies, since it sheds light on various aspects of the civilization that produced them, such as their contacts, economic interactions between communities in a broader area, and even of their technological level. Using analytical methods several measurements are taken to determine the chemical composition, physicochemical properties, and structure of the materials, along with the morphology and physicochemical parameters of the excavation environment. This, in conjunction with their statistical processing, results in the production of numerous important scientific data, which represent a unique 'fingerprint' for each artefact, which will shed light on their (common) provenance, as feature variations between sources should be greater than within sources (Rice 1987; Sterba *et al*. 2009; Tite 2008).

2.1 Pottery in scientific studies

A selection of pottery in provenance studies (and in the majority of the scientific studies assisting archaeological research) appears more advantageous compared to any other material because of the features it exhibits, which allow the evaluation of its initial state and the extraction of valuable information from its composition (e.g. Padeletti and Fermo 2010). More specifically:

- it has a long history and can be found in great abundance virtually all over the world
- it exhibits remarkable resistance to weathering and erosion along with tolerance through time
- it is non-perishable; although it may break, fragments (sherds) are virtually indestructible
- it has multiple functions: it was commonly used in everyday life and was easily transportable and was produced in countless shapes with innumerable decorations

As a result the scientific study of pottery can provide valuable information regarding the manufacturing method, which can be described as 'an additive process in which the successive steps are recorded in the final product', gaining more knowledge about the past as pottery manufacture, like any other productive technology, represents a point where a cultural system interacts directly with its surrounding socio-cultural and natural environment.

Accordingly, pottery represents not only a category of useful containers, but also a simple and convenient means of:

- dating sites
- tracing trade patterns (local and long-distance trade arrangements)
- studying ancient technology (resource selection, forming techniques, firing strategies)
- investigating settlement patterns and demographic factors
- studying a variety of social aspects (dietary habits, ceremonial or ritual activities, etc.).

2.2 Objectives of pottery provenance studies

Pottery provenance studies can have various scopes and the used methodology may involve additional steps or follow specific constraints. More specifically, provenance studies aims at the following (Kazakis and Tsirliganis 2015):

- Identification of the provenance of ceramic artefacts of unknown origin

In this case, the archaeological observation is not adequate to serve as a representative guide for the provenance study and consequently, the use of reference samples, i.e. samples of known provenance (ideally ceramics found at a workshop) is required.

- Classification of ceramics of the same region

In this case, the provenance study is conducted towards the identification of know-how and craftsmanship of certain production workshops in the same region or a different geographical location. For such a study to be successful requires an adequate number of samples of each potential group in order to ensure convincing results.

- Confirmation of the provenance of ceramic samples with a 'suspected' origin

A pottery provenance study may also be utilized to determine the origin of pottery that appears to have many stylistic similarities with major and 'popular' ceramic categories with historically known production workshops (e.g. Attica in ancient Greece). Such a study can basically be regarded as an authenticity test, while it requires a reference group of the 'genuine' articles.

- Building archaeological databanks

All scientific data produced during a pottery provenance study in conjunction with the archaeological data enable a full documentation of the ceramics studied and the creation of large archaeological reference datasets. As a result, new reference groups are produced, while existing ones can be expanded, improved, and/or modified.

2.3 General methodology in pottery provenance studies

The methodology adopted during pottery provenance studies is briefly described as follows:

- first, a small fragment of a ceramic sherd is subjected to one or more laboratory analytical methods, to obtain its qualitative and quantitative characterization and the identification of its unique fingerprint that allows its discrimination among others of different origin or its grouping within those exhibiting similar features
- second, multivariate statistics are used to determine similarities and differences between the specimens, which ultimately lead to their classification into distinctive groups according to their provenance
- third, final conclusions are usually reached with the juxtaposition of the laboratory/statistical data and the archaeological data (primarily based on stylistic features)

2.4 Procedures and scientific data sources in pottery provenance studies

Besides the visual macroscopic observation of any stylistic properties on the pottery under study, which is in principle carried out by archaeologists, several other laboratory scientific procedures are involved in pottery provenance studies, which produce numerous data. Easy-to-use measurements of various physical properties of the clay, such as colour (e.g. Munsell colour system), density, and hardness are taken first, while more advanced approaches follow for the in-depth material characterization. The latter mainly comprises a chemical analysis of the elemental bulk concentrations and a mineralogical investigation.

Chemical analysis is oriented towards the identification of the chemical elements that constitute the ceramic fabric — present in large, small, or trace amounts — which can provide a unique chemical profile, allowing ceramics made from the same raw materials to be grouped together during the statistical analysis of the data. For this purpose, various methods can be used (Tab. 1) (Kazakis and Tsirliganis 2015), individually or in combination (two or more) in the same study in order to increase the validity of the results. Furthermore, in some cases one method may complement another, since the accuracy and sensitivity of the different methods varies, and in some cases they are element-dependent. Consequently, one method may be used for the determination of the major elements, while a second one may be employed for the trace elements.

On the other hand, the *mineralogical investigation* aims at identifying the speciation of the geological components in the ceramic fabric and assessing the potential origin of the raw materials. Mineralogical study is focused on the analysis of the temper, which was added by potters in order to modify the properties of the clay as desired and improve the quality of the final product. The geological data and information acquired by such a study can increase the knowledge regarding the selection and use of local and non-local resources by potters. As in the case of the chemical analysis, various methods can be used for the mineralogical investigation of pottery, the most important of which are presented in Table 1.

The two approaches (chemical and mineralogical analysis) of ceramics characterization provide different kinds of scientific data which complement each other (Rice 1987; Wilson 1978). In most cases, the use of only one of the analyses is not adequate to determine with high certainty the provenance of the pottery studied (Mommsen 2001; 2004). Chemical data alone do not identify fully the geological resources

Tab. 1. Instrumental methods of chemical and mineralogical analysis of ceramics.

Chemical analysis	*Mineralogical investigation*
Neutron activation analysis	Thin-section petrographic analysis
X-ray fluorescence spectroscopy	Scanning electron microscope
Atomic absorption spectrometry	X-ray diffraction
Electron microprobe analysis	
Proton-induced X-ray emission	
Scanning electron microscope + EDS/WDS	
Inductively coupled plasma-atomic emission spectroscopy-mass spectrometry	
Mossbauer spectroscopy	

(raw materials) used, while petrographical analysis alone cannot account for possible phase transitions of the minerals due to the firing of the ceramics. As a result, state-of-the-art provenance studies of ceramics dictate the adoption of an 'integrated' approach, in which the two analyses are combined, while additional measurements of the microstructure and other physicochemical and mechanical properties of the pottery are more than desirable (e.g. Mirti *et al*. 1996; Moropoulou *et al*. 1995; Rice 1987; Wilson 1978). The amalgamation of all data obtained from these scientific activities can offer an optimal characterization of ceramics which, aided by advanced and specially tailored statistical methods (Principal Component Analysis or Hierarchical Cluster Analysis), will provide an accurate and distinct classification of ceramics leading to satisfactory, secure conclusions on their origin.

2.5 Scientific data in pottery provenance studies

A pottery provenance study combines many natural sciences, which serve as detection tools to extract all possible underlying information that will promote archaeological research. Regardless of the approach adopted in a pottery provenance, even if a single analytical method is used, various scientific data are produced demanding different ways of handling and processing. Figure 1 illustrates the various scientific data produced during a pottery provenance study and also reflects the variety and complexity of the scientific data produced in general in archaeological research, which can include:

- Various formats, such as numbers, spectra, diagrams, pictures, models, and maps.

- Various types, such as raw data, calculation results, tables, plotted data, and statistical data.

All the extracted data can be used either for a general approach to an archaeological problem or a 'customized' solution to a specific case. Scientific datasets demand/involve a three-level interpretation (Figure 2):

- 1st level → scientific interpretation (results/conclusions)

In the 1st level, data/results are interpreted and evaluated from a strictly scientific point of view. Inspection of the various data (e.g. elemental concentration) and a comparison between the values are made, allowing the extraction of conclusions, which do not have tangible meaning to the archaeologist, but provide the basis on which the 2nd level of interpretation can take place.

- 2nd level → 'real life' meaning

The 2nd level of interpretation involves the decoding of the scientific data and the conclusions of the 1st level into 'real life' meaning results. In this level, scientific data can actually provide an answer to the archaeological problem and become of practical use.

- 3rd level → implications for the specific archaeological problem

In the final level of interpretation, the new knowledge gained by the acquired scientific data may produce implications for the specific archaeological problem and create new doubts and/ or questions for the archaeologist (e.g. the 'known' provenance of one or more ceramic samples may be put into question).

2.6 Scientific metadata/paradata

There is seldom a perfect and complete set of data that is devoid of any ambiguities and/or outliers. Consequently, to ensure that data is not misused, the assumptions and limitations affecting the creation of data must be fully documented; besides the acquired data, appropriate metadata and/or paradata should also be considered in a complete scientific dataset. Metadata allows a producer to describe a dataset fully so that users:

- can understand the assumptions and limitations

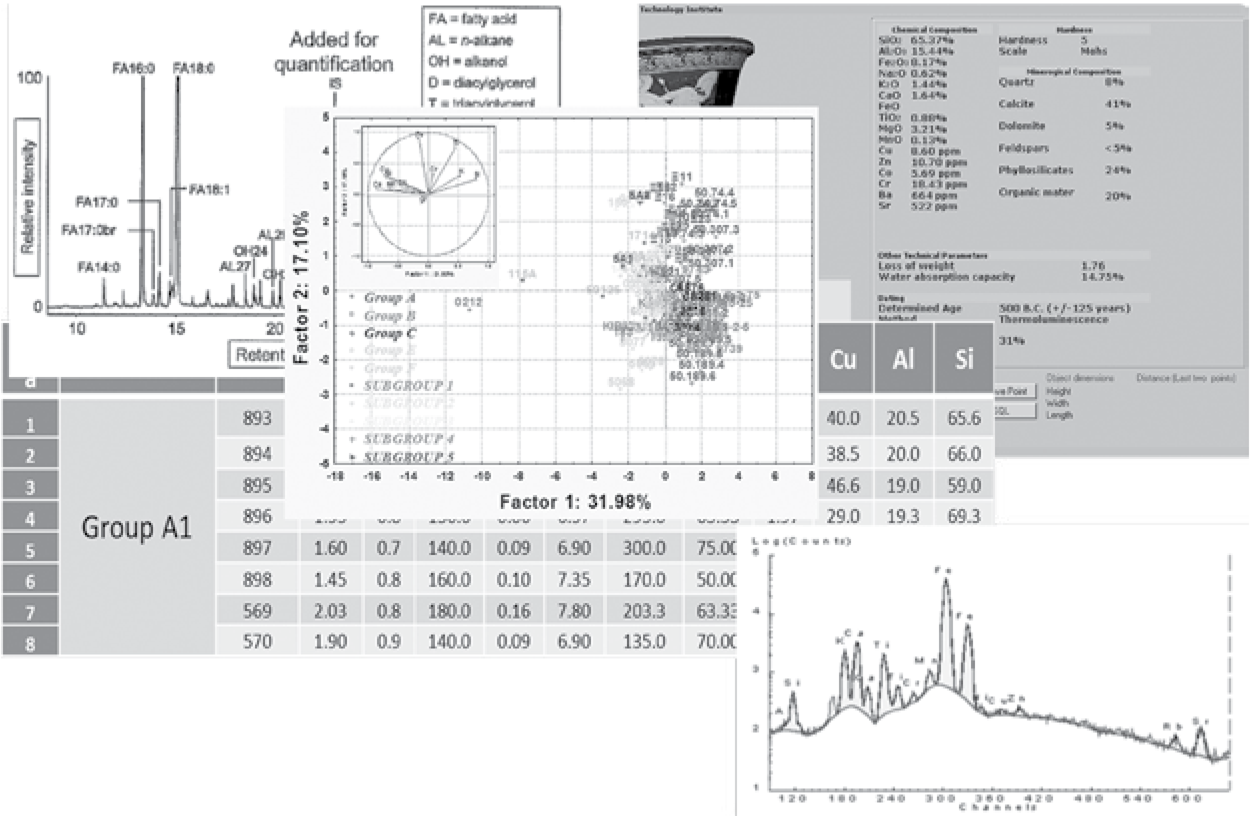

Fig. 1. Example of scientific data produced during pottery provenance studies.

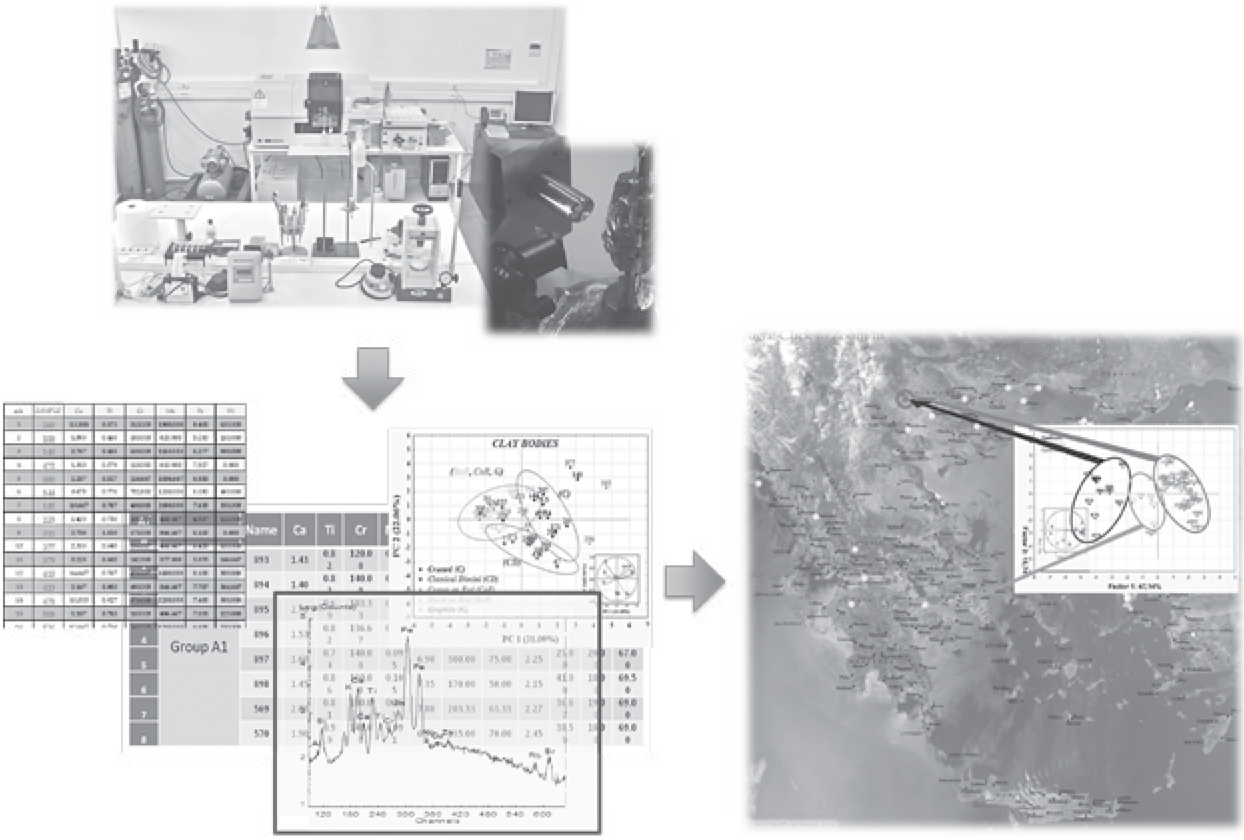

Fig. 2. From the production of scientific data to their 2nd-level interpretation.

- evaluate the dataset's applicability for their intended use
- efficiently use scientific datasets in their research (especially when comparisons are attempted)

A few examples of metadata that should be documented in a scientific dataset are given below:

- laboratory personnel who produced/created the data
- date(s) when the measurements/analyses were undertaken
- experimental method/technique used
- instrumentation used for the production of data
- calibration method-data and standards used

In the same respect, paradata (a.k.a. operational parameters/ conditions and procedure) can also be very important for the certification, assessment of limitations, and 'reproducibility' of the scientific datasets.

Documentation of all the above and their incorporation in a scientific dataset may be more significant for research purposes, such as:

- comparing the results and/or re-estimating the precision of the measurement (e.g. instrument and/or method employed)
- repeating the experiment (e.g. protocols/conditions of the measurement)
- recalibrating the measurement (e.g. reference data and/or standards used)
- using exactly the same method/conditions for new samples in light of new archaeological finds
- determining the provenance of the extracted data (spatiotemporal information, such as who, where and when the measurement was conducted)
- evaluating and certifying the inter-operability of the data

Accordingly, the adoption of a metadata standard seems imperative, as it will assure the credibility and durability of a scientific database and encompass only the necessary data and metadata without any excessive information. A metadata standard should meet several requirements and define (ISO 2003):

- the mandatory and conditional metadata sections and elements
- the minimum set of metadata required to serve the full range of metadata applications (data discovery, determining data fitness for use, data access, data transfer, and use of digital data)
- the optional metadata elements – to allow for a more extensive standard description of the data, if required
- a method for extending metadata to fit specialized needs, as numerous scientific methods are used as diagnostic tools in the various fields of the archaeological research (e.g. dating, provenance, studies of dietary habits)

Implementation of a metadata standard in the scientific datasets produced in the archaeological research would have many benefits, as it would (ISO 2003):

- provide data producers with appropriate information to characterize their data properly
- facilitate the organization and management of metadata
- enable users to apply data in the most efficient way by knowing its basic characteristics
- facilitate data discovery, retrieval, and reuse. Users should be better able to locate, access, evaluate, purchase, and utilize the data
- enable users to determine whether data in a holding will be of use to them.

3 Needs and challenges

The efficient usage of a scientific dataset has several requirements that a user considers. The most important is that the user must get acquainted with the scientific methods available, which are used to support the archaeological research. Knowledge and understanding of the principles, requirements, and types of data produced by the various scientific methods is a prerequisite in order to be able to understand the structure of the database and the nuances of the data ('reading between the lines'). Secondly, in order to tackle an archaeological problem successfully, the user should also learn how to:

- interpret laboratory results/scientific datasets from an archaeological point of view
- manage and read beyond the data (metadata and paradata)
- incorporate laboratory results/scientific datasets into the investigation of an archaeological problem
- design archaeological projects that make use of scientific datasets

Several issues/challenges regarding scientific datasets in archaeological research also exist and should be confronted in order to optimize the availability, accessibility, and inter-operability of the scientific datasets. First of all, such scientific datasets should make up an inextricable part of each archaeological dataset rather than an independent set of additional information. Along with archaeological observations (e.g. dimensions of the object, estimated period, stylistic properties, etc.), all the available scientific data should also be recorded in order to create a complete 'identity' record for all archaeological objects, which should properly be updated after new analyses and/or findings.

Scientific datasets are not created only for in-house use, but also aim to corroborate the work of other researchers. The use of different terminology and definitions, however, may create confusion for scientists of different scientific disciplines, including those that produce data for archaeological research. Consequently, one of the keynote challenges is to agree on common terminology and definitions. Even the definition of the term 'data' may confuse the scientific community. For example, in the case of the determination of the chemical composition of a ceramic artefact by means of X-ray fluorescence spectroscopy, some would regard the concentration of the elements as data, while others would consider the unprocessed information, i.e. the acquired (wholly qualitative) spectrum, as data.

By the same token, agreement on common metadata standards is vital for the scientific community, which serves the broader field of archaeological research in order to bring together and integrate existing archaeological research data infrastructures and facilitate their accessibility and exploitation by researchers. A formal standardized structure that provides a common and extensible semantic framework to which any cultural heritage information can be mapped should be established. Such a modelling of information will assure the credibility and durability of a scientific database, as it will encompass only the necessary data and metadata which, along with their interdisciplinary character, should contribute to the creation of an integral archaeological research infrastructure.

In this respect, several ontologies/metadata standards are available, which are adopted for various natural sciences. A few examples include the DIF (Directory Interchange Format) (Lola Olsen and Chrissy Chiddo 2008), used for exchanging information about scientific data sets primarily for earth sciences and the ISO 19100 series (especially ISO 19115) for geographic information metadata (ISO 2003). In addition, the CIDOC-CRM is intended to promote a shared understanding of cultural heritage information by providing a common and extensible semantic framework to which any cultural heritage information can be mapped. An extension to this with modifications and improvements is under development in the framework of the ARIADNE project (FP7-INFRASTRUCTURES-2012-1-313193) (e.g. Doerr and Hiebel 2014), with the aim of:

- assuring credibility and durability of datasets
- maximizing the information with minimum requirements
- establishing the use of common terminology and definitions
- providing the common denominator for all sciences and studies involved (i.e. facilitating the interdisciplinary character)
- facilitating the building of an integral archaeological research infrastructure

The importance of the adoption of a formal standardized structure is further emphasized if the scientific data are disseminated through open-access repositories. Open-access repositories offer new possibilities to the researchers, such as comparing data/analyses from various excavation sites around the world, sharing knowledge with no limits, and providing additional data to complete and solve the archaeological puzzle without the need for duplicating or repeating analyses to reproduce them. Open-access data from various individual laboratories could provide answers to 'what if' questions elucidating various explicit (e.g. age, place) and implicit (temporal evolution, connection between places) issues in a European or even a global scale, and revealing socio-economic relationships between the various geographical regions. For example, the comparison of the stoichiometric composition of a ceramic sample with similar data in existing databases can instantly provide significant evidence related to the origin of a find in an excavation and/or its route through the trading channels of a given era.

Publishing meaningful data under open access repositories comes with its own barriers, however, stemming from their different organization and management as well as their proper description, validation, and assessment. Metadata standards can alleviate such limitations and foster the use of scientific data repositories as the building blocks of an integral archaeological research infrastructure.

4 Conclusions

Archaeology uses a variety of methods and tools to reconstruct the cultural past. Based on excavation finds, concerted efforts are made to shed light on the structure of ancient societies and their exchanges within sites or regions. This is mainly accomplished through the synergy of archaeology and various fields of natural sciences, which enable the characterization of material findings by means of advanced analytical methods.

As a result a plethora of scientific data (of various formats and types) and metadata are produced, creating large and complex scientific datasets. The role of these datasets is twofold. First, they can be used either for a general approach to an archaeological problem or a 'customized' solution to a specific case. Secondly, they are very important in order to repeat an experiment to validate the results in light of new measurements, and allow comparison between different measurements.

Such scientific reference datasets used in the archaeological research, however, exhibit wide variability among the various research infrastructures. Agreement on common definitions, purposes, and structure and the establishment of standards regarding these scientific datasets is required in order to bring together and integrate existing archaeological research data infrastructures and to facilitate their accessibility and exploitation by researchers.

Bibliography

Buko, A. 1984. Problems and research prospects in the determination of the provenance of pottery. *World Archaeology* 15, 3: 348-65.

Doerr, M., and Hiebel, G. 2014. *Developing common European archaeological concepts through extending the CIDOC CRM within ARIADNE*. Available at: http://www.ariadne-infrastructure.eu/content/download/1844/10313/version/1/file/CHNT-2013_04_GHiebel-MDoerr_cidoc-crm_archaeo-extensions_20131113.pdf [Accessed: 5th june 2015].

Harding, D. W. 1994. Charles Francis Christopher Hawkes 1905-1992. *Proceedings of the British Academy* 84, 323-44.

International Organization for Standardization 2003. *ISO 19115: Geographic information - Metadata*. First edition, Switzerland. Available at: ftp://podaac.jpl.nasa.gov/

misc/outgoing/ed/pre_2013/GHRSST_metadata/ISO%20 19115%20.pdf. [Accessed: 5th june 2015].

Kazakis, N. A., and Tsirliganis, N. C. 2015. Provenance of Ceramics: Methods and Practices. In A. Sarris (ed.), *Special volume on 'Best Practices of GeoInformatic Technologies for the Mapping of Archaeolandscapes'*: 241-52. Oxford, Archaeopress.

Mirti, P., Casoli, A., Calzetti, L. 1996. Technology of production of fine pottery excavated on a western Greek site investigated by scanning electron microscopy coupled with energy-dispersive X-ray detection. *X-ray Spectrometry* 25, 3: 103-9.

Mommsen, H. 2001. Provenance determination of pottery by trace element analysis: Problems, solutions and applications. *Journal of Radioanalytical and Nuclear Chemistry* 247, 3: 657-62.

Mommsen, H. 2004 Short note: Provenancing of pottery-The need for an integrated approach? *Archaeometry* 46 2: 267-71.

Moropoulou, A., Bakolas, A., Bisbikou, K. 1995. Thermal analysis as a method of characterizing ancient ceramic technologies. *Thermochimica Acta* 269-270: 743-53.

Olsen, L., and Chiddo, C. 2008. Directory Interchange Format (DIF) Standard. Available at: https://earthdata.nasa.gov/files/ESDS-RFC-012v1.pdf [Accessed: 5th june 2015].

Padeletti, G., and Fermo, P. 2010. A scientific approach to the attribution problem of renaissance ceramic productions based on chemical and mineralogical markers. *Applied Physics A: Materials Science and Processing* 100, 3: 771-84.

Rice, P. M. 1987. *Pottery Analysis: A Sourcebook*. Chicago and London, The University of Chicago Press.

Sterba, J. H., Mommsen, H., Steinhauser, G., Bichler, M. 2009. The influence of different tempers on the composition of pottery. *Journal of Archaeological Science* 36, 7: 1582-9.

Tite, M. S. 2008. Ceramic Production, Provenance and Use-A Review. *Archaeometry* 50, 2: 216-31.

Wilson, A. L. 1978. Elemental Analysis of Pottery in the Study of its Provenance: A Review. *Journal of Archaeological Science* 5, 3: 219-36.

CHAPTER 7
Spatial Analysis: Theories, Questions and Methods

Fuzzy Classification of Gallinazo and Mochica Ceramics in the North Coast, Peru Using the Jaccard Coefficient

Kayeleigh Sharp
sharpka@siu.edu
Department of Anthropology, Southern Illinois University, Carbondale (SIUC), U.S.A.

Abstract: How can meaningful dimensions of social differentiation be elucidated through the analysis of nominal and categorical archaeological data alone? Unlike traditional ceramic studies, which are largely limited to analysis of binary attributes, or stylistic and iconographic data that are incompatible with quantitative statistical analysis, this investigation uses a fuzzy classification system for analysing ceramic artefact diversity, that is better equipped to capture variation and relationships, even when a high degree of uncertainty is present. Using measures of similarity, in this case, the Jaccard Coefficient, to establish degrees of membership for certain attribute combinations, provided a number of significant advantages over traditional typological and iconographic analyses. In particular, producing datasets upon which high-level spatial statistical analysis can be carried out. The approach is useful in a broader range of applications, and new data can be analysed in conjunction with other lines of multivariate data such as chemical compositional, stratigraphic, or temporal.

Keywords: Jaccard Coefficient, Fuzzy classification, Spatial analysis.

Introduction

This paper addresses problems of carrying out high-level multivariate statistical and spatial analysis, on data that is nominal or categorical in nature. In particular, the focus is upon data traditionally used to classify archaeological ceramics of the Gallinazo and Mochica, which may be the material evidence of multi-ethnic groups that coexisted for centuries on the north coast of Peru (see below). Investigations have long prioritized typological, stylistic and iconographic analyses in the study of these ceramic traditions, which poses significant challenges for carrying out multivariate spatial and/or statistical analysis, as well as for understanding of the dynamics of social interrelationships that existed in the past. A critical point of concern is how, we as archaeologists, can make better quantitative use of nominal and categorical data. Descriptive data such as this is restricted by its existence in binary or nominal states, which renders it incompatible with many high-powered statistical and spatial analysis tools, yet nominal and categorical data remain valuable for addressing broader theoretical and anthropological concerns.

This is an issue that plagues current research in the north coast, including the Zaña Valley, Peru, the area of the present study. Based primarily on the stylistic interpretation of Gallinazo- and Mochica-style artefacts and architecture, traditional views long held that the Mochica: (1) developed from earlier Gallinazo cultural antecedents (Bennett 1939, Larco Hoyle 1945), (2) conquered and replaced ethnically Gallinazo populations (Willey 1953), or (3) all-together doubted the existence of cultural distinctions between the Mochica and the Gallinazo (Ubbelohde-Doering 1957). Today, there exists much controversy over what the Gallinazo label designates (culture, religion, or political administration), as well as the nature of Gallinazo and Mochica coexistence (see in particular Milliare and Morlion 2009). While recent work on has transformed ideas on Mochica statehood, and greatly expanded our understanding of the ideological, ritual, religious and political dimensions of Mochica society (e.g. Quilter and Castillo 2010, Quilter and Koons 2012, Swenson and Warner 2012), much research continues to emphasize urban/rural, elite/commoner dichotomies where the Gallinazo are concerned.

Recent prospection activities at the Zaña Valley site of Songoy-Cojal, however, have produced unexpected evidence of Gallinazo-Mochica ceramic coexistence and variation that does not conform well to traditional typological categories for Gallinazo and Mochica artefacts. Importantly, most data on these groups has been derived from studies of major monumental ritual and urban centres along Peru's north coast (Fig. 1), while the data from Songoy-Cojal, which is a relatively smaller-scale regional centre, was collected from the surface in both residential and looted funerary contexts. The observed diversity has raised a number of important questions about Gallinazo-Mochica coexistence and social differentiation that cannot be effectively addressed using the traditional artefact categories. In particular, do residential Gallinazo- and Mochica-style artefacts suggest that dichotomous dominant/subordinate relationships were in place? More broadly, how can meaningful dimensions of social differentiation be elucidated through the analysis of nominal and/or categorical ceramic data alone? Recognizing that the inability to answer such questions arises due to the form and context, rather than quality of north coast datasets, it was necessary to rethink our approach to the ceramic remains we had encountered. In this study, I focus on the foundational question of how to use nominal and categorical data in more meaningful ways. The answer, I propose, lies in the adoption of a Fuzzy Approach that is better equipped to capture and analyse datasets that contain a high degree of uncertainty, such as the new data from Songoy-Cojal.

1 A Fuzzy Approach using Jaccard's Coefficient

Fuzzy set theory (after Zadeh 1965) provides an excellent alternative to traditional binary or Boolean thought. The advantages of applying fuzzy logic, are observed in a wide range of disciplines from archaeology (Barceló 1996), geology (Klir 2004), and the behavioural and social sciences (Smithson 1987), to accounting (Qu and Zhang 2008), and computer

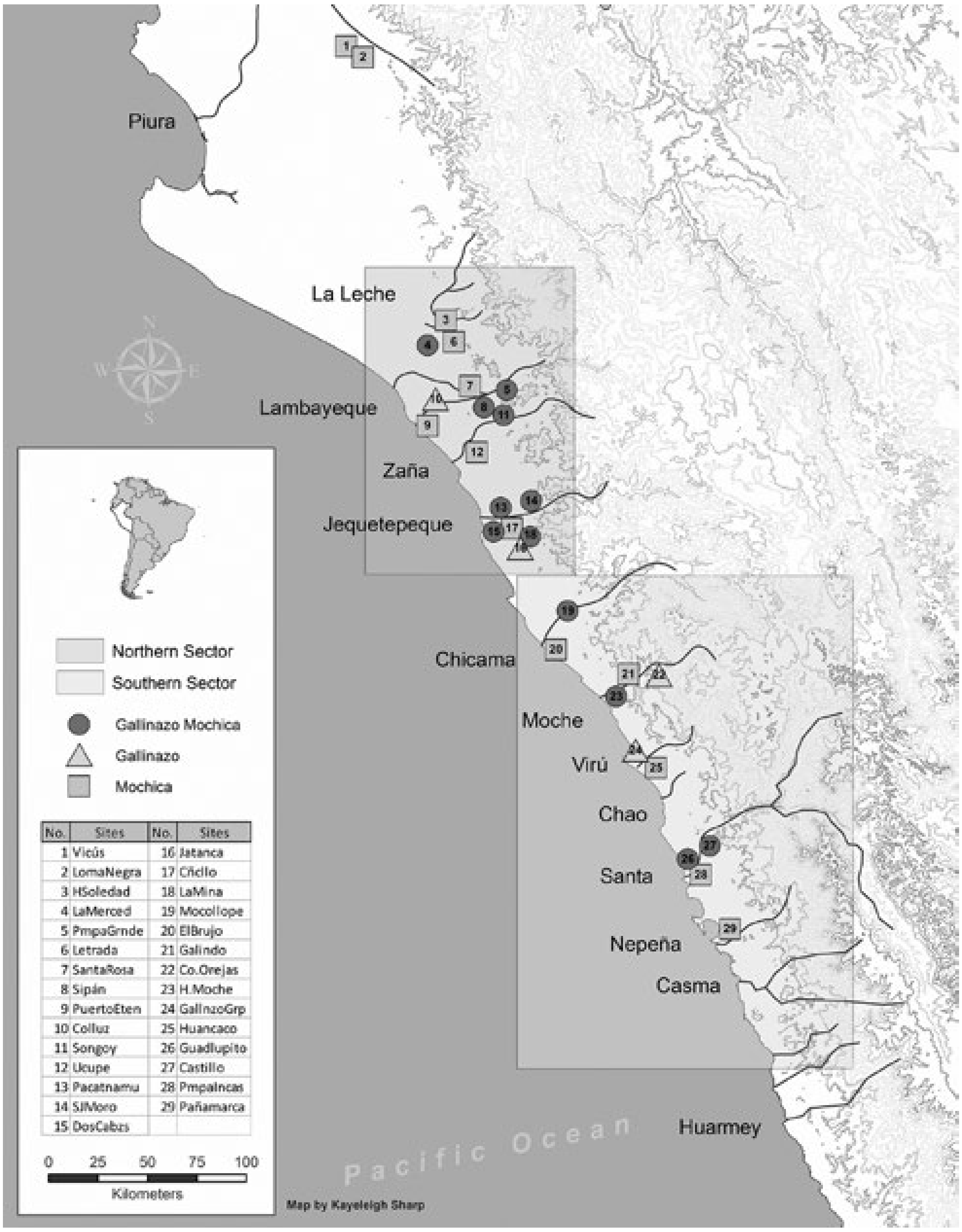

Fig. 1. Regional map of northern coastal Peru, and sites originally identified as Gallinazo, Mochica or both.

science (e.g. Chen *et al.* 2000; Khan *et al.* 2011), to name just a few. As these and other scholars have aptly recognized, fuzzy logic provides a means by which to re-examine data in a way that more closely approximates reality.

In its original form, Lofti Zadeh's (1965) fuzzy logic computing permits the exploration of data, even when it exists in only partial states. It is useful in cases, such as the analysis of fragmentary ceramics (see Barceló 1996), where data is uncertain, incomplete, imprecise, or vague (Nguyen and Walker 2000, Smithson 1987). Fuzzy sets depart significantly from datasets consisting of Boolean variables that are reliant upon probability estimates (Albrecht 2007, Klir 2004, Nguyen and Walker 2000). Fuzzy sets logic takes into account data that fits only partly into a given category or class, and therefore contains datasets that fit completely into class or another. The key difference is that fuzzy set membership is expressed in terms of degrees that range from 0 to 1, rather than on a 0 or 1 basis as in the case of ordinary Boolean mathematics (see Fig. 2).

An effective way to express degree of membership between 0 and 1 among items in various types of fuzzy datasets, is by calculating the Simple Matching Coefficient (total number of matches divided by the total number of variables, see Qu and Zhang 2008). In certain cases, such as the Gallinazo-Mochica assemblage, it was necessary to understand relationships among variables that occur seldom together (e.g. the strength of the relationship, or the degree to which relationships between variables such as additive designs and surface treatments are similar or different and how frequently they occur). While Euclidian Distance is a common and effective measure of similarity and distance among variables, is poorly suited to the analysis of unranked or categorical data, although data can be reorganized into separate variables expressed in terms of present/absent variables which can then be analysed. Another

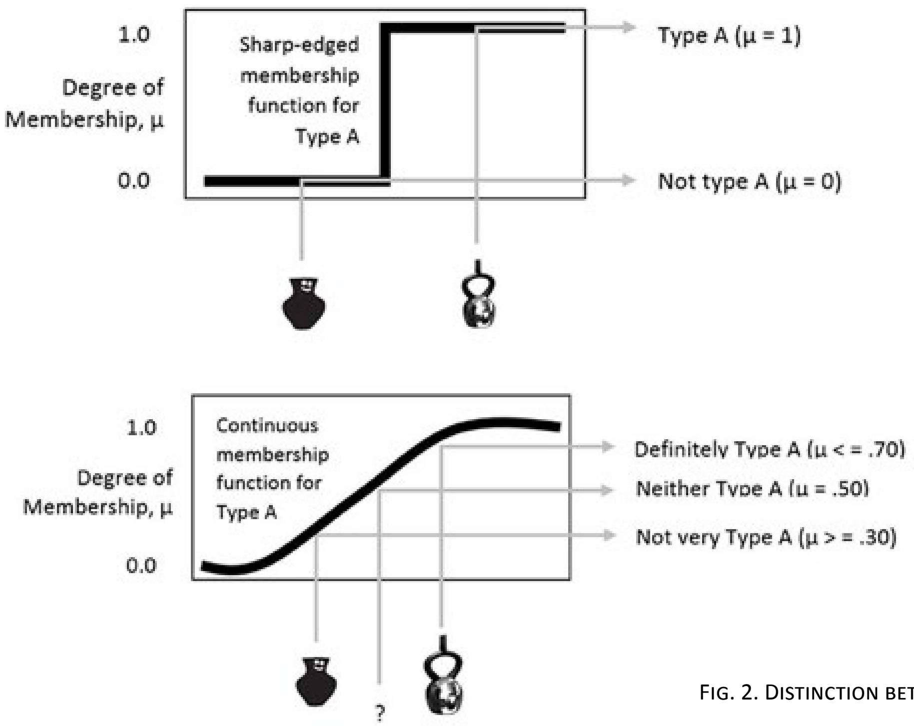

Fig. 2. Distinction between traditional crisp sets and fuzzy sets.

limitation is that, Euclidian Distance measures are not designed to understand relationships among categories that rarely co-occur. However, when data consists of only two categories (present/absent), there are several similarity coefficients, such as Simple Matching Coefficient or Jaccard's Coefficient that can be used to explore relationships between variables and cases. When attributes with present/absent variables are available and present/present cases may be more meaningful, Jaccard's Coefficient is the preferred technique for exploring relationships between cases, especially those that rarely co-occur within a given dataset (see Drennan 2009: 271-9).

It is for the above reasons that the Jaccard Coefficient was used in this study. Originally developed to explore species diversity in a given geographical zone (Jaccard 1912), the Jaccard Coefficient has been effectively used in a range of archaeological applications from iconographic studies of Aztec sculptures (see Baquedano and Orton 1990), to studies of plant domestication (Emshwiller 2006), and also in the analysis of ceramic traditions (see Solheim *et al.* 2006). Calculation of Jaccard's Coefficient was also desirable because: (1) it produced results that were easily translated as partial degrees of membership (or similarity), within the context of the fuzzy ceramic classification system, and (2) suitable for expressing these relationships as numerical values that were then used to create the feature class layer for spatial analysis.

2 Analysis and Interpretation: The Fuzzy Classification of Gallinazo and Mochica Technological Choices and Spatial Analysis

2.1 Fuzzy Classification Using Jaccard Coefficient

Visual attributes were recorded for fragmentary specimens collected from the surface of both residential and looted funerary sectors of the Songoy-Cojal site. The sample used to generate the fuzzy taxonomy, consists of 139 specimens that could be broadly classified as Gallinazo or Mochica (e.g. application or extractive designs, rough surfaces and coarse temper for Gallinazo, and painted designs, polished and slipped surfaces and fine temper for Mochica artefacts).

To better understand the diversity and rarity of attribute co-occurrences (e.g. Gallinazo applied or extractive designs and burnished surfaces) observed on the Songoy-Cojal assemblage, the present data were subdivided into nominal (and categorical) technological attributes, rather than stylistic or iconographic attributes mentioned above. These include: (1) APPLICATION: designs applied to surfaces including a range of eye forms and body lugs, (2) EXTRACTION: extractive designs made by gouging, incising, partially puncturing (i.e. punctate designs) the surface, (3) surface coating (SLIP or WASH), (4) PAINT: painted designs of various line widths, including the well-known Mochica fineline variant, (5) surface modifications such as MODELLED or MOULDED or STAMPED decorations, (6) surface treatment (BURNISHED, POLISHED, ROUGH, SMOOTHED or WIPED surfaces), and (7) temper additives categorized as FINE, MEDIUM, or COARSE size.

For this research, the typical artefact class identifiers (i.e. Gallinazo and Mochica) were retained in order to explore variation among the attributes traditionally used to define each of the known assemblages, as well as to test assumptions about social differentiation and coexistence. After being reformulated as separate variables and assigned presence/absence values as Drennan (2009) proposed, the data was analysed using MYSTAT program, applying commonly used techniques for exploring similarity and difference among the variables in each ceramic tradition (see Table 1), to understand the basic relationship among variables in different

Tab. 1. Results of analysis of 139 observations using Jaccard and Simple Matching similarity, and Euclidian Distance techniques for exploring relationships between attributes present in across the combined Gallinazo and Mochica sample. Felds are highlighted in green, light green, yellow, orange and red, which correspond to 'very similar', 'somewhat similar', 'neither similar nor different', 'somewhat different' and 'not like' classes in the fuzzy classification system.

Jaccard Binary Similarity Coefficients

	Application	Extraction	Slip	Washed	Paint	Modelled	Moulded	Stamped	Burnished	Polished	Rough	Smoothed	Wiped	Fine Temper	Medium Temper	Coarse Temper
Gallinazo	0.707	0.817	0.173	0.48	0.055	0.463	0	0	0.063	0	0.131	0.254	0.38	0.137	0.295	0.384
Mochica	0.042	0.039	0.266	0.209	0.471	0.05	0.629	0.081	0.03	0.097	0.096	0.484	0.022	0.513	0.125	0.095

Simple Matching Binary Similarity Coefficients

	Application	Extraction	Slip	Washed	Paint	Modelled	Moulded	Stamped	Burnished	Polished	Rough	Smoothed	Wiped	Fine Temper	Medium Temper	Coarse Temper
Gallinazo	0.827	0.892	0.417	0.626	0.259	0.683	0.165	0.41	0.468	0.403	0.475	0.345	0.647	0.273	0.554	0.619
Mochica	0.173	0.108	0.583	0.374	0.741	0.317	0.835	0.59	0.532	0.597	0.525	0.655	0.353	0.727	0.446	0.381

Normalized Euclidean Distances (Difference*)

	Application	Extraction	Slip	Washed	Paint	Modelled	Moulded	Stamped	Burnished	Polished	Rough	Smoothed	Wiped	Fine Temper	Medium Temper	Coarse Temper
Gallinazo	0.416	0.329	0.763	0.612	0.861	0.563	0.914	0.768	0.73	0.773	0.725	0.809	0.594	0.852	0.668	0.617
Mochica	0.91	0.945	0.646	0.791	0.509	0.827	0.407	0.64	0.684	0.635	0.689	0.588	0.805	0.523	0.744	0.787

typological (Gallinazo or Mochica) categories. This laid the groundwork for the fuzzy classification system, where degree of membership is expressed in terms of the similarity between variables. Within this system of attribute classification, high similarity coefficients correspond to 'very similar' membership classes, while low similarity coefficients translate to 'not like' membership classes.

After the initial calculation of the Jaccard Similarity Coefficient, the next task was to visualize relationships among attributes. The values of the Jaccard Coefficient served as the baseline for determining the underlying shape, and classes into which the attribute data fit. Relationships among attributes in the Gallinazo and Mochica datasets are shown in the attribute matrix (Tab. 2) and in the tree chart (Fig. 3). An intriguing observation derived from the fuzzy sets shown here is that traditionally defined Gallinazo and Mochica artefacts do not fit precisely into prescribed taxonomic categories, but possess a great deal of overlap when certain attribute combinations are considered. This suggests that social differentiation cannot be most effectively assessed based on traditional ways of classifying artefacts.

Importantly, only a small percentage of the residential context sample (27% or 75 specimens) could be classified as Gallinazo or Mochica based on the traditional classification system because the remains are highly fragmentary and incomplete. Remaining artefacts in their partial states that could not be attributed to either culture were classified as unidentified. Such unattributed materials are typically left behind in stylistic and iconographic studies, which may account for a great deal of the confusion that remains concerning Gallinazo-Mochica social differentiation. However, within the new fuzzy classification system, it is possible to show quantitatively, that differentiation is far more subtle and overlapping.

Using the techniques outlined above, it was possible to incorporate a number of unidentified specimens that could be analysed spatially. Calculation of the Jaccard Coefficient made it possible to reclassify some specimens, ultimately assigning them to categories such as 'Somewhat Gallinazo' or 'Somewhat Mochica'. Because it was possible to quantify the relationship between attributes, a total of 26 unidentified fragments were found to fit partially into the reformulated Gallinazo and Mochica categories based on very incomplete data. While this still leaves over half the specimens unidentified in typological terms, they remain analytically significant entities. This ability to quantify and account for the uncertainty present in this fragmentary dataset, offering many new opportunities to better

Tab. 2. Jaccard matrix showing relationship among technological attributes observed in the Gallinazo/Mochica assemblage.

	Application	Extraction	Slip	Washed	Paint	Moulded	Modelled	Stamped	Burnished	Polished	Rough	Smoothed	Wiped	Fine T.	Medium T.	Coarse T.
Application	1															
Extraction	0.709	1														
Slip	0.202	0.209	1													
Washed	0.396	0.444	0	1												
Paint	0.052	0.089	0.333	0.124	1											
Moulded	0.01	0.018	0.132	0.17	0.242	1										
Modelled	0.413	0.456	0.141	0.31	0.095	0	1									
Stamped	0.015	0	0.024	0.041	0.049	0	0	1								
Burnished	0.061	0.068	0.125	0.013	0.071	0.022	0.042	0	1							
Polished	0	0.013	0.128	0	0.128	0.071	0.021	0	0	1						
Rough	0.157	0.139	0.057	0.156	0.098	0.075	0.13	0.045	0	0	1					
Smoothed	0.264	0.254	0.152	0.361	0.239	0.369	0.178	0.038	0	0	0	1				
Wiped	0.25	0.316	0.167	0.226	0.045	0	0.25	0.028	0	0	0	0	1			
Fine Temper	0.155	0.164	0.237	0.198	0.288	0.357	0.1	0.017	0.105	0.088	0.072	0.347	0.073	1		
Medium Temper	0.316	0.298	0.136	0.256	0.136	0.07	0.176	0.105	0.023	0.024	0.1	0.189	0.211	0	1	
Coarse Temper	0.265	0.31	0.143	0.314	0.096	0.11	0.328	0	0	0	0.154	0.216	0.213	0	0	1

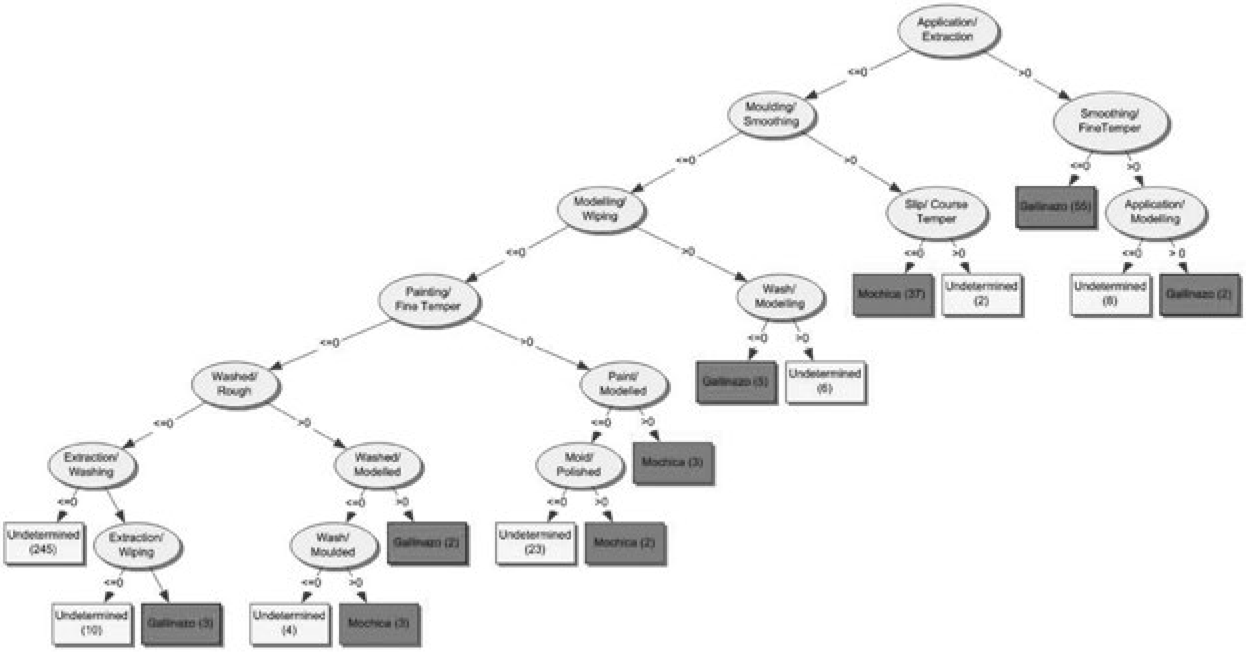

Fig. 3. Tree-chart based on Jaccard Binary Similarity Coefficient, showing various type of attribute combinations to which artefacts in each of the typological classes correspond. Tree chart originally generated in Weka 3 (http://www.cs.waikato.ac.nz/ml/weka/), using weka.classifiers.trees.J48 classifier for generating a decision tree (Quinlan 1993).

understand incomplete and ambiguous data more effectively in future works.

2.2 Spatial Analysis with Refined Fuzzy Dataset

Figures 4 a and b show the estimated position of only Gallinazo, and Mochica artefacts, collected from the surface of the residential sector of Songoy-Cojal in proposed functionally distinct architectural zones. In the left visualization, ceramic artefacts were mapped using the traditional typological system (i.e. stylistic or iconographic attributes defined as Gallinazo or Mochica artefacts) while in the right visualization, artefacts were mapped using the new fuzzy classification system. Comparing the maps, it is possible to see the type of homogeneity that occurs using traditional typological techniques. As the figure on the right shows, artefacts that were formerly 'unidentified'

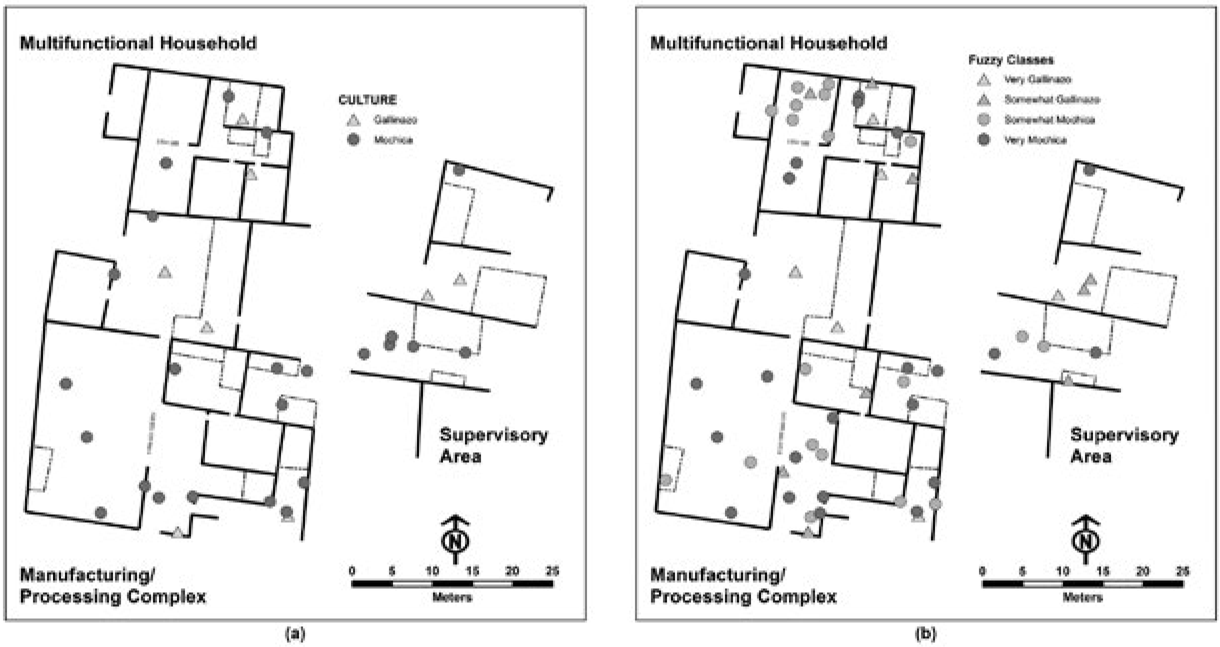

Fig. 4 a, b: (a) Gallinazo and Mochica artefacts mapped using traditional typological classification system. (b) Artefacts mapped using the fuzzy classification system.

now have a meaningful place somewhere between the upper and lower (0 and 1) fuzzy boundaries constituting Gallinazo and Mochica or Gallinazo/Mochica technological assemblage.

Immediately recognizable, is that attributes of both known and unknown specimens can be meaningfully visualized, based on membership degrees. The categories that possess members of more and less Gallinazo and Mochica specimens will be useful for determining what types of technologies correspond to what types of functional contexts when excavations are complete. At present, the assignment of values to attribute variations derived from the Jaccard Coefficient have helped to elucidate relationships among variables that were previously unknown and much unexpected, as shown in the tree diagram above, and as observed in the maps.

By adopting the Jaccard's Coefficient as the baseline from which to establish the fuzzy classification system, it was also possible to understand precisely which attributes contribute most, to distinguishing one technological group from another. In this way, the fuzzy taxonomic layer, helped to elucidate other important social dimensions of the dataset. While it is possible to see how the distribution of major attributes, that define the Gallinazo and Mochica assemblages, changes from one area of the site to another, such rare combinations may tell us something about the users, manufacturers or patrons of the artefacts. In fact, knowing precisely where specific types of [rare] attribute combinations co-occur is of particular interest given that the architectural configurations suggest a range of supervisory and household/habitational activities that may not correspond to typical elite/commoner dichotomies thought to characterize Gallinazo/Mochica social differentiation, but in fact, may reflect more complex types of worker/supervisor/patron/user interrelationships in which the lines between elites and commoners are not so clearly defined. The ability to map and visualize changing distribution of attributes that are relatively more and less 'Gallinazo' and 'Mochica' presents an exciting opportunity to explore ideas of coexistence and social differentiation at Songoy-Cojal in much greater detail than expected (Fig. 5).

The key advantage of using the fuzzy classification system in conjunction with the site GIS, is that other lines of data can be integrated as they come available. Because the fuzzy layer is both spatial and quantitatively meaningful, it is well suited for higher-level multivariate statistical analysis and to the incorporation of a wide range of data, from metrics and morphology, stratigraphy and construction sequence, to quantitative archaeometric datasets including INAA or portable X-ray Florescence Analyser (pXRF), which is already underway. Because ceramic artefacts are now understood as entities sharing relative degrees of membership, the fuzzy taxonomy adds a new dimension of detail and richness to the interpretation. Because it is possible to understand the relationship and similarities between attributes that entities possess, it is also possible to better understand the ways in which they are different, no matter how infrequent such differences or similarities may be.

As this study illustrates, through the development and implementation of a strategy that combines soft computing and spatial analysis techniques, it is possible to gain a clearer understanding of the shape and magnitude of variation in archaeological datasets, even those that start as nominal or categorical. With the aid of the fuzzy classification system and the Jaccard Coefficient, it was possible to quantify and begin analysis of previously unrecognized variation that exists in residential ceramics from the Songoy-Cojal site. Although a significant departure from traditional studies of Andean ceramics, exploration of the relationships among different

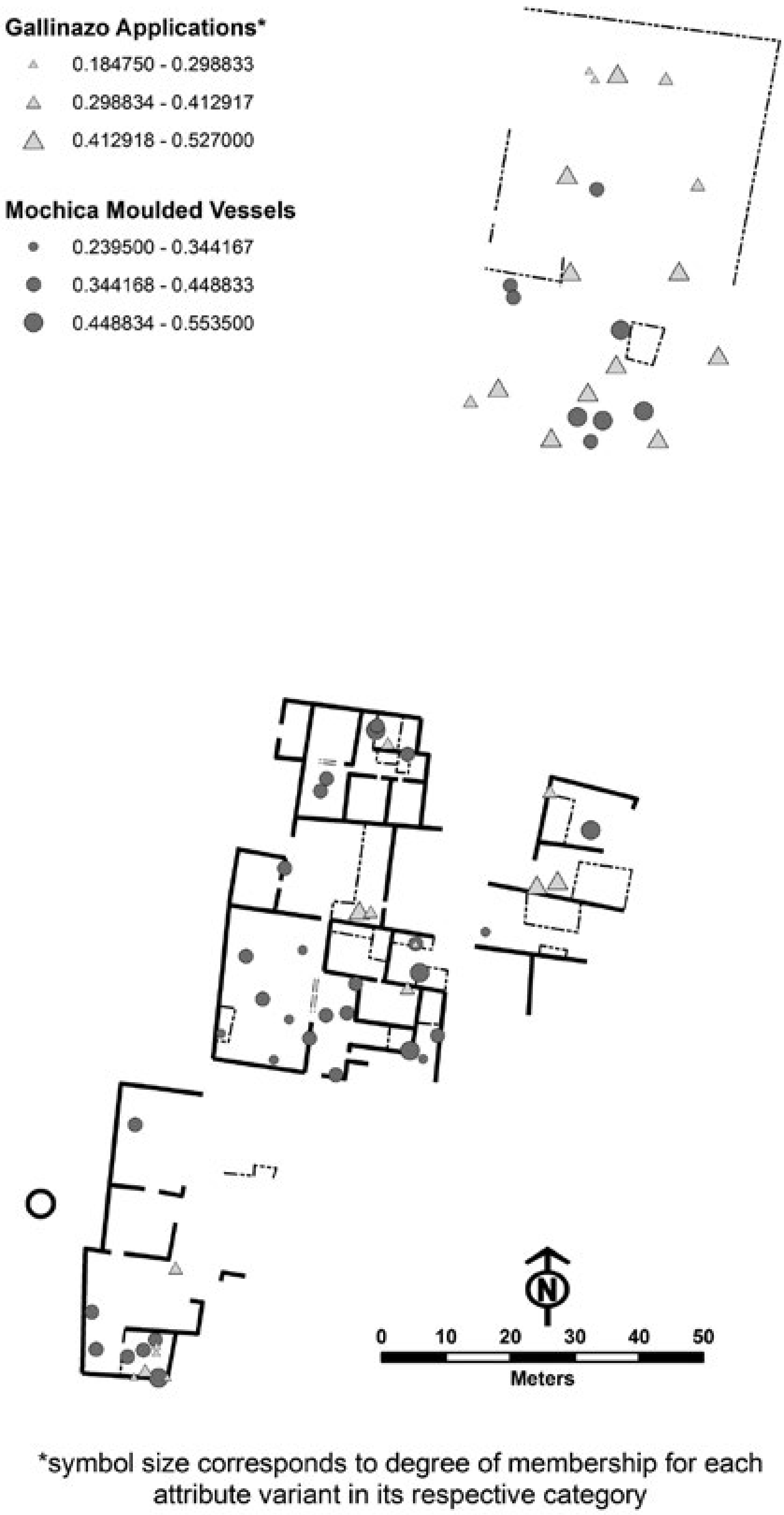

Fig. 5. Artefacts with characteristic Gallinazo applied designs (triangles) and Mochica mould and moulded vessel fragments (circles).

combinations of attributes appears to have the greatest potential for elucidating the many dimensions of Gallinazo/Mochica social differentiation that are present. Even with this singular line of evidence, the fuzzy classification of these artefacts has begun to alter previous perceptions. This said, perhaps the most important contribution of this case study is the ability to analyse data that has long been de-emphasized, overlooked and restricted to descriptive characterization and narrative explications alone.

3 Concluding Remarks

Many scholars fail to recognize the tenuous nature of the Gallinazo-Mochica dichotomy widely in use today. While there is a range of contradictory evidence that suggests this view has been put forth without adequate study, critical factors to consider are that few north coast archaeologists have dealt with non-funerary artefacts (see Kaulicke 2009; Shimada 2010) and few have worked in smaller valleys away from major urban centres. New data from preliminary fieldwork at Songoy-Cojal, which is comparatively small, rural, and poor when compared to major urban centres, has revealed a *much wider qualitative variability in Gallinazo ceramics than previously known*, which not only suggests that production was less tightly controlled at this mid-scale site but that a substantial amount of social differentiation was present. Furthermore, the residential assemblage departs significantly from the widely accepted idea of an inherently oppositional Gallinazo-Mochica dichotomy. As the new fuzzy classification clearly demonstrates, attributes known to be expressly Gallinazo or expressly Mochica comprise a very small part of the overall assemblage despite being highly prioritized in north coast studies.

While the persistent debate as to the nature of the Gallinazo-Mochica coexistence has been heavily shaped by a series of major biases and an overly simplistic dichotomous perspective, the discovery and ability to analyse the far greater variability in Gallinazo ceramics than previously recognized holds great potential for future research projects. The emphasis that was placed on technological attributes rather than typology, combined with the development and implementation of a fuzzy classification system for analysing ceramic artefacts, has drawn attention to the limitations of basing inferences on data that are biased and incomplete. Here, the importance of recognizing that artefacts cannot be effectively discussed in binary terms, when they are in fact much more nuanced and dynamic like the people that created and used them has been emphasized. With the fuzzy innovation, this investigation shows is that it is possible to adopt a wide range of new strategies and techniques for the study of our archaeological data, and that many are well equipped to capture important nuances.

With this in mind, approaches which are designed to explore uncertainty and relationships between datasets are most appropriate and valuable, yet they are often overlooked in more traditional investigations. The application of a fuzzy classification system which identifies meaningful nominal attributes in terms of membership degrees rather than expressions of presence or absence, reveals nuanced similarities and differences in the north coast ceramic data that more closely approximate the observed technological diversity and archaeological reality of this setting. The approach advocated here holds much potential to be more widely applied. In particular, because the fuzzified dataset is numerical, it can be used in conjunction with broader ranges of multivariate quantitative data, such as chemical compositional (e.g. INAA or pXRF), stratigraphic, architectural seriation or radiocarbon dates derived from excavation units.

Ultimately, while our abilities to address complexities of dynamic social interrelationships are made stronger by analytical tools that become more powerful every day, the present work proposes a foundational shift in the way basic nominal attributes that characterize archaeological data in a meaningful way, are conceived and studied. While only a preliminary step, this work has begun to eliminate a number of strong biases that have become increasingly more entrenched over the past century. Techniques such as the one presented in this paper may serve useful to other researchers who share similar concerns.

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Data discussed in this manuscript is based on the prospection activities carried out during the 2010 field season of the Proyecto de Investigacion Arqueologica Zaña (PIAZ), co-directed by Natalia Guzman and Kayeleigh Sharp. I wish to recognize and thank Melissa Litschi who assisted with data collection in the laboratory at the Museo Nacional Sicán in Ferrenafe, Peru in 2013 and 2014. I also wish to thank my reviewers for their helpful comments and recommendations, and my dissertation advisor, Izumi Shimada for his continued support.

Bibliography

Albrecht, J. 2007. *Key Concepts and Techniques in GIS*. SAGE Publications.

Baquedando, E. and Orton, C. 1990. *Similarities Between Sculptures Using Jaccard's Coefficient in the Study of Aztec Tlaltechuhtli.* Institute of Archaeology, UCL AC UK.

Barceló, J. A. 1996. Heuristic Classification and Fuzzy Sets. New Tools for Archaeological Typologies. *Acta Praehistorica Laidensia* 28, 1996.

Bennett, W. C. 1939. *Archaeology of the North coast of Peru; an account of exploration and excavation in Viru and Lambayeque valleys,* New York, American Museum of Natural History.

Chen, G., Wei, Q., Kerre, E. E. 2000. Fuzzy Data Mining: Discovery of Fuzzy Generalized Association Rules. In G. Bordogna and G. Pasi (eds.), *Recent Issues on Fuzzy Databases.* Warsaw, Physica-Verlag, A Springer-Verlag Company.

Drennan, R. E. 2009. *Statistics for Archaeologists: A Common Sense Approach.* Springer.

Emshwiller, E. 2006. Genetic Data and Plant Domestication. In Zeder, M., Bradley D.G., Emscwiller, E., Smith B.D. (eds.), *Documenting Domestication: New Genetic and Archaeological Paradigms.* Unversity of California Press.

ESRI 2015. *Hot Spot Analysis (Getis-Ord Gi*).* Available: *http://pro.arcgis.com/en/pro-app/tool-reference/spatial-statistics/hot-spot-analysis.htm*.

Jaccard, P. 1912. The distribution of the flora of the alpine zone. New Phytologist 11: 37-50.

Kaulicke, P. 2009. Concluding Remarks. In Millaire, J. F. and Morlion, M. (eds.), *Gallinazo : An Early Cultural Tradition on the Peruvian North Coast.* Los Angeles, Cotsen Institute of Archaeology Press.

Khan, M. S., Muyeba, M., Coenen, F., Reid, D., Tawfik, H. 2011. Finding Associations in Composite Data Sets: The CFARM Algorithm.

Klir, G. J. 2004. Fuzzy Logic: A Specialized Tutorial. In R. V. Demicco, G. J. Klir (eds.), *Fuzzy*

Logic in Geology: 1-9. Amsterdam, Boston, Elsevier Academic Press.

Larco Hoyle, R. 1945. *Los mochicas (pre-chimu, de Uhle y early chimu, de Kroeber),* Buenos Aires, Sociedad Geográfica Americana.

Nguyen, H. T. and WALKER E. 2000. *A First Course in Fuzzy Logic*. 2nd ed. Chapman and Hall, Boca

Raton, FL.

Qu, X. and Zhang, G. 2008. *Measuring the Convergence of National Accounting Standards with International Financial Reporting Standards: The Application of Fuzzy Clustering Analysis*. Available at: http://ssrn.com/abstract=1295884 [Accessed: 26 Feb 2015].

Quilter, J. and Castillo, L. J. 2010. *New Perspectives on Moche Political Organization*, Washington, D.C., Dumbarton Oaks Research Library and Collection.

Quilter, J. and Koons, M. L. 2012. The Fall of the Moche: A Critique of Claims for South America's First State. *Latin American Antiquity,* 23: 127-43.

Quinlan, R. 1993. *C4.5: Programs for Machine Learning*. San Mateo, CA, Morgan Kaufmann Publishers.

Shimada, I. 2010. Moche Sociopolitical Organization: Rethinking the Data, Approaches, and Models. In Quilter, J. and Castillo B, L. J. (eds.) *New perspectives on Moche political organization.* Washington, D.C., Dumbarton Oaks Research Library and Collection.

Smithson, M. 1987. *Fuzzy Set Analysis for Behavioral and Social Sciences*. Recent Research in

Psychology. New York, Springer-Verlag.

Solheim, W.G. II. 2006. *Archaeology and Culture in Southeast Asia: Unraveling the Nusantao*. University of the Philippines Press.

Swenson, E. and Warner, J. P. 2012. Crucibles of power: Forging copper and forging subjects at the Moche Ceremonial Center of Huaca Colorada, Peru. *Journal of Anthropological Archaeology,* 31: 314-33.

Ubbelohde-Doering, H. 1957. *Der Gallinazo-Stil und die Chronologie der altperuanischen Frühkulteren,* München, Verlag der Bayerischen Akademie der Wissenschaften, in Kommission bei Beck.

Willey, G. R. 1953. *Prehistoric settlement patterns in the Virù Valley, Peru. Bureau of American Ethnology Bulletin 155 ,* Washington, DC, Smithsonian Institution.

Zadeh, L. 1965. Fuzzy Sets. *Information and Control,* 8: 338-53.

Dynamics of the Settlement Pattern in the Aksum Area (800-400 Bc). an ABM Preliminary Approach

Martina Graniglia[(1)], Gilda Ferrandino[(2)], Antonella Palomba[(1)], Luisa Sernicola[(3)], Giuseppe Zollo[(1)], Andrea D'Andrea[(2)], Rodolfo Fattovich[(2)], Andrea Manzo[(2)]

[1] Università degli Studi di Napoli 'Federico II'
[2] Università degli Studi di Napoli 'L'Orientale'
[3] Hiob Ludolf Centre for Ethiopian Studies, Hamburg University

Abstract: In order to test the theories explaining the diachronic changes of the settlement pattern in the Aksum area (Ethiopia), a team, composed of African archaeologists and engineers, started an interdisciplinary research project. The project is based on the use of an Agent Based Modelling approach to create a dynamical settlement model of the earliest phases of development of the hierarchic societies in the region of Aksum (800-400 BC).

The model, based on palaeo-climatic, palaeo-environmental, geological, archaeological and ethnographical data, simulates different settlement patterns describing the rate of growth of population, the demographic density and aggregation at different scales and also considering the real distribution of resources on the ground. The preliminary results show how this approach can be useful for testing different hypothesis, as the outputs can be easily compared with real parameters observed in the available data. Moreover, new questions and issues emerged from the observation of tipping points which seem to determinate the rate and type of resilience of the simulated ecological system in the model.

Keywords: Agent Based Modelling, Simulation, Dynamic System, Aksum

Introduction

From about the mid-1st millennium BC, the area of Aksum, Central Tigray, northern Ethiopia, developed as one of several polities of the Tigrean plateau, progressively emerging as the capital city of a vast kingdom that flourished between the 1st century BC and the 7th/8th century AD (Fig.1). At its greatest extent, Aksum stretched its control as far as the Red Sea coast to the north-east, the Eritrean/Sudanese lowlands to the west and the Takazze River to the south, including during the first half of the 6th century AD part of south-western Arabia (Phillipson 2012: 47-50).

The appearance and evolution of complex societies on the highland regions of the northern Horn of Africa during the 1st millennium BC is strictly related to the interregional economic dynamics which had long before developed along the Red Sea and the Nile Valley, and that Aksum's emergence and expansion parallels its participation in long-distance exchanges (Fattovich *et al.* 2000: 21-6). Starting from the mid-1st millennium BC, Aksum was included in an exchange circuit which included the northern Horn of Africa, the Nile Valley, the Mediterranean, Southern Arabia, and, by the 1st/2nd century AD, the western coastal regions of India. The prominent role played by Aksum in these long-distance exchange activities significantly contributed to the increase of its social complexity and to the consolidation of its economic and political leadership over the Tigrean plateau.

Beside the traces of international exchanges, archaeological and historical sources provide further direct evidence of Aksum's progressive power and expansion, proving that during the 1st millennium AD the Aksumite kings erected unique monuments utilizing substantial quarrying and engineering skills and conducted victorious military campaigns in and out of Africa (Marrassini 2014).

1 The archaeological area of Aksum

Between 2005 and 2006 a systematic, comprehensive survey of the entire territory of Aksum was conducted in the framework of the Italian Archaeological Expedition at Aksum of the University of Naples 'L'Orientale' directed by Rodolfo Fattovich,[1] and of the World Bank *Ethiopian Cultural Heritage Project – Aksum branch – Site Planning and Conservation Component*, co-directed by Rodolfo Fattovich and Takla Hagos (Fattovich, Takla Hagos 2005). The data collected during these two intensive surface survey projects concurred to provide a complete archaeological map of the area of Aksum and to reconstruct changes that occurred in the ancient occupational dynamics and land-exploitation strategies in the area of Aksum in the light of the results of recent researches and of a well established chronological and cultural sequence (Bard *et al.* 2014: 285-313).

In addition, geological, geo-archaeological and environmental studies enabled the generation of thematic maps on soil productivity[2] (Schmid *et al.* 2008: 93-101), water resources distribution and slope gradient.

The combined analysis of all these data has resulted in a general reconstruction of the social, economic and political dynamics which characterized the emergence, development and decline of the so-called 'Kingdom of Aksum' and of the reasons for the location of its political core in the western sector of the generally rich highlands of northern Ethiopia. Favourable environmental and climatic conditions, namely the

[1] The survey by the Italian Archaeological Expedition at Aksum was the continuation of a project launched in 2000 by the Italian-American joint research project at Bieta Giyorgis co-directed by R. Fattovich and K. A. Bard (Fattovich, Bard 2002: 32-3).

[2] Soils classification has been also compared to the traditional system of soil evaluation presently used by local farmers.

Fig. 1. Map of Ethiopia and geographical position of Aksum.

abundance of water resources and productive soils (Sernicola 2008: 157-67; Sernicola, Sulas 2012: 562-3; Sulas *et al.* 2009: 2-15; Takla Hagos 2010: 139-56, the occurrence of a relatively stable humid phase between the 5th century BC and the 5th century AD (Machado, Gonzalez, Genito 1998: 312-21), and the effectiveness of a long established economic system based on mixed agricultural products and domesticated livestock allowed some Aksumites to invest their economic surplus in gaining control over the procurement and long-distance distribution of African goods and products. In this perspective, Aksum's location at the hub of a radiating network of river valleys along which a complex system of intra-regional and inter-regional communication and exchange routes developed undoubtedly played a significant role.

Fig. 2. The Aksum area.

2 A new approach: Agent Based Model (ABM)

In order to better test the archaeological theory about the evolution of the settlement pattern and the emergence of a progressively more centralized hierarchical society in the area of Aksum, a new approach based on ABM has been undertaken.

ABM is a useful method for simulating dynamics of a system's behaviour and observing the direction of change in respect of a case of study (Lake 2014; Wurzer *et al*. 2014)). It is based on agents that in archaeological research are frequently considered human beings (individuals or groups). Agents have knowledge, experience and reasoning and they act in artificial environment and interact reciprocally and with environment. This feedback produces a set of behaviours that define how the system evolves. In an archaeological and historical perspective, human beings, through interaction, create a network characterized by cluster of aggregates that change over time. ABM makes the archaeological data interpretations more explicit by codifying through rules time, environment and agents.

Furthermore, computer simulation generates a virtual human aggregation in a artificial environment whose patterns then could be compared with the archaeological hypothesis. To reach this target it is necessary to model our archaeological knowledge starting by defining a temporal and spatial resolution. At this stage of the research we focused on the passage between the pre-Aksumite and the Proto-Aksumite periods (ca. 800-50 BC), the latter being the formative phase of the subsequent Aksumite kingdom and culture.

GIS analysis carried out in a previous research on the area showed that since the 1st millennium BC, settlement locations were always selected according to three major environmental factors (Fig. 3):

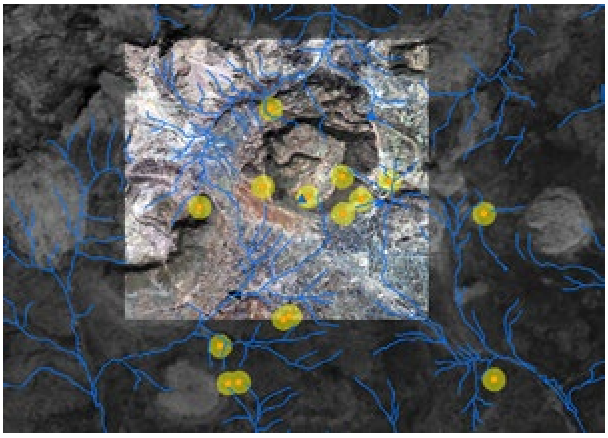


Fig. 3. Settlement pattern along the river network during the Proto-Aksumite phase (elaborated by Sernicola 2008).

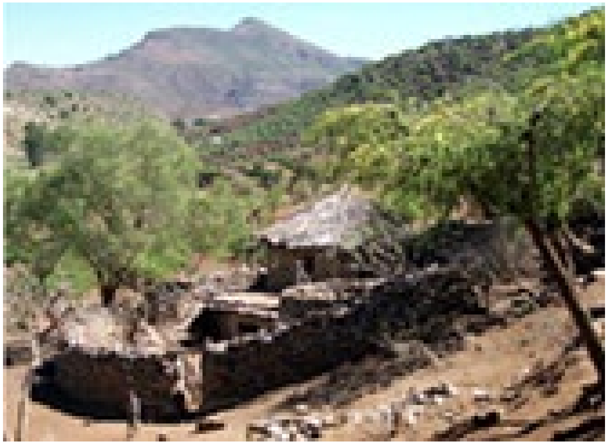


Fig. 4. Modern compound.

A. close proximity to water resources (all settlements were located no more than 250m from rivers, streams or water cisterns);

B. close proximity to productive soils (all settlements were located within or along the borders of more fertile soils generated by volcanic rocks);

C. slope gradient (Sernicola, 2008; Sernicola, Sulas 2012).

Data from field survey and GIS-based settlement pattern analysis were fundamental for the implementation of the ABM simulation as they provided information on the different types of settlements, their density and quantitative changes through time.

Geo-archaeological investigations suggest a remarkable stability and resilience of the landscape in the region of Aksum over the whole 1st millennium BC/1st millennium AD period (Ciampalini *et al.* 2008: 18-27; French *et al.* 2009: 218-33). Results from pollen analysis point to a vegetation cover characterised by a predominance of herbaceous species and small trees; palaeo-zoological and archaeological evidence demonstrates that during the pre-Aksumite period local communities already relied on the ox-plough agricultural complex and suggests the presence of a relatively wide range of cultivated crops.

Regarding the choice of agent and their relative granularity (individual, group, population), which involves specific logics of interaction, settlement pattern reconstruction suggests that during the 'pre-Aksumite' period (ca. 800-400 BC), the settlement pattern at Aksum was characterized by scattered isolated compounds, hamlets and small villages (Sernicola, 2008; Sernicola, Sulas, 2012). The difference between these three levels of aggregation depends on the size of the sites, witnessed by archaeological investigations, and in a social view on the number of households. For these reasons we decided to identify as low level of aggregation the household.

Available materials from surface surveys and archaeological excavations point to the absence in the area of a strong political focus in this period although a social hierarchy presumably existed, as suggested by the presence of structures with more massive walls and administrative devices in the pre-Aksumite levels at Kidane Mehret (Phillipson 2000). In this first phase, during which a hierarchical society (traditionally identified as D'MT)[3] emerged and declined on the Ethiopia/Eritrean highlands,[4] Aksum was apparently a minor centre based on agriculture with respect to nearby sites,[5] where evidence of temples and other monumental buildings has been recorded. In our model we assumed all inhabitants of the Aksum area were farmers, because no archaeological evidences testify a hierarchy.

The agents have properties that qualify them as households; these properties are relevant in defining set of rules of interaction (agent-agent and agent-environment) that generate the set of behaviours.

As pre-Aksumite and Proto-Aksumite social structures are still scarcely known, the archaeological evidence has been integrated with ethnographic evidence (Fig. 4). Particularly, the ethnographic investigations conducted in 1974 provided significant, additional information on the social environment: general dimension of households, creation of new households, public spaces, kinship relations and neighbourhood policy, and subsistence economy. So far very few can be said on ancient land tenure strategies due to the paucity of available historical data.

The results of simulations in terms of demographic growth, number of aggregations and type of aggregations are compared with archaeological data corresponding to the Proto-Axumite period.

Between 400-50 BC, during the Proto-Aksumite period, a changed settlement pattern possibly mirrors substantial social and economic changes. The increase in the number of settlements and of their spatial aggregation, the appearance

[3] For the debate on the so-called 'Pre-Aksumite' culture and for a comprehensive, updated discussion on the D'MT, see Fattovich 2012: 1-60 and Phillipson 2009: 257-74.

[4] Having its religious/political core at Yeha.

[5] I.e. Seglamen and Hawelti, respectively 12km to the south-west and 15km to the south-east of Aksum.

on the hilltop of Beta Giyorgis of a monumental residential complex and of a royal cemetery point to a tendency towards a social hierarchy in the area. The presence of a wide range of imported items from the Nile Valley suggests that this process is probably related to the gradual increase of the role played by Aksum in inter-regional exchange networks.

3 Methods

In order to understand the dynamics involved in the formation of the Proto-Aksumite society, some essential aspects of the rural population have been analysed. In particular we took into account climatic and environmental factors which focus on mechanisms stimulating aggregation process. The model describes agents farming the landscape, aggregating in settlements, sharing resources with other agents or settlements and moving to new locations. A bottom-up design technology has been used in modelling the evolution of settlement systems. This approach is mainly based on pre-decided set of rules for individual behaviour and local interaction, starting from a set of rural settlements.

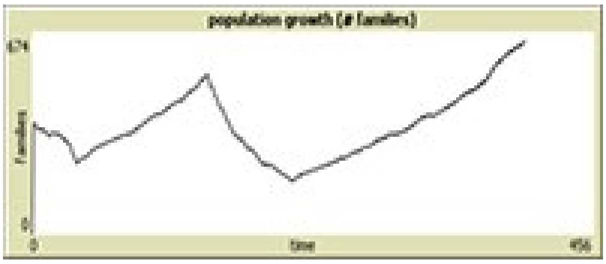
The model or the settlement area of Axum was implemented by Netlogo, a programmable modelling environment for simulating natural and social phenomena. This software has been already used to build many models to simulate the interaction between environment and human in a specific time-span (Janssen 2009)

We may briefly sum up the characteristics of the model according to the categories of ODD methodology (Grimm *et al.* 2006), which stands for 'Overview, Design concepts and Details'. Of these categories, the Overview category is broken down into three sections: Purpose, State Variables and Scales and Process Overview and Scheduling; and the Details category has 3 sections: Initialization, Input and Submodels.

Purpose. Three concepts are defined: i) The 'compound' as an isolated household. It does not share its space with other agents and has no neighbours; ii) The 'hamlet' as an organized space consisting of more than one household. In the simulation, hamlets correspond to patches that include a number of agents >1; iii) a 'village' as an agglomeration of hamlets. Archaeological researches showed that these different types of spatial aggregation co-existed; we can find isolated compounds populated for a long period by a single household, and meantime aggregations of multiple households in hamlets or villages. The purpose of the Agent-based model is to find possible simple explanations of the dynamics that result in new hamlets and villages, starting from a near-random distribution of families in compounds.

State Variables and Scales. The geographical space is represented by a grid of 100 x 100 cells. Each cell or patch reproduces the natural environment of Aksum region, with plains, hills, and a network of rivers. Moreover, patches are characterized by natural and agricultural resources which can be exploited by the population. The moving agents are the Families. They reproduce and move within the geographical space according to processes defined as follows. In the simulation time zero corresponds to the Pre-Aksumite period (ca. 800 BC). The model runs for 400 years in annual time steps, until the Proto-Aksumite period. During this time-span the population organize itself in groups. Each aggregate, such as compound, hamlet and village, includes only one agent moving in a 2D virtual landscape Process Overview and Scheduling. There are four processes defined: i) 'harvesting': updating of resources of the agent. The amount is equal to the productivity of the patch where the agent lives in. ii) 'reproducing': updating of household of reproductive age according to the number of the members. iii) 'settling': 90% of the new households occupies the patch near to their family of origin, sharing the same landscape and the same resources. A percentage equal to the mobility rate is localized away from the family of origin. iv) 'aggregating': families, without resources, are aggregate to the neighbours.

Tab. 1. Growth rate of household based on the parameters: mobility rate 0.1, growth rate of population 2, and periods of drought and epidemics.



Design Concepts. Families are the moving agents, while territorial cells are the fixed agents (patches) of the simulation. The parameters controlling the simulation are: i) two shock events: drought (2 values: ON/OFF) and epidemy (2 values: ON/OFF); ii) mobility-rate (3 values: 0.01 (minimum), 0.05 (intermediate), 0.10 (maximum)); iii) birth-rate (3 values: 2, 3, 4 years). These parameters control the following variables: i) the demographic growth of agents; ii) the explorative capability of agents; iii) the exploitation capability of agents; iv) the resilience of agents. Experiments aim at testing the space of all the possible 'behaviours' of the models.

We made 18 different experiments, according to significant combinations of parameters. Any experiment was replicated 50 times. Each run lasted 400 ticks. For each run we collected the average and the variance of the following variables: i) total number of agents; ii) the number of isolated compounds; ii) the number of hamlets; iii) the density agents. These outputs have been tested through a bilateral T-Student test in order verify the accordance between the 'field' value and the 'virtual-lab' value. Most significant experiments were characterized by a birth-rate equal to 2, mobility-rate equal to 0.1 and shock events ON.

Initialization and Input. Inputs of simulations are Natural-Resources (soil productivity and water resources) and Families. Both these variables are distributed on the territory' cells. Families may share the same patch if the soil productivity and proximity to water resources (< 250 m) let them to survive. The Montecarlo method has been introduced to avoid the deterministic effects of simple assumptions.

No submodels are present.

4 Results

Thanks to this approach we tested aggregation in an ecological perspective. Simple rules of individual behaviour and local

TAB. 2. SIMULATION RESULTS WITH MOBILITY RATE 0.1, GROWTH RATE OF POPULATION 2, AND PERIODS OF DROUGHT AND EPIDEMICS.

	HOUSEHOLDS	COMPOUNDS	HAMLETS	DENSITY
MEDIA 50 RUN	899,06	6,2	27,34	8,9906
VAR	197534,4249	28	253,3718367	19,75344249
SIGMA	444,4484502	5,291502622	15,91765802	4,444484502
μ0 =	726	6	12	7,7
t=	2,753342924	0,267261242	6,814456004	2,05331352
g1	0,90	1,04	0,71	0,90
g2	0,32	0,10	-0,25	0,32
g1/s1	2,58	2,97	2,03	2,58
g2/s2	0,46	0,15	-0,36	0,46
intervals	[793; 1004]	[4.9; 7.5]	[23.6; 31.2]	[7.9; 10]

interaction explained the self-organization of the system and specific parameter values the quantitative distribution of settlements. High mobility rate 0.1, high growth rate of population 2, and periods of drought and epidemics reproduced rather well a plausible distribution of settlements during the examined 400 years, very similar to the reconstruction taken by the archaeological evidences (tab 1 and tab. 2). The exploration dynamics explain the high mobility rate and give rise to exploitation capacity of resources, producing self-organization of the agents. The high demographic growth, depending on the reproduction rate, is normal in an ancient rural community, which needs labour force. The simulation shows a growth rate of 2 showing an acceptable value of the population over the Proto-Aksumite period. The ethnographical studies on the rural traditional households in the Tigray region, which have a lifestyle similar to the Aksumites in terms of space organization and land management, suggest a growth rate of 3.

The graph in Tab. 1 shows the growth rate of the households over all Pre-Aksumite period. The line in the graph is one of the possible trajectories that the system can assume after each run based on a particular set of values. In this simulation the values of variables sent on mobility rate =0.1, reproduction=2 and shock events=ON, have produced an interesting patterns that, notwithstanding it includes some negative points, seems show a constant increasing of the population. While the shock event push down the growth rate of households, the reproduction and the mobility indexes represent the capability of the system to adopt a flexible behaviours able to equalize the increasing.

The mobility allows the agents to explore all the space, producing not only the formation of new settlements or isolated compounds but, in our case, the growth of particular sites as well as the formation of hubs. The high mobility rate is a crucial factor explaining the movement of individuals or groups in the territory. The agents explore and exploit new opportunities. According to archaeological data, the Aksumite economy was based on the farming management, the use of large mammals (oxen) to plough the fields, and small mammals (goats and sheep).

As the ecological rules appear to better explain the settlement pattern of early Proto-Aksumite time, most likely the élite component did not influence the land tenure and the aggregation of the rural system. The archaeological evidences record no élite administrative/residential buildings at Aksum between 800 and 400 BC suggesting that other areas (Yeha, Matara, Seglamen, Houlti) served as political foci at that time. Only between the late pre-Aksumite and early Proto-Aksumite period (ca. 500-400 BC) traces of a local élite progressively appear as a starting point of a process of progressive hierarchy which culminated with the emergence of Aksum as a capital city (Sernicola 2008; Sernicola, Sulas 2012). Probably the presence and increase of the élite component was a product of self-organization of the system, the growth rate of population and aggregations that, in a complex network, induced the formation of preferential hubs.

6 Conclusion

The results reached in this first preliminary work are encouraging. In the future we plan to investigate when the system reached the threshold and innovations became necessary for carrying out the growth of the system and developing its hierarchical structure. For doing this, it is necessary to take into consideration further aspects, such as land-management strategies, joint efforts, exchange networks. Furthermore, the properties of agents will be implemented by considering also different specializations (potters, lithic workers, merchants, etc.). Climatic fluctuations will be introduced as well. All these elements, codified as set of rules and/or parameters, would provide different behavioural scenarios. Our goal is to increase the number of simulations in order to observe the possible evolution(s) of the system, outline the trajectories of the changes and, hopefully, observe the emergence of new properties and relationships within Aksum's ancient socio-natural system.

Bibliography

Bard, K. A., Fattovich, R., Manzo, A., Perlingieri, C. 2014. The chronology of Aksum (Tigray, Ethiopia): a view from Bieta Giyorgis. *Azania*. 49 (3): 285-316.

Ciampalini, R., Billi, P., Ferrari, G., Borselli, L. 2008. Plough-marks as a tool to assess soil erosion rates - A Case-Study in Axum (Ethiopia). *Catena*, 75 (1): 18-27.

Fattovich, R. 2012. The northern Horn of Africa in the first millennium BCE: local traditions and external connections. *Rassegna di Studi Etiopici*, IV (Nuova Serie): 1-60.

Fattovich, R., Bard, K. A. 2002. Scavi archeologici nella zona di Aksum. K. Bieta Giyorgis. *Rassegna di Studi Etiopici*. 45: 23-36.

Fattovich, R., Tekle Hagos, A. 2005. *Ethiopian Cultural Heritage Project - Aksum branch - Site Inventory and Documentation Component - Archaeological Survey - Report of Activity, October-November 2005*, technical report submitted to HYDEA s.r.l., Florence, Italy.

Fattovich, R., Bard, K., Petrassi, L., Pisano, V. 2000. *The Aksum Archaeological Area: a Preliminary Assessment*. Naples: Istituto Universitario Orientale.

French, C. I., Sulas, F, Madella, M. 2009. New geoarchaeological investigations of the valley systems in the Aksum area of northern Ethiopia. *Catena*. 78 (3): 218-33.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., Robbins, M. M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R. A., Vabø, R., Visser, U., Deangelis, D. L. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198, 1-2: 115-26.

Janssen M. A. 2009. Understanding Artificial Anasazi. *Journal of Artificial Societies and Social Simulation* 12, 4. Available at: http://jasss.soc.surrey.ac.uk/12/4/13.html [Accessed: 15th November 2015].

Lake, M. W. 2014. Trends in Archaeological Simulation. *Journal of Archaeological Method Theory* 21: 258-87.

Machado, M. J., Gonzalez, A. P., Benito, G. 1998. Palaeoenvironmental changes during the last 4000 years in the Tigray, Northern Ethiopia, *Quaternary Research* 49: 312-21.

Marrassini, P. 2014. *Storia e leggenda dell'Etiopia tardoantica*. Brescia, Paideia Editrice.

Phillipson, D.W. 2009. The first millennium BC in the highlands of northern Ethiopia and south-central Eritrea: a reassessment of cultural and political development. *African Archaeological Review*. 26: 257-74.

Phillipson, D.W. 2012. *Foundations of an African Civilisation - Aksum & the Northern Horn 1000 BC-AD 1300.* Woodbridge, Boydell & Brewer Ltd.

Phillipson L. 2000. Contributions on stone dressing, lithics, *Mestah Worki*, rock engravings, ivory-working techniques and site distributions. In D. W. Phillipson (ed.) *Archaeology at Aksum, Ethiopia, 1993-97* (2 vols.): 254-66, 352-63, 408-11, 421-3, 433-47, 449-53, 460-8, 470-1. London, British Institute in Eastern Africa & Society of Antiquaries.

Sernicola, L. 2008. *Il modello d'insediamento sull'altopiano tigrino (Etiopia settentrionale/Eritrea centrale) in epoca Pre-Aksumita e Aksumita (ca. 700 a.C. - 800 d.C.). Un contributo da Aksum*. Unpublished PhD thesis, Dipartimento di Studi e Ricerche su Africa e Paesi Arabi, Università degli Studi di Napoli 'L'Orientale', Napoli.

Sernicola, L., Sulas, F. 2012. Continuità e cambiamento nel paesaggio rurale di Aksum: dati archeologici, etnografici e paleoambientali. In A. Bausi, A. Brita, A. Manzo (eds.), *Aethiopica et Orientalia - Studi in onore di Yaqob Beyene, Studi Africanistici, Serie Etiopica* 7: 549-73.

Schmid, T., Magaly, K., Di Blasi, M., Hagos, M. 2008. Spatial and Spectral Analysis of Soil Surface Properties for an Archaeological Area in Aksum, Ethiopia, Applying High and Medium Resolution Data. *Catena* 75: 93-101.

Sulas, F., Madella, M., French, C. 2009. State formation and water resources management in the Horn of Africa. *World Archaeology* 41: 2-15.

Tekle Hagos, A. 2010. The choice of Aksum as a metropolis. *Annales d'Ethiopie* 25: 139-56.

Wurzer, G., Kowarik, K., Reschreiter, H. 2014. *Agent-based Modelling and Simulation in Archaeology*. Wien, Springer

OpenABM http://www.openabm.org [Accessed: 15th November 2015].

An Application of Agent-Based Modelling and GIS in Minoan Crete

Angelos Chliaoutakis[(1,2)]
angelos@ims.forth.gr

Georgios Chalkiadakis[(2)]
gehalk@intelligence.tuc.gr

Apostolos Sarris[(1)]
asaris@ims.forth.gr

[1] Laboratory of Geophysical - Satellite Remote Sensing and Archaeo-environment (Lab GeoSat ReSeArch),
Institute for Mediterranean Studies - Foundation for Research and Technology, Hellas (IMS-FORTH), Rethymno, Greece
[2] Technical University of Crete (TUC), Chania, Greece

Abstract: Agent-based modelling, including simulation within a GIS environmental framework, has been increasingly in use in Archaeology during the past decade, as a tool for assessing the plausibility of (alternative) hypotheses regarding ancient civilizations within a specific geographical context. In this paper, we describe a generic agent-based model for simulating ancient societies. We employ this model to evaluate the impact of different social organisation paradigms and agricultural strategies population dynamics and evolving spatial distribution of settlement locations. As a case study, we employ our model on an artificial ancient society during the Bronze Age (Minoan civilization) located in the area of Malia at Eastern Crete. Model parameter choices are based on archaeological studies, but are not biased towards any specific assumption. Results over a number of different simulation scenarios demonstrate increased sustainability for settlements adopting a socio-economic organisation model based on self-organisation.

Keywords: Agent-based modelling, GIS-based model, Computational archaeology, Self-organisation

Introduction

Nowadays, computer science and modern information systems provide us with the opportunity to build virtual laboratories in which we can address various questions and hypotheses about (historical) social and environmental change. Such transitions are essential for improving our current understanding of human behaviour and history. At the same time, knowledge of historical events that have actually occurred provides the possibility of evaluating the accuracy of specific computational models or simulations. As such, computational archaeology has emerged as the discipline that focuses on the study of ancient societies via the use of computer models and simulations. Archaeology is a data oriented discipline, with a strong focus on the collection of material information for the study of past human societies; and computational archaeology builds on this information in order to enhance our understanding of the long-term human behaviour and behavioural evolution, via modelling and simulating the socio-environmental processes at play.

In the context of computational archaeology, the concept of agent-based modelling (ABM)[1] has drawn much attention over the last two decades (Lake 2014). ABMs define a social system as a collection of agents, which represent individual entities within a wider population. These entities are assumed to be acting autonomously, and may be able to learn and adapt in their environment. Agent actions occur in time and space, affecting the wider environment while individuals cooperate and/or compete with each other. ABMs can model systems that are either highly diverse or heterogeneous in terms of both agent abilities and underlying environment, and allow the study of interactions and (potentially emerging) behaviours that would be difficult to examine by using simple aggregate styles of representation (Batty *et al.* 2012). ABM is particularly appealing when coupled with a GIS, as it promotes a style of modelling that reflects the characteristics of our real world, in a way that appears to fit well with existing explanations of how spatial structures such as settlements, cities, states, our global system and all its natural components evolve.

In this work, we present a functional ABM system prototype for simulating an artificial ancient society of agents residing at the Malia area of the island of Crete during the Early Bronze Age. Agents correspond to 'households', which are considered to be the main social unit of production for the period (Whitelaw 2007). The ABM attempts to assess the influence of different social organization paradigms on population growth by exploring the sustainability of agricultural technologies in use at the time, and examine their impact on population dispersion. Importantly, the model evaluates a social paradigm of agents *self-organizing* into a hierarchical social structure, and continuously re-adapting the emergent structure, if required. Self-organization mechanisms function without any external control and adapt to changes in the environment through spontaneous reorganization. This self-organizing ability makes these natural systems robust to changing environmental conditions, thus enhancing their survivability (Serugendo *et al.* 2006). Intuitively, in social self-organization methods like the one of Kota (2009), adaptation targets organization-wide characteristics, rather than the individual agent's characteristics. Our simulation results demonstrate that, indeed, the self-organizing agent populations are the most successful, growing larger than populations employing different social organization paradigms. The success of this social organization paradigm

[1] ABM acronym denotes both 'agent-based modeling' and 'agent-based model'.

that gives rise to 'stratified', that is, non-egalitarian societies, provides support for so-called 'managerial' archaeological theories which assume the existence of different social strata in Neolithic/Early Bronze Age Crete; and consider this early stratification a pre-requisite for the emergence of the Minoan Palaces, and the hierarchical social structure evident in later periods (Cherry 1986; Gilman 1981). We note that this is the first time a self-organization approach is incorporated in an ABM system used in archaeology.

1 Background

ABM is a field research methodology originally developed as part of computational modelling, but widely used by other disciplines, from life and physical sciences to environmental and social sciences. ABMs incorporate computational models that can be run to test whether agents are behaving as their designers intended. It must be understood, however, that this has little or nothing to do with how well they might reproduce observable data (Batty *et al.* 2012). This is not necessarily a drawback: ABMs are no longer built for prediction per se, but (to a large extent) to feed structured debate and dialogue, and to provide a tool for apprehending and explaining certain underlying properties of the world (Epstein 2008). Thus, a key objective of ABM is enriching our understanding of fundamental processes that appear in a variety of archaeological applications.

In most cases in archaeological field research, scholars explore past processes that occurred at a given geographical landscape. Thus, an effective means for modelling is the coupling or integration of Geographical Information Systems (GIS) with ABMs when spatial and temporal design and analysis is required (Crooks and Castle 2012). When one or more agent actions involves movement, when agent's location within the environment influences its decision making, or when spatial arrangement of features on the landscape can be altered by the agents, then a geospatial ABM can better support the research requirements of the modeller. Moreover, in geospatial ABMs the importance of the spatial resolution is equally as important as the temporal resolution, where descriptive characteristics of events and phenomena such as duration and frequency, are essential for temporal and spatial (pattern) analysis. Thus, when geographic context constitutes an important aspect of the conceptual model, the translated computational ABM needs to be coupled or linked with a GIS computational library.

Moreover, geospatial ABMs can be also enhanced via the use of 'cellular automata' (Von Neumann 1996) to model simple or even complex systems, an insightful approach for building a system of many agents that have varying states over time. Agents are cell objects existing on a grid (a tessellation of n-dimensional Euclidean space), where cell states evolve over a series of computational time steps: a cells' new state is a function of all the states in the cells neighbourhood at the previous time step, along with a set of simple rules for the cell to follow. Depending on the complexity, insightful spatial patterns can emerge. Therefore, the use of cellular automata allows the conceptualization of a variety of real-world systems, with complex behavioural patterns and intelligence emerging out of the interactions among simple agents.

On a parallel direction, von Neumann and Morgenstern (1944) invented the mathematical theory of games. Since the 1970s, *game theory* became the main instrument for the analysis of the strategic interactions among rational agents – that is, entities that encompass preferences or goals and act upon them. Agents can be described by means of an abstract concept called 'utility', referring to some ranking of the subjective welfare an agent derives from other objects, events, or interactions with others; the aim of the rational agent is to maximize its utility. Subjective welfare can be evaluated by reference to the modeller's own implicit or explicit judgments of it, depending on the conceptual ABM. The concept of a game refers to all situations in which an agent can act to maximize its utility through anticipating (either consciously, or just implicitly in its behaviour) the responses to its actions by one or more other agents. Game theory aims to provide an explanatory account of strategic reasoning based on 'rational' actions of agents – and thus to prescribe 'optimal' strategic behaviour for use by agents in rather small games. In situations where this is not the case, i.e. when agents can learn their optimal behaviour and adapt to new situations through (complex) strategic interactions within large societies, then *evolutionary game theory (EGT)* can be of use (Bloembergen *et al.* 2015). The concept originated as an application of game theory to biological contexts, arising from the realization that frequency-dependent 'fitness' introduces a strategic aspect to evolution. EGT has been applied in evolutionary biology with some success (Maynard Smith 1982), but has also recently attracted the interest of social scientists, as 'evolution' need not be strictly biological, but can be understood as 'cultural evolution' as well: beliefs and norms change over time, and EGT can assist on answering questions about the conditions under which language, concepts of justice, altruism, and other non-designed general social phenomena are likely to arise (Skyrms 1996).

The above methodological approaches can be fruitfully combined within an ABM, depending on the theories and hypotheses that need to be 'plugged-in' to a simulation model. The next step for ABM methodology is the design of the environment, the agents and their interactions. As argued by Wellman 2014, this should be largely based on concepts derived from *artificial intelligence (AI)* and *multiagent systems (MAS),* which offer the state of the art in designing *simple* or *sophisticated* agents, including complex knowledge structures, reasoning or learning from data and experience (Russell and Norvig 2002; Wooldridge 2002); nevertheless, more often than not, this is not the case in practice (Drogoul *et al.* 2003; Wellman 2014).

1.1 ABM design

The entire process of building an ABM begins with a conceptual model, where the main questions or hypotheses of the researcher determine model's elements – i.e. agent entities – with their characteristics, behavioural and interaction rules between themselves and the environment. A typical ABM has the following structural elements: a set of agents with their attributes and behaviours, a framework for simulating agents in which they interact with their environment in addition to other agents and a set of agent relationships, along with the methods of interaction in which an underlying topology of connectedness defines how and with whom agents interact.

While ABM originates from computer science as a computational modelling approach, the interdisciplinary nature of the approach may not permit a universally accepted definition on the term agent. Nonetheless, one of the most widely accepted definitions of an agent is provided by Jennings (2000). According to Jennings, an agent is a software-based computer system, situated in some environment, and which is capable of autonomous action in order to meet its design objectives. Therefore, the main property emanating from the above definition for an agent is 'autonomy'. An agent can be *pro-active* (exhibiting goal-directed behaviour), or *reactive* (responding to precepts in a simple manner); *socially able*, *interactive*, or *communicative* (being able to share or exchange information with other agents, and act within a given social environment); *boundedly rational* (i.e. not having unlimited access to information resources); *mobile*, rather than fixed within its environment; and *adaptive*, able to alter its state depending on *memory* (i.e. previous perceptions), or *learning* – depending always on the situation being modelled (Russell and Norvig 2002).

Agents can have additional properties, and, depending on the application, some of their features will be more important than others. Thus, the above list is not exhaustive or exclusive. Barring agent behavioural characteristics, the structural design of the agent is of equal importance. The appropriate design of the agent depends on the nature of the environment modelled. For example, in a simple case scenario of an archaeological ABM, designing the simplest agent structure could be sufficient a reactive (or simple reflex) agent. These agents select actions based on their current perception of the environment, ignoring previous perceptions history. They are based on simple *condition-action* (or *if-then-else*) rules – i.e. providing immediate ('reflexive') responses to perceptions. Although such an agent design has low computational power demands, the resulting agents are of limited sophistication or intelligence. For complex settings, a *deliberative* or *rational* agent needs to be designed. Such an agent is able to store previous perception history; use an internal model; employ some goal information for its decision making; or use a utility function to evaluate how close to its goal the agent is, rather than simply perceive whether a goal has been achieved or not, and then choose an action (Russell and Norvig 2002).

Furthermore, agent *interactions* with other agents and with the environment are determined by their perception (within a sphere of visibility and influence) and *action capabilities*. As a matter of fact, a key property of multiagent systems can be 'heterogeneity'– i.e. agents possess different capabilities or characteristics. In an archaeological application, for example, one may consider 'household' agents that have different number of inhabitants or possessing different skills (Wooldridge 2002). What is more, when agents interact there is typically some underlying organisational context, representing the nature of the relationships among the agents. The interaction topology very much depends on the modeller's needs. For example, a grid or lattice interaction topology can be possibly selected, when agents need to represent either a grid's cells (cellular automata), or (one or more) entities situated in that cell. Likewise, a polygonal (employing polylines as well) tilling scheme can be used when a realistic GIS map needs to be the environmental framework of the model. Moreover, a Euclidean 2D continuous space can be used, when agents need to move and interact within a simple representation of physical space. Finally, a network interaction topology can be used, representing (weighted) connections between the agents, where both directed and undirected relationships (links) may exist.

1.2 Related work

In recent decades, archaeologists have used simulations and ABMs to test possible explanations for the rise and fall of simple or complex ancient societies. An example of such an ABM is the study on the reasons why there have been periods when the Pueblo people, in the region of the Long House Valley in Arizona, lived in compact villages, while in other times they lived in dispersed hamlets (Kohler *et al.* 2000). A similar ABM study involved the cause of the collapse of the Anasazi, around 1300 CE in Arizona, USA (Dean *et al.* 2000). Scholars have argued for both a social and an environmental cause (drought) for the collapse of this society. The authors reinforce the hypothesis that environmental factors alone cannot account for the collapse. Simulations involved individual decisions of *household* agents, on a very detailed landscape of physical conditions of the local environment. In both studies, however, agents' architecture is a simple reactive one, and they do not interact, but rather act independently.

ENKIMDU (Christiansen and Altaweel 2006) is a societal modelling framework that has been employed in several 'spin-off' projects, due to its ability to create a virtual world on which to run simulations based on environmental and social parameters. The original ENKIMDU work focused on the study of the Bronze Age Mesopotamian settlement system dynamics. The system can represent settlement populations that are demographically and socially plausible, and provides detailed models of social mechanisms that can produce and maintain realistic textures of social structure and dynamics over time. Agent decisions are influenced by natural and social circumstances (such as low crop yields, endogamous or exogamous marriage patterns, and prevailing death rates), limiting agent autonomy somewhat.

MayaSim (Heckbert 2013) is a very recent example of a simulation model integrating an agent-based, cellular automata, and network model of the ancient Maya social-ecological system. The model examines the relationship between population growth, agricultural production, pressure on ecosystem services, forest succession, value of trade, and the stability of trade networks. These combine to allow agents representing Maya *settlements* (rather than households), to develop and expand within a landscape that changes under climate variation and anthropogenic pressure. The work was able to reproduce spatial patterns and timelines somewhat analogous to that of the ancient Maya, although this proof of concept model requires refinement and further archaeological data.

Finally, another ABM model that is worth mentioning is that of Janssen (2010). That work attempted to understand how prehistoric societies adapted to the American southwest landscape of their era. It explores how various assumptions concerning social processes affect the population aggregation and size, and examines the dispersion of settlements. Our ABM model shares several basic features with it, but it is also in many ways distinct to that model. Agents in both models correspond to households, and use a similar process to decide whether to migrate or not. We also model population dynamics, as a model should do, but via an entirely different population

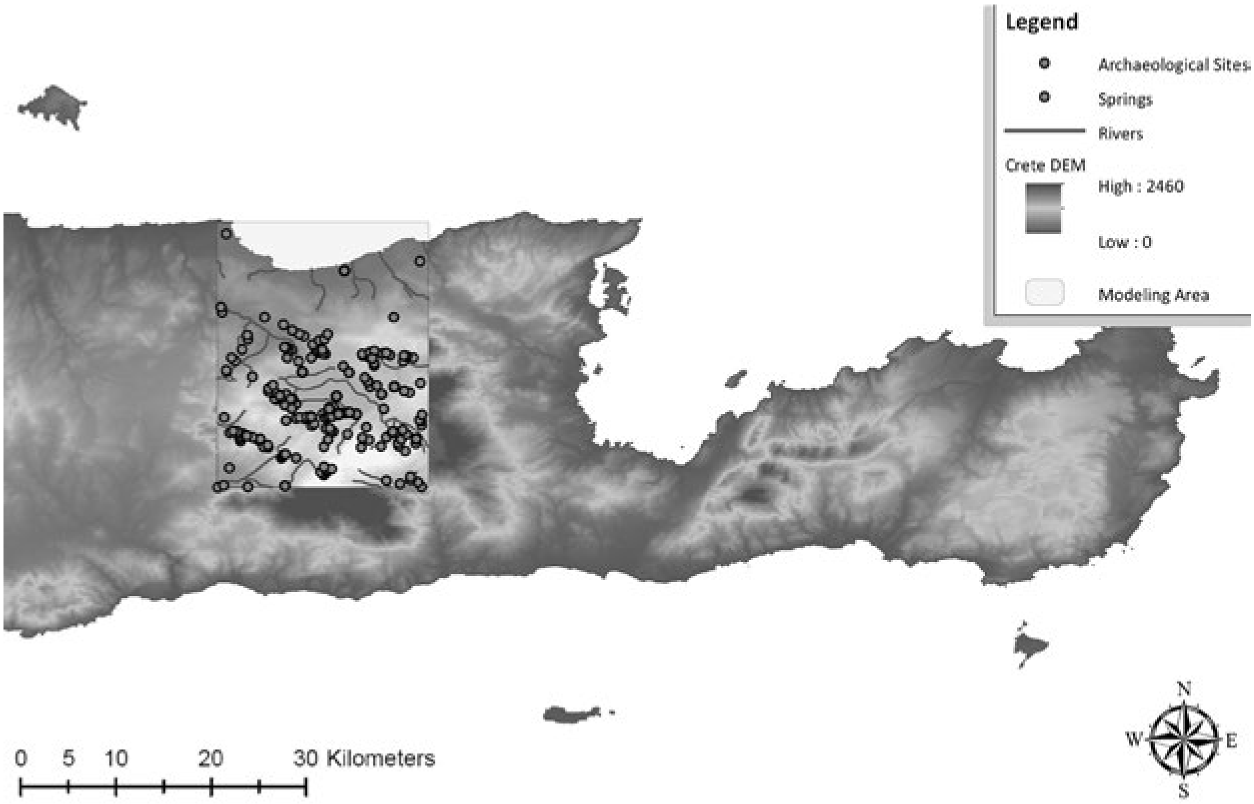


Fig. 1. GIS view of the ABM environmental area.

growth function. Apart from these similarities, the models are different in all other aspects.

2 Case study: an ABM for 'Minoan' Crete

Archaeology scholars do not have enough information about what kind of relationships existed between the Minoans or how this ancient civilization was organized before the 'Post-palatial' (Late Minoan) period. Archaeological evidence strongly suggests that the Minoans were agriculturalists and pastoralists (Hood 1971), as well as traders. Certainly, there are several hypotheses or theories that may be suggested for the Minoans' social organization and subsistence. For example, scholars try to find if there are any signs of a 'settlement hierarchy' in the 'Prepalatial' period, based on the variation of settlement sizes within a region, or by the number of *tholos* graves in use in each cemetery (Sbonias 1999). Some argue that no clear evidence of social stratification exists in the Early Minoan (EM) period (Haggis 1999), while others argue that a strongly stratified society can be assumed to have existed well before the end of the Neolithic period (Bintliff 1984). Although any such specific hypothesis can be the subject of modelling, our main concern here is to keep the model as generic as possible, in order to obtain clues about the underlying organization of the society and its evolution. Towards this direction, we developed a prototype model of agents that are autonomous, can build and maintain complex social structures, and can incorporate a self-organising social organisation paradigm (Chliaoutakis and Chalkiadakis 2014). The concept of self-organisation is inspired from natural systems, which function without any external control and adapt to changes in the environment through spontaneous reorganisation. Moreover, the model employs a utility-based agent design, rather than a simple reactive one. The ABM is generic and it can incorporate a number of different social organisation paradigms and various technologies (e.g. agricultural), and does not aim to prove or disprove a specific theory.

The ABM was developed using the NetLogo modelling environment and aims to study social organization, settlement distribution patterns at the 'Malia' area at the eastern part of the island of Crete during the Early Bronze Age (Figure 1). Considering farming to be the main activity for sustaining the Minoan civilization, the ABM evaluates the impact of different social organisation models and agricultural strategies on population viability and the spatial distribution of settlement locations over a 2000 year period (3200 to 1200 BCE), considering annual time steps. The artificial society evolves in a 2-dimensional grid, spanning a 20 x 25km area, with a cell size resolution of 100 x 100m.

Various aspects of the model's natural landscape contribute indirectly to an agent's decision-making process, like where to settle in or which land cells to cultivate. The input spatial data is derived from current topographical data, such as slope and known aquifer locations (rivers and springs) provided as a density map of a radius of 1250m (Fernandes *et al.* 2012). Figure 2 depicts the respective GIS data of the modelled area.

Agents in our model correspond to households, each containing a specific number of individuals (household inhabitants). Each household agent resides in a cell within the environmental grid, with the cell potentially shared by a number of agents. Adjacent cells occupied by agents make up a settlement – and

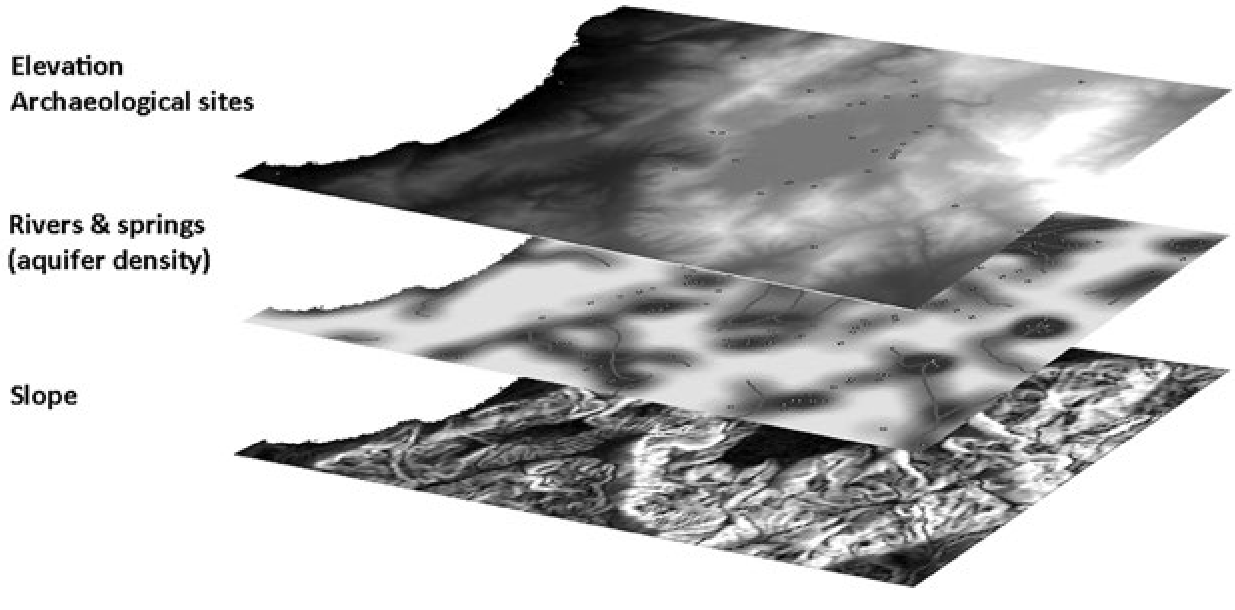


Fig. 2. GIS data layers of the ABM environmental area.

there is at least one occupied cell in a settlement. Each agent cultivates a number of cells located next to the settlement. At every (annual) time step, household agents first harvest resources located in nearby cells (corresponding to the fields they have a potential for cultivation). They then check whether their harvest (added to any stored resource quantities) satisfies their minimum perceived needs. If not, they might ask others for help (depending on the social organisation behaviour in effect), or they might even eventually consider migrating to another location (or settlement). Population size affects the land productivity in two ways: positively since the continuous occupation or cultivation of an area by a large populace leads to experience and subsequent higher crop yield; and negatively, since the soil quality of lands cultivated continuously by a large population degrades due to erosion processes. The land productivity of an individual cell is also affected by the cell's geo-morphological characteristics (in particular, land slope) given its location on the map, decaying with increasing slope. Population levels at a given area are affected by migration, as well as natural population change by birth and death of agents. Lower amount of resources reduces birth rate, and thus leads to a reduced population size and threatens the agents with extinction. Birth and death rate values used in our simulations, produce a population growth rate of 0.1%, when households consume adequate resources. This corresponds to estimated world-wide population growth rates during the Bronze Age according to Cowgill (1975). Furthermore, resources exist in cells at fixed locations, and may vary with respect to the amount of energy they embody, and their availability through time. In our simulations, a cell's initial resource at a given run (corresponding to 2,000 years) is multiplied with a sample from a standard normal distribution, and thus varies across runs.

Moreover, there are two *agricultural technologies* the agents can use: (i) *intensive agriculture*, where agents cultivate intensively the neighbouring land area leading to greater production per hectare and (ii) *extensive agriculture*, where agents 'expand' their cultivated areas, using more land but producing less per hectare (Jusseret 2010). The output associated with intensive agriculture in our model is 1500kg/ha, while for the extensive agriculture is 1000 kg/ha (Isaakidou 2008). Currently in our model, the only technology influencing the agent utility is agriculture, as this was assumed, for simplicity, to be the main activity sustaining the Minoan civilization. The model can be readily extended, however, to incorporate utilities gained by other means. Furthermore, agents in our model may also possess distinct behavioural modes or social organization paradigms, describing the way by which the distribution of harvested resources takes place among the population. We include three different behavioural modes corresponding to distinct social organization paradigms: (i) *independent,* where agents act independently and there is no sharing of harvest or stored resources among the agents, (ii) *an egalitarian-like* social paradigm, by which agents may share energy amounts within a settlement; all storage and harvest is pooled each year and distributed equally among the agents, and (iii) a *self-organized* social model, where agents re-arrange their (hierarchical) structure autonomously, without any external control, in order to adapt to changes in requirements and environmental conditions. Our self-organization algorithm incorporates a set of agent relations influencing the various social interactions, and a decentralised structural adaptation mechanism, suitable for open and dynamic organizations. In more detail, agents in our model constantly evaluate and possibly alter the relations or links with other agents. This process affects the way resources are ultimately distributed among the community members, leading to agent 'social mobility'. The details of the underlying social-organization algorithm determining the continuous re-adaptation of the agent relationships are, to an extent, based on a recent model originating in the MAS community (Kota 2009). Due to space restrictions, we do not provide the details of our algorithm here. Instead, we refer to the work of Kota *et al.* (2009) and of Chliaoutakis and Chalkiadakis (2014; 2015), which provide an extensive description of our model.[2]

[2] The ABM source code can be found at http://www.intelligence.tuc.gr/~angelos/ABM_nlogo_v1.zip

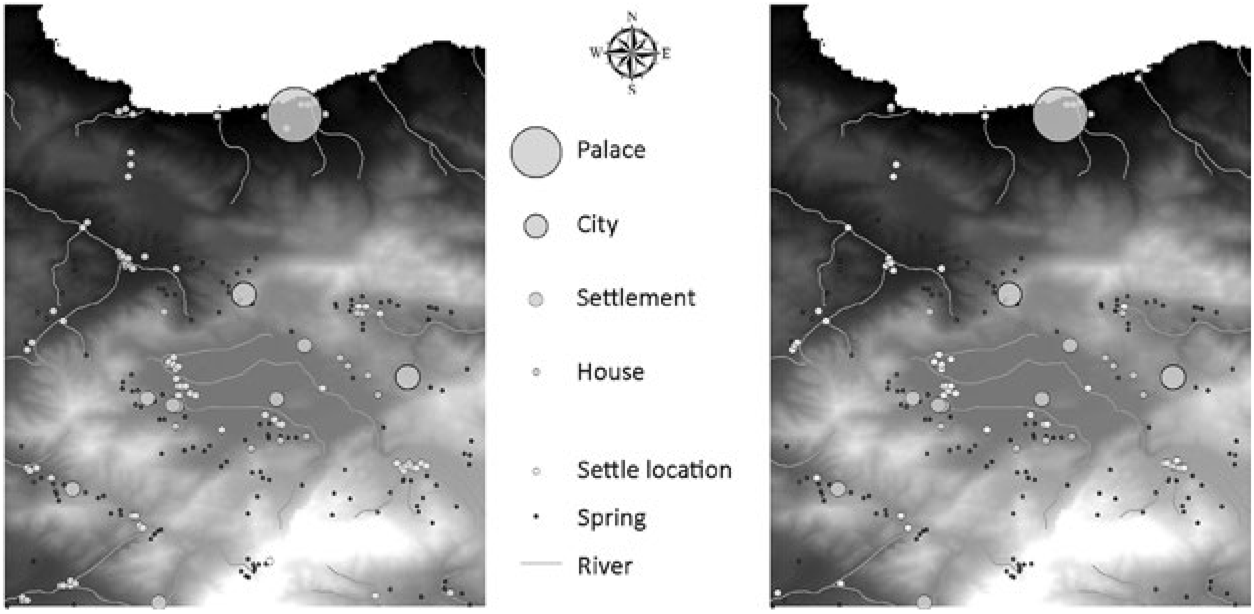


Fig. 3. Settlement locations of agents after 2,000 years employing the self-organisation behaviour; when (left) intensive and (right) extensive agricultural strategy is used and a requirement for settling near an aquifer.

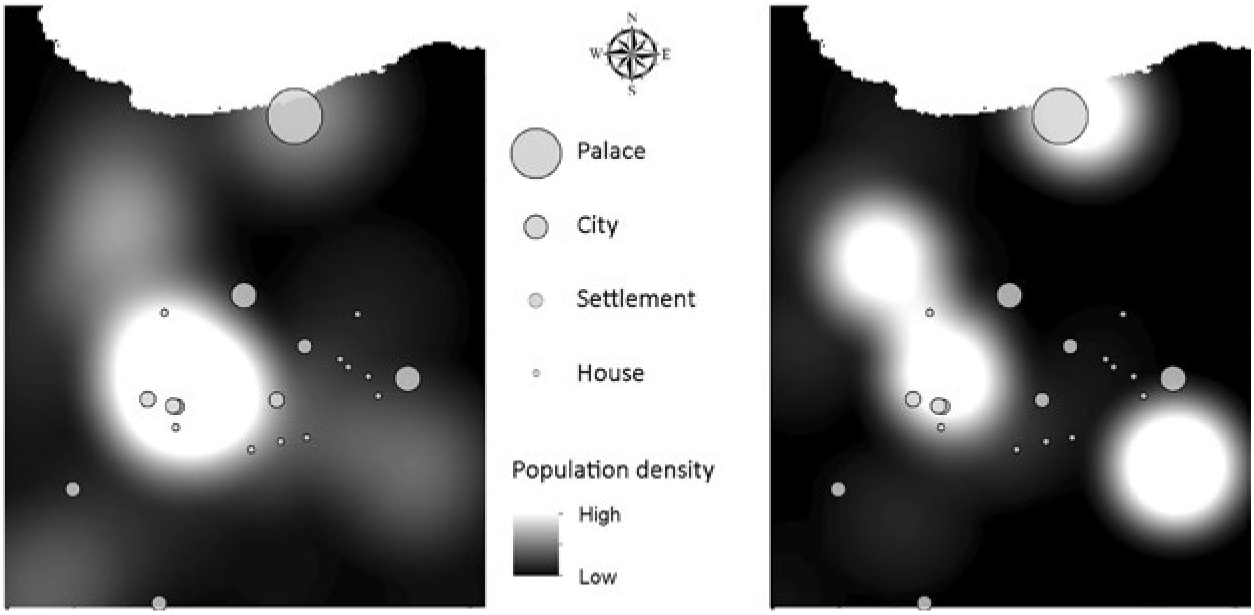


Fig. 4. Population density of agents after 2,000 years employing the self-organisation behaviour; when (left) intensive and (right) extensive agricultural strategy is used and a requirement for settling near an aquifer.

Model parameters are based on archaeological studies, but are not biased towards any specific assumption. The number of agents is derived from the user-defined variables of maximum number of individuals/cell (default: 100), divided by the maximum number of inhabitants/household (default: 10) as a random number given between 1 and 10 (100/10). The agent can store some resource amount for a number of (user-defined) years of storage (default: 5 years). The figure of 250kg was used as the minimum amount of resources required per individual per year, based on Isaakidou (2008). The number of settlements is also user-defined (default: 2), initialized at random locations, while an agent senses only agents within the settlement area. Various scenarios were taken into account for the experimental setup, with different parameterization for the three behavioural modes (i.e. the social organization paradigms) and the two different agricultural regimes specified above. Each scenario was simulated for 30 runs, generating a total of 180 simulations.

Regarding our results, first of all, the correctness of our model is confirmed by the fact that agents can be observed to mostly settle near actual settlement locations of the Minoan period, for both agricultural technologies (Fig. 3). Secondly, we conducted a population density analysis over the settlement locations, weighted by the average years settled for household agents, with interesting results. The analysis indicates that the area on

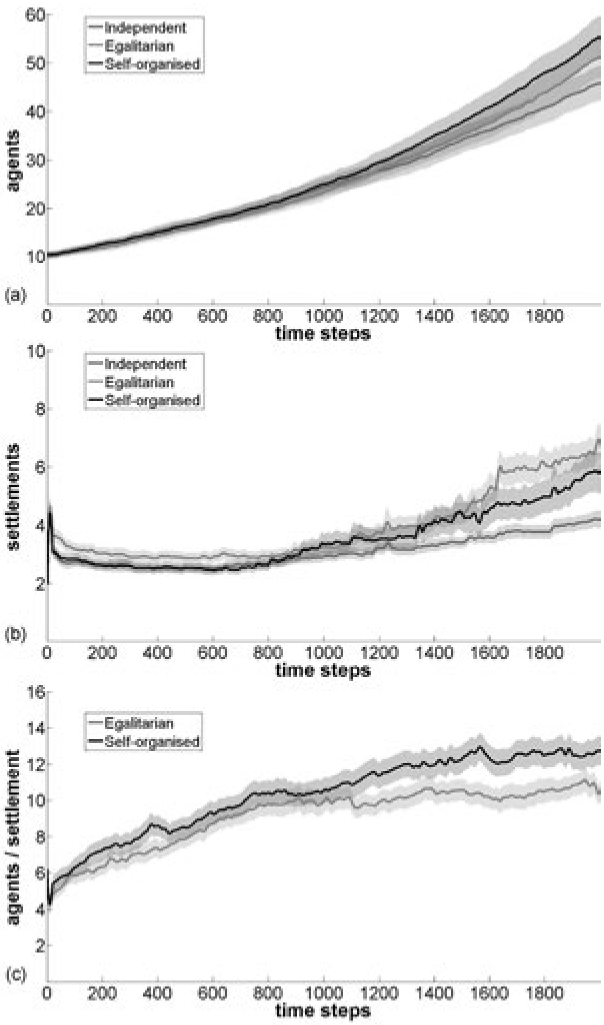


FIG. 5. NUMBER OF (A) AGENTS, (B) SETTLEMENTS AND (C) AGENTS PER SETTLEMENT OVER 2,000 ANNUAL TIME STEPS, WITH RESPECT TO INTENSIVE AGRICULTURAL STRATEGY. ERROR SHADING AREAS INDICATE 95% CONFIDENCE INTERVALS. RESULTS ARE AVERAGES OVER 30 SIMULATION RUNS.

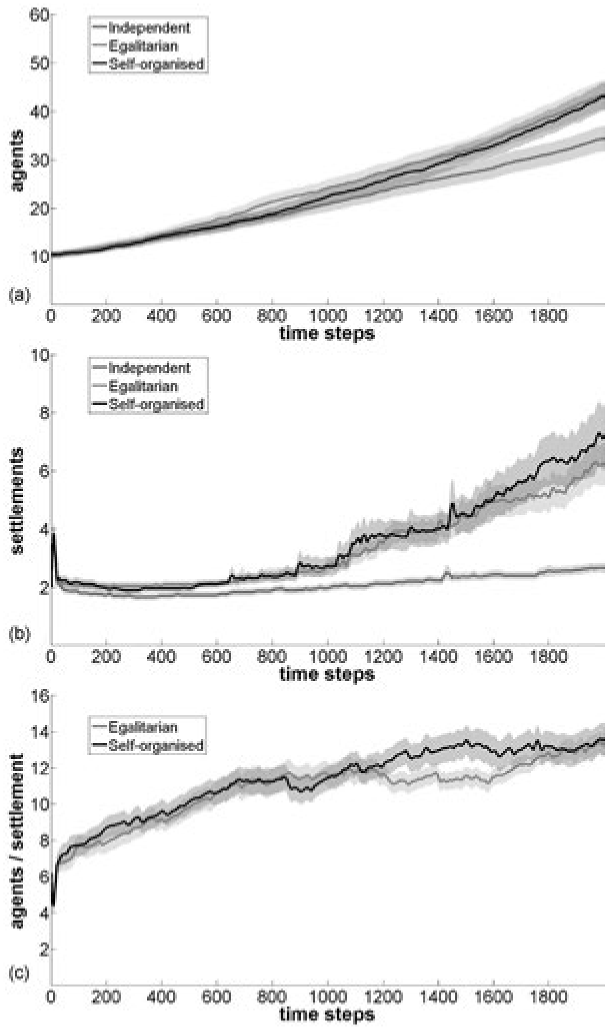


FIG. 6. NUMBER OF (A) AGENTS, (B) SETTLEMENTS AND (C) AGENTS PER SETTLEMENT OVER 2,000 ANNUAL TIME STEPS, WITH RESPECT TO EXTENSIVE AGRICULTURAL STRATEGY. ERROR SHADING AREAS INDICATE 95% CONFIDENCE INTERVALS. RESULTS ARE AVERAGES OVER 30 SIMULATION RUNS.

the upper right corner of the figure - where the palace of Malia is located – has a higher population density when an extensive (rather than an intensive) agricultural technology is used (Fig. 4). Moreover, the area at the centre of Figure 4 – the Lassithi Plateau – is most preferred by agents using intensive farming. Naturally, the main factors for agents selecting the particular areas for extensive and intensive agriculture respectively are landscape characteristics and settlement proximity to aquifers.

Finally, population growth results regarding the intensive agricultural strategy and the extensive agricultural regime are shown in Figs. 5 and 6 respectively. These simulation results indicate an increased sustainability for settlements adopting a socio-economic organisation model based on self-organisation, since the emerging 'stratified' populations are more populous than their egalitarian counterparts. As such, our ABM results do provide support for theories proposing the existence of different social strata in Early Bronze Age Crete, considering them a pre-requisite for the emergence of the complex social structure evident in later periods.

3 Conclusions

In this work we presented an ABM system to gain new insights into the social organization and agricultural activities of Minoan households residing at the Malia area in Crete during the Bronze Age. To that end, we incorporated, for the first time in an archaeological simulations system, a self-organisation method. Interestingly, our simulation results indicate that a social model based on continuously readapted relations among Minoan households might well have existed in the area of study. The self-organisation model gives rise, naturally, to implicit agent hierarchies.

Our prototype ABM is based on archaeological evidence, and is meant to be used as a tool enabling archaeology researchers to assess the potential validity of competing hypotheses; or even consider aspects of the past that have not yet been thought of. The system is generic and fully parameterized, and allows for the easy incorporation of new data or alternative theories. It can therefore potentially be employed to model different civilizations, areas, and eras – or even provide the basis for a fully interactive tool, to help popularize archaeological theories. In terms of future work, we need to run more scenarios with a variety of initialization setups. We also intend to equip the ABM with additional information (vegetation data, soil depth, geological information, other archaeological evidence or scenarios of interest) and additional types of utility-generating activities, and to examine the economic and political interactions among settlements (as opposed to those among households alone).

Acknowledgments

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Bibliography

Batty, M., Crooks, A. T., See L. M., Heppenstall A. J. 2012. Perspectives on Agent-Based Models and Geographical Systems. In A. J. Heppenstall, A. T. Crooks, L. M. See, M. Batty (eds.), *Agent-Based Models of Geographical Systems*: 1-15. Springer.

Bintliff, J. L. 1984. Structuralism and myth in Minoan studies. *Antiquity* 58: 33–8.

Cherry, J. 1986. Polities and Palaces: Some Problems in Minoan State Formation. In C. Renfrew and J. F. Cherry, *Peer Polity Interaction and Socio–Political Change*. Cambridge, Cambridge University Press: 19–45.

Chliaoutakis, A, Chalkiadakis, G. 2014. Utilizing Agent-Based Modeling to Gain New Insights into the Ancient Minoan Civilization. *Proceedings of the 2014 Autonomous Agents and Multi-agent Systems*: 1371-2. Paris, International Foundation for Autonomous and Multiuagent Systems.

Chliaoutakis, A. and Chalkiadakis, G. 2015. *Agent-Based Modeling of the Early Minoan Social Organization Structure*. Version 1.1. TUC/IMS-FORTH, Working paper [Online]. Available at: <http://www.intelligence.tuc.gr/~angelos/WorkingPaper.pdf> [Accessed 9 Nov 2015].

Christiansen, J. H. and Altaweel M. 2006. Simulation of Natural and Social Process Interactions: An Example From Bronze Age Mesopotamia. *Social Science Computer Review*. **24**(2): 209–26.

Cowgill, G. L. 1975. On the causes and consequences of ancient and modern population changes. *American Anthropologist*. 77(3): 505–25.

Crooks, A. T. and Castle C. J. E. 2012. The Integration of Agent-Based Modelling and Geographical Information for Geospatial Simulation. In A. J. Heppenstall, A. T. Crooks, L. M. See, M. Batty (eds.), *Agent-Based Models of Geographical Systems*: 219-51.

Bloembergen, D., Tuyls, K., Hennes, D. and Kaisers M. 2015. Evolutionary Dynamics of Multi-Agent Learning: A Survey. *Artificial Intelligence Research*. **53**: 659-97.

Dean, J. S., Gumerman G. J., Epstein J. M. *et al.* 2000. Understanding Anasazi Cultural Change Through Agent-Based Modeling. In T. A. Kohler and G. J. Gummerman (eds.), *In Dynamics in Human and Primate Societies*: 179–206. Oxford, Oxford University Press.

Drogoul, A., Vanbergue D., Meurisse, T. 2003. Multi-agent based simulation: Where are the agents? In: J. S. Sichman, F. Bousquet, P. Davidsson (eds.), *Multi-agent-based simulation II*: 1-15. Berlin, Heidelberg, Springer-Verlag.

Epstein, J. M. 2008. Why Model? *Journal of Artificial Societies and Social Simulation*. 11, 4: 12.

Fernandes, R., Geeven G., Soetens S., Klontza-Jaklova V. 2012. Mapping the probability of settlement location for the Malia-Lasithi region (Crete, Greece) during the Minoan Protopalatial period. In S. J. Kluiving, E. B. Guttmann-Bond (eds.), *Proceedings of Landscape Archaeology between Art and Science: From a Multi to an Interdisciplinary Approach*: 353-68. Amsterdam, Amsterdam University Press.

Gilman, A. 1981. The Development of Social Stratification in Bronze Age Europe. *Current Anthropology* 22, 1: 1-23.

Haggis, D. C. 1999. Staple finance, peak sunctuaries, and economic complexity in Late Prepalatial Crete. In A. Chaniotis (ed.), *From Minoan farmers to Roman traders: sidelights on the economy of Ancient Crete* 1: 53-85. Stuttgart, Franz Steiner Verlag.

Heckbert, S. 2013. MayaSim: An Agent-Based Model of the Ancient Maya Social-Ecological System. *Journal of Artificial Societies and Social Simulation* 16, 4: 11.

Hood, S. 1971. The Minoans: the story of Bronze Age Crete. *Ancient peoples and places* 75.

Isaakidou, V. 2008. 'The fauna and economy of Neolithic Knossos' revisited. In V. Issakidou, P. Tomkins (eds.), *Escaping the Labyrinth. The Cretan Neolithic in Context*: 90–114. Oxford, Oxbow Books.

Jennings, N. R. 2000. On agent-based software engineering. *Artificial Intelligence* 117, 2: 277–96.

Jusseret, S. 2010. Socializing geoarchaeology: insights from Bourdieu's theory of practice applied to Neolithic. *Geoarchaeology* 25: 675–708.

Kohler, T. A., Kresl, J., West, C. V. *et al.* 2000. Be There Then: A Modeling Approach to Settlement Determinants and Spatial Efficiency Among Late Ancestral Pueblo Populations of the Mesa Verde Region, U.S. Southwest. In T. A. Kohler and G. J. Gummerman (eds.), *Dynamics in Human and Primate Societies*: 145–78. Oxford, Oxford Univeristy Press.

Kota, R. 2009. *Self-Adapting Agent Organisations*. Unpublished PhD thesis, University of Southampton, UK.

Kota, R., Gibbins, N., Jennings, N. R. 2009. Self-Organising Agent Organisations. In S. Decker, J. Sichman, C. Sierra, C. Castelfranchi (eds.), *Proceedings of the 8th International Conference on Autonomous Agents and Multiagent Systems 2009, 10-15 may 2009, Budapest*: 797–804. Budapest, Ifaamas.

Lake, M. W. 2014. Trends in Archaeological Simulation. *Journal of Archaeological Method and Theory* 21: 258–87.

Maynard Smith, J. 1982. *Evolution and the Theory of Games*. Cambridge, Cambridge University Press.

Russell, S. J. and Norvig, P. 2002. *Artificial Intelligence – A modern approach*. Prentice-Hall.

Sbonias, K. 1999. Social development, management of production, and symbolic representation in prepalatial Crete. *From Minoan farmers to Roman traders: sidelights on the economy of Ancient Crete*. 1: 25-52.

Di Marzo Serugendo, G., Gleizes, M. P., Karageorgos, A. 2006. Self-organisation and emergence in multi-agent systems: An overview. *Informatica* 30, 1: 45-54. Berlin Heidelberg, Springer Verlag.

Skyrms, B. 1996. *Evolution of the Social Contract*. Cambridge, Cambridge University Press.

Von Neumann, J. 1996. *Theory of Self-Reproducing Automata*. Champaign, IL, USA, University of Illinois Press.

Von Neumann, J. and Morgenstern, O. 1944. *The Theory of Games and Economic Behavior*. Princeton, Princeton University Press.

Wellman, M. P. 2014. *Putting the Agent in Agent-Based Modeling*. [online]. Available at: <http://web.eecs.umich.edu/srg/?page_id=1579> [Accessed 9 Nov 2015].

Whitelaw, T. 2007. House, households and community at Early Minoan Fournou Korifi: Methods and models for interpretation. In R. Westgate, N. Fisher, J. Whitley (eds.), *Building Communities: House, Settlement and Society in the Aegean and Beyond*. British School at Athens Studies.

Wooldridge, M. 2002. *An Introduction to Multiagent Systems*. John Wiley and Sons.

Evaluating the Crisis: Population and Land Productivity in Late Medieval Salento, Italy

Giuseppe Muci
giuseppe.muci@unisalento.it
Laboratory for Medieval Archaeology, University of Salento, Lecce, Italy.

Abstract: The paper illustrates a theoretical model designed to investigate on-going complex demographic and economic dynamics in the interval between the Middle Ages and Early Modern times in southern Salento (south Apulia, Italy). GIS spatial and quantitative analyses focus on the relationship between population fluctuations and average productivity of cultivated land, estimated on the basis of Archaeological Land Suitability Classification derived from FAO Land Evaluation methodology. The resulting theoretical model can be read through the lens of 'resilience theory', which provides a conceptual framework to understand transformations in socio-ecological systems.

Keywords: GIS-based modelling, Resilience theory, Demography, Land Suitability Classification

Introduction

Archaeological data and written sources show that between the 14th and the first half of the 15th century Europe witnessed a massive economic and demographic crisis (Russell 1985; Le Roy Ladurie and Goy 1982; Malanima 2009; Bintliff 2012). As happened elsewhere, southern *Terra d'Otranto* − roughly corresponding to the present day district of Lecce in Apulia − underwent a large population decline and disintegration of the pre-existing settlement pattern (Fig. 1), with the number of villages decreasing by 1/3 in the period between 1350 and 1450 (Visceglia 1988; Arthur 2006: 111). The negative conjuncture seems to have ended around the middle of the 15th century, when a marked demographic and economic recovery is clearly evidenced by archaeological data and documents (Da Molin 1979). The post-medieval settlement pattern, discernible in the landscape until the last century, was the outcome of these epochal changes.

The research workflow focuses on relationships between population fluctuations and average land productivity, in order to evaluate the sustainability of the local late medieval economic system. The main questions we seek to answer are: how many people might be fed in the region depending on exploited lands and available technologies of the time? Had the local economic system reached is sustainability limit during the 14th century, or there were still opportunities for population growth? Should we look to other factors to explain the demographic shift, which marked the end of the Middle Ages?

In order to answer some of these questions, in the first part of this paper we attempt to estimate the landscape gradient of sustainability by building an experimental land exploitation model, based on attractors, detractors, facilitators, obstacles and average soil productivity estimates (see Citter 2015: 257). In the second part, the resulting quantitative evaluations on potential production are compared with historical demographic series, in order to see if the sustainable population limit had been reached.

The model described below is based on a large amount of data collected through archaeological excavations, surveys, historical sources and geographic datasets, by the Laboratory for Medieval Archaeology, University of Salento, all implemented in a GIS environment (ESRI ArcMap 10.2). Through this model we try to interpret some of the dynamics that characterized the transition from medieval to early modern Salento. It is important to stress that a model is not intended to be a duplicate of reality, but a simplification based on a certain number of variables chosen because of their relevance to the question we are addressing (Macchi Jánica 2009: 57-9; Kvamme 1989).

1 Accessibility-Catchment Analysis

The basic assumption made is that the success of pre-industrial agrarian villages widely depended on good soils and available resources; we can also assume as true that people preferred high potential land at a short distance from the settlement (Verhagen *et al.* 2007: 177). Therefore, as a first step, we tried to predict the accessibility of lands to medieval peasants. To do this an *'accessibility-catchment'* model of the study area was built, starting from a cumulative friction surface calculated taking into account significant human and environmental variables (Van Leusen, 2002: 6/4-6/9). The final goal was to locate the approximate exploitation area for each known late medieval settlement (see Arthur and Gravili 2006).

In the building of a cumulative raster cost-surface model, slope, hydrography, land coverage and wetness were assessed as deterring factors, while the presence of roads and major towns were seen as facilitating ones.

1.1 Slope

Movements through landscape, especially when carrying goods, are easier on flat or low slope surfaces. Slopes were classified through the *3D Analyst* toolset (*Slope* and *Reclassify*) on the basis of a 20m resolution *Digital Terrain Model* specifically generated from height points and contour lines stored in the vectorial regional map of Apulia (http: //sit.puglia.it/). In the evaluation process we took into account that slopes higher than 70% are inaccessible, while best values are those between 2% and 10%, where water stagnation is avoided. We decided to build an isotropic grid surface, presuming that paths to/from fields were reiterated so that asperities were symmetrically

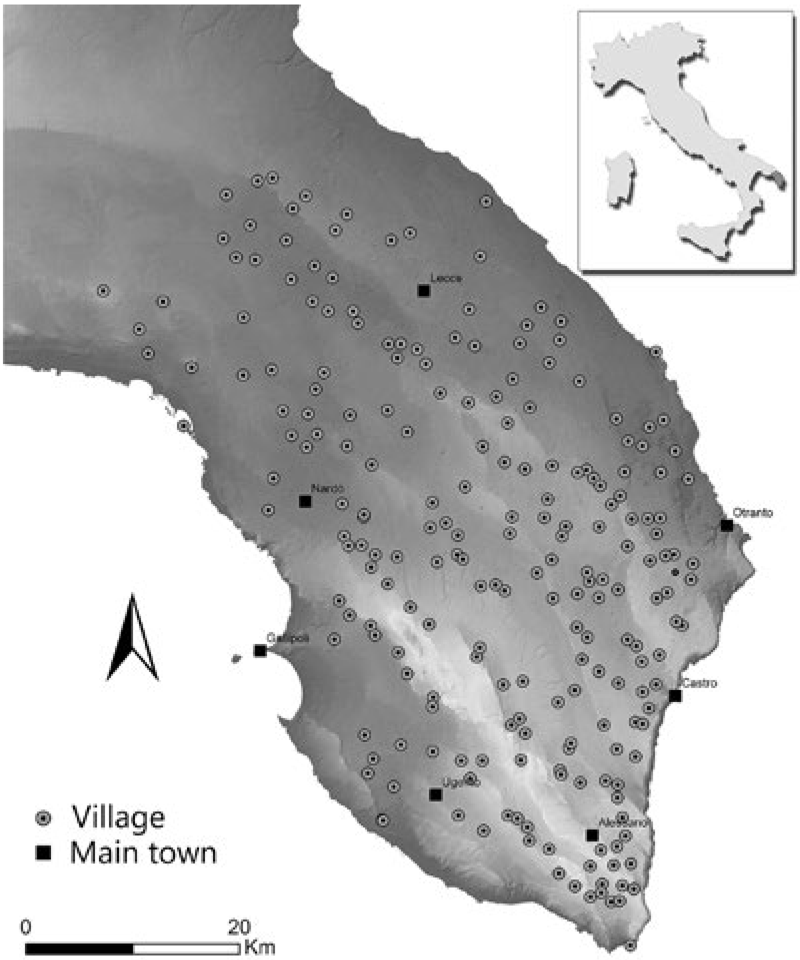

Fig. 1. Southern *Terra d'Otranto* Late Medieval (13th-14th centuries) settlement pattern.

erased (Llobera 2000; De Silva and Pizziolo 2001; Citter and Arnoldus-Huyzendveld 2011: 87-8).

1.2 Hydrography

Nowadays the area corresponding to medieval *Terra d'Otranto* shows a limited hydrographic network with extremely irregular flow rates; few lagoons and marshes are present especially in coastal zones where water outflow is obstructed by dunes. Data for the late Middle Ages are scarce, but we can assume few differences over the last 500 years or so: a little more substantial water flow was maybe the consequence of the cold period documented between the 13th and the 14th century, as during the Little Ice Age (Le Roy Ladurie 1971; Grootes and Stuiver 1997).

Water streams, preliminarily listed in a linear shapefile, have been classified according to estimated ancient flow rate, which could have influenced their crossing. To avoid critical situations due to the later conversion of linear features into a grid raster (see Van Leusen 2002: 16/16), and to better reflect true environmental characteristics, the shapefile was processed using the *Multiple Ring Buffer* tool: two buffers – respectively of 40 and 120m – were created for major streams, a single buffer of 40m for minor ones. Then relative friction values were assigned to each feature: 100 for lakes and coastal lagoons; 70 for major water streams with their first buffer area; 25 for temporary water streams and second buffer area of major water streams; 1 for all remaining surfaces (1 instead of 0 is necessary to avoid null cost values as a result of the following *Raster Algebra* calculations). The shapefile was then converted into a grid surface with 20m resolution.

1.3 Land coverage and wet areas

Walking through marshes, waterlogged areas and dense forests, should have increased moving costs, so can be presumed that their crossing was avoided when possible (Macchi Jánica 2001: 155). Palaeoecological data, historical sources, modern cartographic and toponomastics datasets, paired with the use of *regressive method* (Bloch 1966) and GIS overlay capabilities, help us to approximately locate late medieval woods, scrubs and wet areas.

Again, starting from a polygonal shapefile where ancient known marshes, woods and scrubs were listed, we calculated a cost raster with the following friction values: 85 for marshes and floodable areas, where walking costs should have been relatively high; 50 for woods and 15 for scrubs, where walking was generally possible with a relative low cost; finally a 1 friction value was assigned to all remaining areas.

1.4 Road network

Existing roads have rarely been taken into account when building historical accessibility models. Nonetheless, movement never occurred in an immaculate landscape. Using existing paths rather than building new ones was obvious and convenient (Van Leusen 2002: 125); of course, roads where a medium to control territory and move products from fields to central places and commercial hubs.

As previously stated, the late medieval road system has been added in the building process of a cumulative cost-surface as a facilitating element. Partial reconstruction of the medieval road pattern was based on *Linear Nearest Neighbour Analysis* method, which provided a probabilistic model of the ancient road network. The technique, derived from ordinary *Nearest Neighbour Analysis*, instead of analysing the patterning of points, measures the distributions of a set of points along linear segments (Levine 2004). In our case points are represented by late medieval villages, while lines are ancient roads extrapolated using regressive methods on post-medieval cartographic data. Points that tend to cluster along roads may be read as an evidence for the antiquity of these tracks (Arthur *et al.* 2005: 176-8).

Multiple Ring Buffer was used to avoid critical issues after the vectors conversion into a raster surface (first buffer corresponding to carriageways) and to include in the model 'better connected' terrains thanks to the presence of main roads (second buffer of 2km). As the road network is a facilitating variable, the following values were set to ease movements through these paths: 1 for carriageway, 10 to the second buffer, 25 to all the other areas.

1.5 Main towns

An additional variable taken into account was represented by lands located close to main settlements, which should have been more accessible. For this reason a 2km buffer with a low cost value was calculated around late medieval major towns and codified in a raster map.

To obtain the cumulative land-accessibility model, all achieved individual cost-surfaces were aligned and combined according to *Map Algebra* principles (Tomlin 1990; Lake and Conolly 2006: 188), using the ArcGIS *Raster Calculator* tool. Instead of merely summing up raster surfaces, we decided to weigh them according to *Weighted Linear Combination* technique (Drobne and Lisec 2009):

Different weights to variables were assigned using *Pairwise Comparison* (Malczewski 1999). For *Pairwise Comparison* each variable is matched with each of the other variables, giving a value which represents the relative importance of the first variable in respect to the second.

The following formula was entered in the *Raster Calculator* in order to merge the different cost factors in a cumulative cost map:

*('Slope' * 0.05) + ('Hydrography' * 0.15) + ('Land coverage' * 0.05) + ('Roads' * 0.35) + ('Main towns' * 0.4)*

The achieved relative cost map (Fig. 2) was the basis for individuation of lands which were more easily reachable from existing settlements, and whose exploitation was consequently more convenient. *Cost Allocation* and *Cost Distance* tools used to perform the analysis require two input datasets: some seed locations, represented in our case by medieval settlements existing between the 13th and 14th centuries, and a friction surface (the above calculated cost-raster). In a first instance, lands allocated within one hour's walk from settlements were calculated (for ethnographic studies about site catchments see e.g. Chisholm 1962). Then one hour isochrones shapefile was overlaid and cut with Voronoi polygons, built through *Cost Allocation* analysis, to obtain the allocated land pertinent to each settlement and reachable within 60 minutes (Fig. 3).

2 Archaeological Land Evaluation

The method of *Land Evaluation* developed by FAO compares soil requirements for a specific use with qualities and characteristics of *Land Units*, in order to determine their agricultural suitability (FAO 1976). This framework, originally meant for present day land use, can be applied to ancient landscapes (*Archaeological Land Evaluation*), and in this case it is used to establish the potential suitability of past soils for ancient land use (Kamermans 2000; Van Joolen 2003).

In order to build a suitability map according to FAO *Land Suitability* procedure one should compare the characteristics of *Land Units* with specific *Land Use Requirements* (LUR), that is to say all the necessary conditions of soil for successful and sustainable implementation of a specific cultivation.

In the specific case of this study, soils information implemented in the GIS environment and used to perform suitability analysis come from the Apulia Regional Soil Map (http: //sit.puglia.it/): for the scope of the analysis Tassonomic Soil Units, as stored in the regional map, have been converted following the WRB Soil Resources system (FAO 2006). Although present-day landscape underwent some changes, these cannot be considered particularly significant given the scale of the research area. During the process, we took into account only wheat's LUR: indeed, according to archaeobotanical and documentary data, nude wheat (*Triticum aestivum* / *durum* / *compactum*) and barley (*Hordeum vulgare*) were preponderant in human diet during the entire Middle Ages. Nude wheats are rather tolerant. They prefer a hot and dry environment and clay soils with a minimum depth of at least 30cm, moderate fertility and good water drainage; flat stone-free and easy-to--plough lands are preferable. There are no specific requirements for irrigation and manuring, yet two-field crop rotation mitigates the loss of soil fertility.

Relying on these observations, *Land Units* − included in a polygonal shapefile − were divided into three classes, according to different suitability levels in relation to wheat cultivation. The resulting suitability map shows the study area divided into the following classes (Fig. 4):

- *S1* = suitable land which in optimal conditions allows maximize yields;

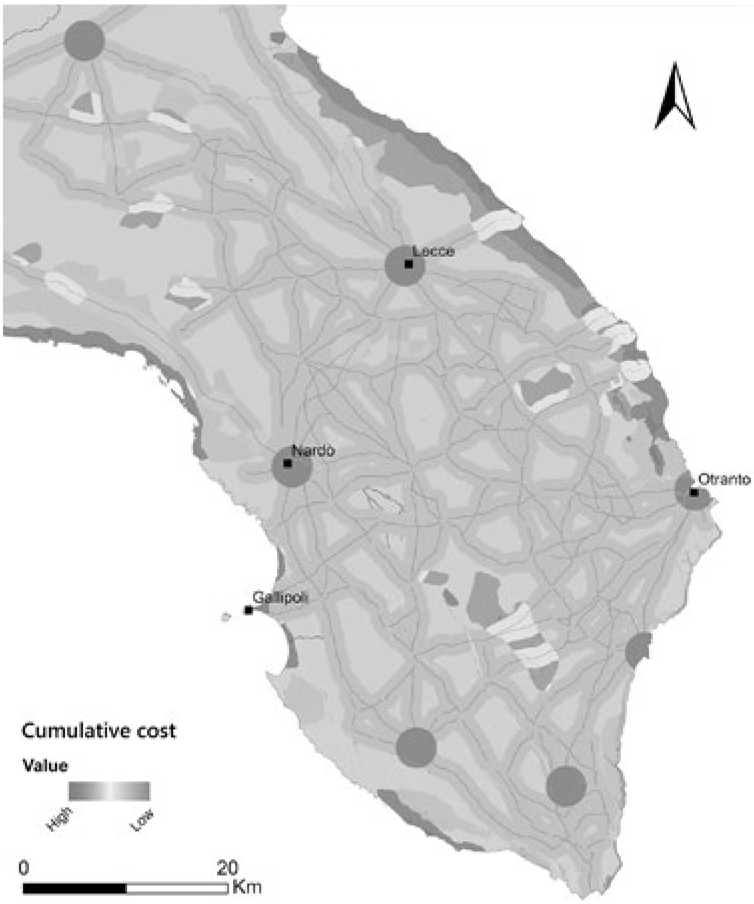

Fig. 2. Cumulative cost map.

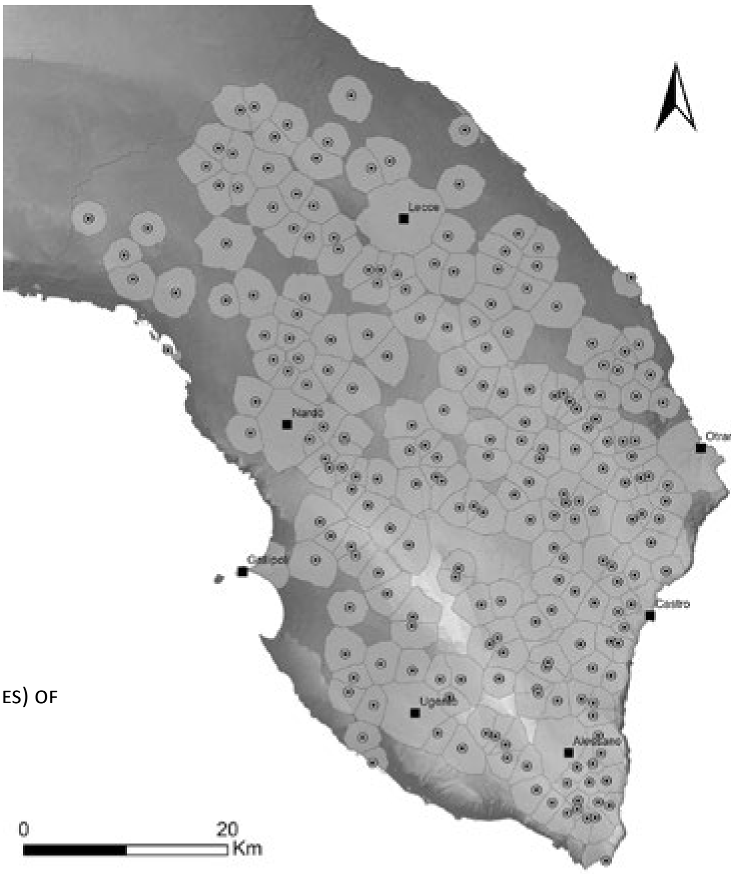

Fig. 3. Cumulative site catchment (1 hr isochrones) of Late Medieval villages.

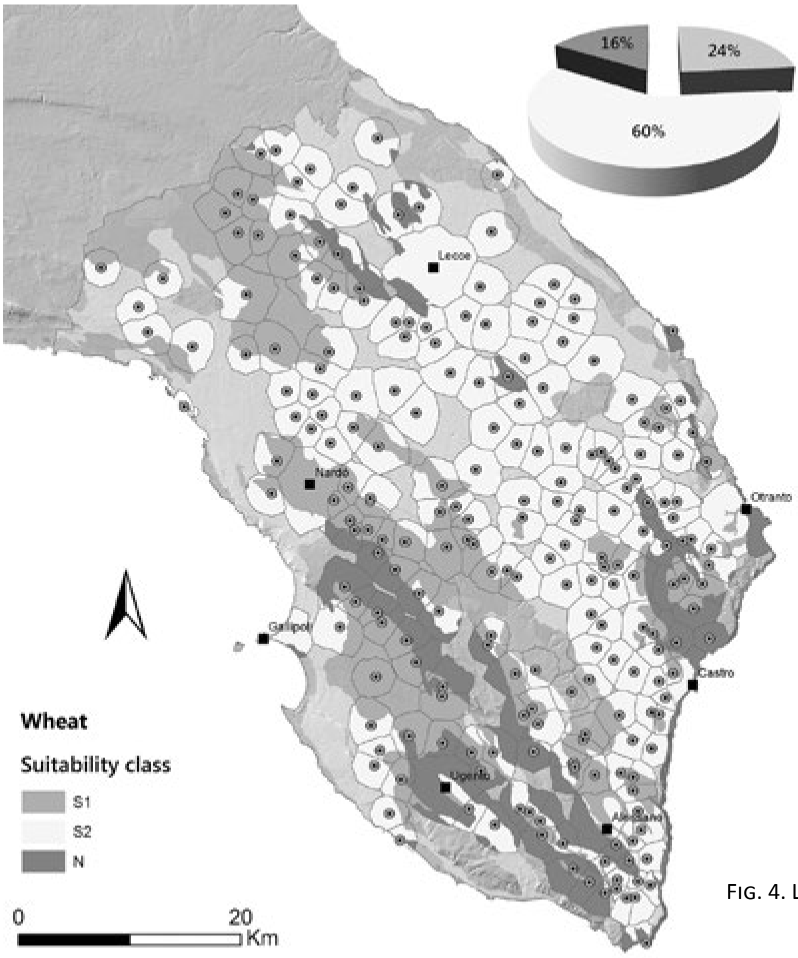

Fig. 4. Land Suitability Evaluation for wheat and estimated available land per class.

- *S2* = marginally suitable land, with reduced yields;
- *N* = unsuitable land, with extremely low or absent yields.

In the end wood and marsh polygons, corresponding to uncultivated lands, were deducted from the suitability map shapefile.

3 Productivity Evaluation

Both the accessibility-catchment map and the suitability map were overlaid and processed (*Intersect* tool) in order to estimate how much land could have been cultivated by late medieval communities, the corresponding suitability classes in each catchment area (Fig. 4), and finally the cumulative average wheat production.

The amount of land in each suitability class was compared with estimates of crop productivity during the 13th-14th centuries gathered from late medieval documents; sources generally show very low productive levels, with a documented maximum ratio of 500-600 kg/ha under optimal circumstances in northern Italy and Europe (Montanari 1985; Slicher Van Bath 1963). In the following calculations we used 500 kg/ha ratio for *S1* soils (close to the value observed in central Italy) and a 1/3 lower ratio for *S2* soils (330kg/ha). Moreover, in order to improve the model's realism, we included some additional parameters reflecting documented ancient agricultural practices: crop deduction for seeding (130kg/ha), the presence of alternative cultivations, and a two-field crop rotation practice (mostly employed in medieval Southern Italy). Net production estimates multiplied by the hectares of soil per class falling inside catchment areas yield an average maximum wheat production of 12,440,000 kg per year.

Supposing an average daily consumption of 2,600kcal/person, a peasant's wheat-based diet could have consisted of 650g/day of wheat products, covering around 60-70% of caloric daily needs, with remaining calories provided by other foods. The yearly wheat needs can be estimated at 250kg/person (Verhagen *et al.* 2007: 178; Goodchild 2007: 303-11). Relying on these calculations it is possible to estimate 1,35 hectares of *S1* soil planted with wheat *per capita*. This value is similar to the one calculated for the Grosseto area during the same period, where one hectare of *S1* class soil planted with wheat was sufficient to satisfy one person's yearly needs (Citter and Arnoldus-Huyzendveld 2011: 111). On this basis, local estimated wheat production was enough to feed about 50,000 inhabitants.

From the analysis of data reported by an Angevin fiscal document *(cedularium)* wrote in 1378 (Coco 1915), the population of the study area should have consisted of at least 46.000 inhabitants in the last quarter of the 14th century, when the demographic crisis was almost certainly at its apex.

Tab. 1. Wheat production estimate.

Wheat production (13th-14th centuries)								
Land class	Average product (kg/ha)	Seeding (kg/ha)	Net product (kg/ha)	Available lands (ha)	Other cultivations %	Crop rotation	Net lands (ha)	Final product (kg)
S1	500	130	370	44895	20%	1/2	17958	6644460
S2	350	130	200	115856	50%	1/2	28964	5792800
							TOTAL	12437260

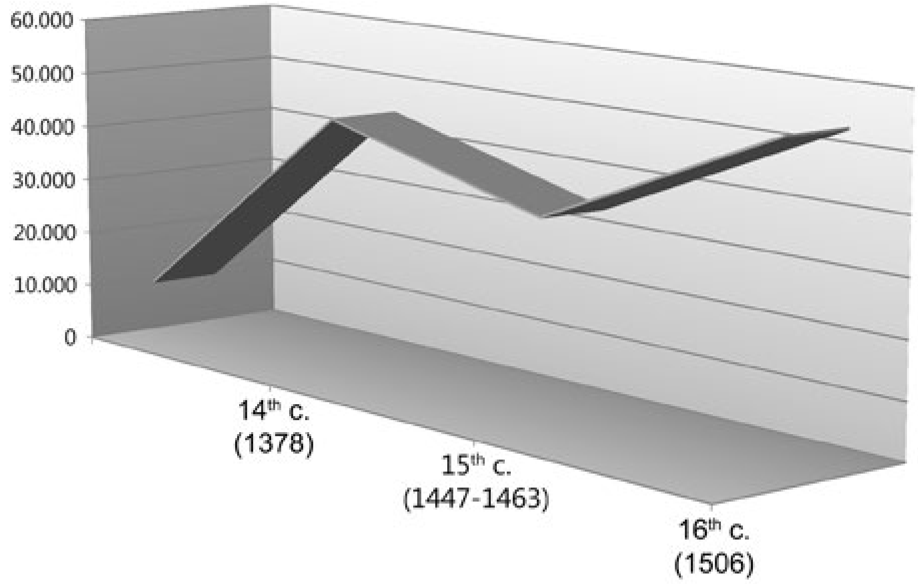

Fig. 5. Estimated demographic trend between late Middle Ages and early Modern times.

Relying on these numbers, a minimum of 11,500,000 kg of wheat should be enough to feed the whole local population.

4 Final Considerations

The resulting estimations of the above sustainability model open the field to new questions. Following previous calculations the late medieval system appear to be sustainable, as wheat production should be enough to feed the whole known 14th century population. However, it is important to underline that the evaluation refers to a 'best-case scenario': in other words estimated maximum productivity didn't necessarily correspond to actual production values. We know that throughout the Middle Ages harvest sizes were extremely variable, often depending on environmental and incidental factors, including traumatic events. Moreover the above data should be considered as underestimated, as fiscal documents didn't take into account the entire population, and part of the harvest wasn't available as it was appropriated in the form of feudal taxation.

Considering the vulnerability of local pre-industrial systems, it is possible to imagine that one or more contingent stress factors (e.g. the Black Death and/or the political succession struggles of the 14th century) influenced the whole socio-economic structure, which was already running close to its sustainability limit, triggering the substantial demographic decline that occurred between the 14th and 15th centuries. Documents testify a population loss of about 10,000/15,000 inhabitants in the study area (-20,000 in the whole *Terra d'Otranto*), with the contextual abandonment of more than 70 villages and a surviving population of 30,000-35,500 inhabitants (Fig. 5).

At the actual state of knowledge this experimental model is not able to directly explain the causes after the crisis, but it shows that there are complex dynamics such as isolated catastrophic events or non-linear decision making processes which go beyond the archaeological or historical records and are difficult, yet not impossible, to be modelled. The strength of a quantitative approach like the one proposed here relies in is objective nature, which let researchers reflect about the

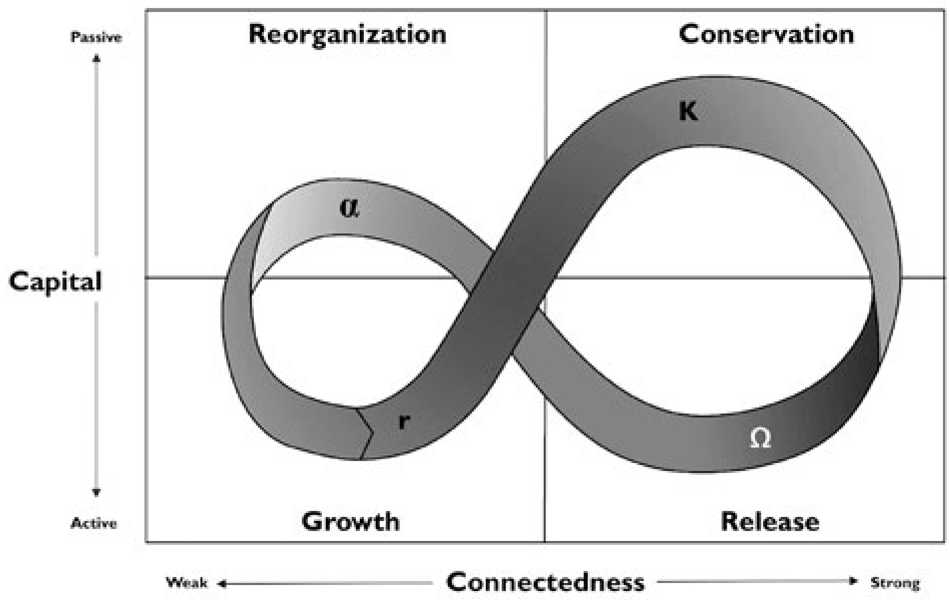

Fig. 6. Adaptive cycle of complex systems (after Holling 2001).

variables involved, their presumed weights and the existence of other non-assessed factors that influenced the whole system.

Going back to the local dynamics, the demographic crisis was followed by a period of reorganization (α) (Holling 2001; Redman and Kinzig 2003) (Fig. 6), apparently driven by local aristocracies. By the end of the 15th and the beginning of the 16th century economic and social systems underwent revolutionary changes. The implementation of more rational productive strategies led to a significant reassessment of the settlement pattern, reflected in the spread of new productive structures (*masserie*) in formerly uncultivated land (Fig. 7), and the appearance of closed villages or *Terrae* (Fig. 8). The new settlement organization reveals diversified choices in relation to different soil capabilities. A new pre-capitalistic system boosted, *inter alia*, a phase of overwhelming economic and demographic growth (*r*) (Arthur 2010): in the early 16th century, despite recurring plague epidemics (1466, 1470, 1498, 1527) and political uncertainty, local population had reached about 55,000-60,000 inhabitants, widely overtaking the above estimated productivity limit, while technological progress and agrarian rationalization made possible the achievement of 1: 7 yield ratios. Even without considering newly acquired lands, the new estimated wheat production of 20,000.000kg was enough to feed the entire population and to grant a notable surplus. After a hundred years of considerable growth, in the second half of the 15th century the system achieved a temporary equilibrium (*K*). This lasted until the 18th century, when a new crisis crushed the existing socio-economic structures.

Acknowledgments

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Bibliography

Arthur, P. 2006. L'archeologia del villaggio medievale in Puglia. In M. Milanese (ed.), *Vita e morte dei villaggi rurali tra Medioevo ed Età Moderna*, QUAVAS 2: 97-121. Firenze, All'Insegna del Giglio.

Arthur, P. 2010. Verso un modellamento del paesaggio rurale dopo il Mille nella Puglia meridionale. *Archeologia Medievale* 37: 215-28.

Arthur, P. and Gravili, G. 2006. Approcci all'analisi degli insediamenti e loro confini territoriali nel Medioevo. In R. Francovich, M. Valenti (eds.), *IV Congresso Nazionale di Archeologia Medievale*, *Chiusdino-Siena, 26-30 September 2006*: 31-6. Firenze, All'Insegna del Giglio.

Arthur, P., Gravili, G., Limoncelli, M., Bruno, B., Leo Imperiale, M., Portulano, C., Lapadula, E. and Sarcinelli G. (2005) La chiesa di Santa Maria della Strada, Taurisano (Lecce). Scavi 2004, *Archeologia Medievale* 32: 173-205.

Bintliff, J. 2012. *The complete archaeology of Greece: from hunter-gatherers to the 20th century AD*. Oxford-New York, Wiley.

Bloch, M. 1966. *French rural history: an essay on its basic characteristics*. Berkeley, University of California Press.

Chisholm, M. D. I. 1962. *Rural settlement and land use: an essay in location*. London, Hutchinson University Library.

Citter, C. 2015. Landscapes, settlements and sustainability. In A. Chavarria Arnau and A. Reynolds (eds.), *Detecting and understanding historic landscapes*. PCA Studies. 2: 253-71. Mantova, SAP Società Archeologica.

Citter, C. and Arnoldus-Huyzendveld, A. 2011. *Uso del suolo e sfruttamento delle risorse nella pianura grossetana nel Medioevo. Verso una storia del parcellario e del paesaggio agrario*, Roma, Artemide.

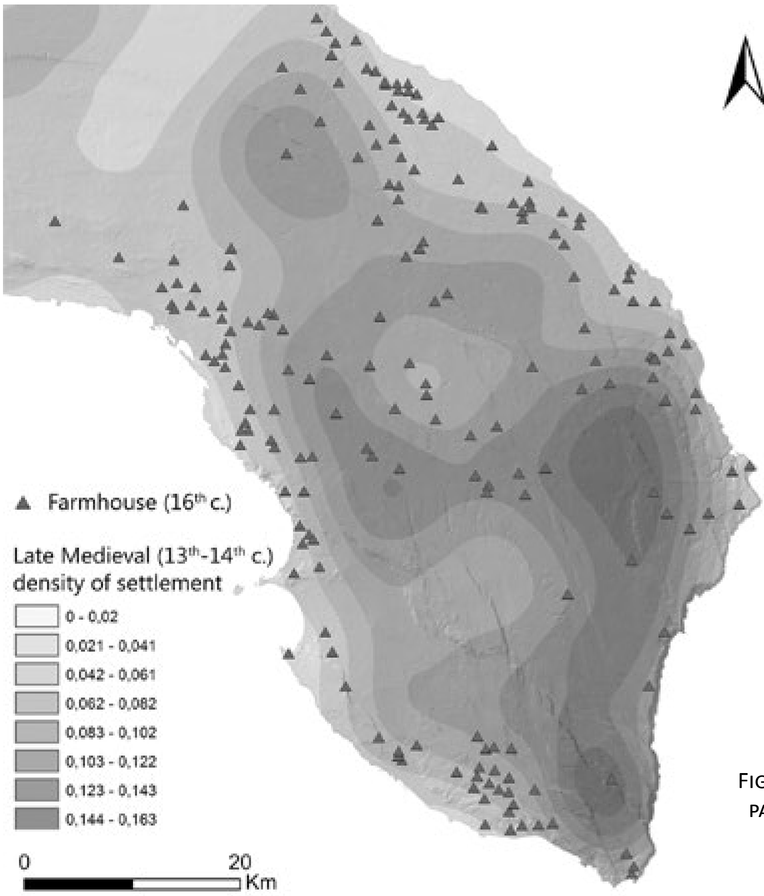

Fig. 7. Late Medieval and early Modern settlement pattern: medieval settlements density compared with 16th century farmhouses (*masserie*) distribution.

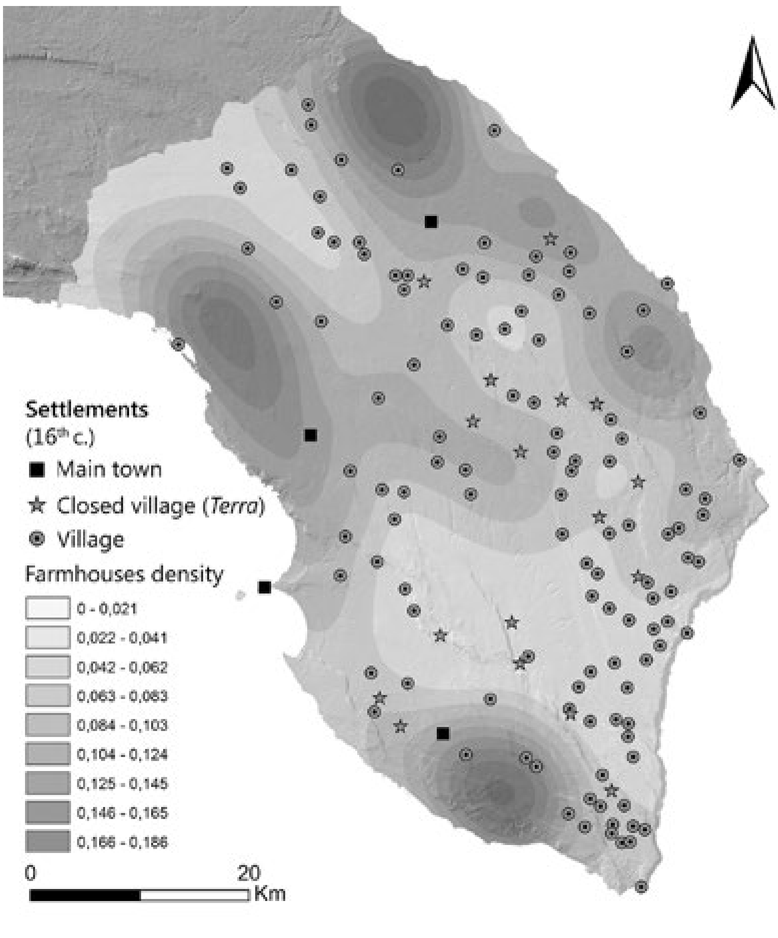

Fig. 8. Early Modern settlement pattern: towns distribution compared with farmhouses density.

Coco, A. P. 1915. *Cedularia Terrae Idronti 1378*, Taranto, Lodeserto.

Da Molin, G. 1979. *La popolazione del Regno di Napoli a metà Quattrocento: studio di un focolario aragonese*. Bari, Adriatica.

De Silva, M. and Pizziolo, G. 2001. Setting up a 'human calibrated' anisotropic cost surface for archaeological landscape investigation. In Z. Stančič and T. Veljanovski (eds.), *Computing Archaeology for Understanding the Past, Computer Applications and Quantitative Methods in Archaeology (CAA) Proceedings of the 28th Conference, Ljubljana, April 2000*: 279-286. British Archaeological Reports International Series 931. Oxford, Archaeopress.

Drobne, S. and Lisec, A. 2009. Multi-attribute decision analysis in GIS: Weighted Linear Combination and Ordered Weighted Averaging. *Informatica* 33: 459-74.

FAO 1976. A framework for land evaluation. *Soils Bulletin* 32. Rome: FAO.

FAO 2006. World Reference Base for Soil Resources (W.R.B.). A framework for international classification, correlation and communication. *World Soil Resources Reports* 103. Roma, FAO.

Goodchild, H. 2007. *Modelling Roman agricultural production in the Middle Tiber Valley, Central Italy*, Unpublished PhD thesis. Birmingham, University of Birmingham.

Grootes, P.M. and Stuiver, M. 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^{-3}- to 10^{5}-year time resolution. *Journal of Geophysical Research* 102 (C12): 26455-70.

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4: 390-405.

Kamermans, A. 2000. Land evaluation as predictive modelling: a deductive approach. In G. Lock (ed.), *Beyond the map. Archaeology and spatial technologies*: 124-46. Amsterdam, IOS Press.

Kvamme, K. L. 1989. Geographic Information Systems in regional archaeological research and data management. In M. B. Schiffer (ed.), *Archaeological method and theory* 1: 139-203. Tucson, University of Arizona Press.

Lake, M. and Conolly, J. 2006. *Geographical Information Systems in archaeology*. Cambridge, Cambridge University Press.

Le Roy Ladurie, E. 1971. *Times of feast, times of famine. A history of climate since the year 1000*. New York, Doubleday.

Le Roy Ladurie, E. and Goy, J. 1982. *Tithe and agrarian history from the Fourteenth to the Nineteenth Ccenturies. An essay in comparative history*. Cambridge, Cambridge University Press.

Levine, N. 2006. Crime mapping and the CrimeStat program. *Geographical Analysis* 38: 41-56.

Llobera, M. 2000. Understanding movement: a pilot model towards the sociology of movement. In G. Lock (ed.), *Beyond the map. Archaeology and spatial technologies*: 65-84. Amsterdam, IOS Press.

Macchi Jánica, G. 2001. Sulla misurazione delle forme d'occupazione sociale dello spazio medievale, *Archeologia e Calcolatori* 12: 143-65.

Macchi Jánica, G. 2009. *Spazio e misura. Introduzione ai metodi geografico-quantitativi applicati allo studio dei fenomeni sociali*. Siena, Università degli Studi di Siena.

Malanima 2009. Decline or growth? European Towns and Rural Economies, 1300-1600. *Jahrbuch für Geschichte des ländlichen Raumes* 6: 18-43.

Malczewski, J. 1999. *GIS and multicriteria decision analysis*. New York Wiley.

Montanari, M. 1985. Tecniche e rapporti di produzione: le rese cerealicole dal IX al XV secolo. In B. Andreolli, V. Fumagalli, M. Montanari (eds.), *Le campagne italiane prima e dopo il Mille. Una società in trasformazione*: 44-68. Bologna, Forni.

Redman, C. L. and Kinzig, A. P. 2003. Resilience of past landscapes: resilience theory, society, and the Longue Durée. *Conservation Ecology* 7, 1. Available from: http://www.consecol.org/vol7/iss1/art14/. [Accessed: 26 June 2015].

Russell, J. C. 1985. *The control of late ancient and medieval population*. Philadelphia, The American Philosophical Society.

Slicher Van Bath, B. H. 1963. *The Agrarian History of Western Europe A.D. 500-1850*, London, Edward Arnold.

Tomlin, C. D. 1990. *Geographic Information Systems and cartographic modelling*. Englewood-Cliffs, Prentice Hall College.

Van Joolen, E. 2003. *Archaeological land evaluation. A reconstruction of the suitability of ancient landscapes for various land uses in Italy focused on the first millennium BC*. Unpublished PhD thesis, Rijksuniversiteit, Groningen.

Van Leusen, M. 2002. *Pattern to process: methodological investigations into the formation and interpretation of spatial patterns in archaeological landscapes*. Unpublished PhD thesis. Rijksuniversiteit, Groningen.

Verhagen, P., Gili, S., Micó, R. Risch, R. 2007. Modelling prehistoric land use distribution in the Río Aguas Valley (S.E. Spain). In P. Verhagen (ed.), *Case studies in archaeological predictive modelling. Archaeological Studies* 14: 171-91. Leiden, Leiden University Press.

Visceglia, M. A. (1988) *Territorio, feudo e potere locale. Terra d'Otranto tra Medioevo ed Età Moderna*. Napoli, Guida.

When GIS Goes to the Countryside: Detecting and Interpreting Roman Orchards from the 'Grand Palais' (Drôme, France)

Christophe Landry
christophe.landry@inrap.fr

Bertrand Moulin
bertrand.moulin@inrap.fr

Institut National de Recherches Archéologiques Préventives (Inrap), CNRS – UMR 5138 'Arar', Lyon, France

Abstract: Preventive archaeology has a huge impact on our understanding of Roman agriculture in Gaul, but little has been done so far on the remains of olive groves and other orchards. The recent preventive excavations of Châteauneuf-du-Rhône (France), provide very opportune information to fill this gap.

On the site, the large number of planting pits – more than 1000 pits found on less than 1ha, makes it impossible to recognize coherent patterns at first sight.

To search for the meanings in the distribution, we used a method based on interpretation models that were constructed and tested. This work, through systematization of geometrical parameters measurement thanks to GIS, statistical analysis of the dataset, a correspondence analysis, followed by a hierarchical cluster analysis, led to define a typology of Roman orchards remains. This article provides a spatial characterization guideline for plantation analysis and a welcomed meaning to a spatial dataset in which patterns first seemed totally invisible.

Keywords: Roman orchards remains, Pattern recognition, Analytic spatial methods

1 Research background and main issues

For the last three decades, the identification of plantation traces in Roman Gaul is a recurring problem in rural and suburban archaeology. Research took great benefits of the major interest in wine and vine studies (syntheses on this subject have been published in Gallia 58 and 68.1, in 2001 and 2011) (Brun, Laubenheimer 2001; Poux, Brun, Hervé-Monteil 2011), and of the extensive excavations related to the development of rescue archaeology (TGV Méditerranée, highway A75). Thus, our understanding of vineyards is growing fast; the bibliography on this topic is extremely abundant, not only concerning Narbonnaise (for example the works of Philippe Boissinot, Martial Monteil, Laurent Vidal, Hervé Pomarèdes and Cécile Jung; in particular: Boissinot 2001; Monteil *et al.* 1999; Pomarèdes *et al.* 2008), but also Lyonnaise, Aquitaine and Belgian Gaul (in particular: Cribellier 2011; Garcia *et al.* 2010; Poux 2011; Toupet, Lemaître 2003; Vallat, Cabanis 2009).

However, research on other aspects of arboriculture is just beginning. Indeed, even if antique olive-growing could be studied thanks to the oil mills excavated in Narbonnaise (Brun 2005), as well as exhaustive studies on fruit-growing during Middle Ages (Ruas 2006), tree plantations studies are still very scarce for Antiquity. Moreover, many limits make it difficult for interpreting their archaeological traces.

About 20 sites with plantations not related to wine-growing have been collected for the whole Roman Gaul territory (Fig. 1), not always published. Besides, it is almost certain that further investigations into the excavation archives of some regions would increase this dataset. This one is essentially compiled from data derived from rescue archaeology excavations (TGV Méditerranée: Barberan *et al.* 1997; Le Meur *et al.* 1997; A75 highway: Mauné 2003; Jung, Bel 2010; Jung 2011; Pomarèdes 2011; Bourgaut 2010; Ronco 2012; Ott, Pancin 2006; Vallat, Cabanis 2009), within which only a very few sites led to a precise study of arboreal traces. The first studies were made on the outskirts of Reims, in the Marne (Koehler 2003), and the last in the Côtes-d'Armor (Arramond, Requi 2012). But it is the plantations discovered on the A75 delineation, in Valros (Hérault), which gave the impulse to undertake systematic and thorough analyses of these types of remains (Jung *et al.* 2008). Thus, the works in progress of the group 'Territoires et sociétés de l'Antiquité au Moyen Âge' (UMR 5140 'Archéologie des Sociétés méditerranéennes'; dir. C. Jung and H. Pomarèdes), should give an answer to many questions in this new field of research.

But, up to now, one must admit that palaeoenvironemental analyses, as well as metrological data, are not systematically used on sites with agrarian traces that are not related to wine. Indeed, presented values are generally limited to approximated means, which do not permit statistical approaches, even if they do coincide with the study protocol proposed by Philippe Boissinot (Boissinot 2001) (lo/la/de/re/dc/rc).

2 Presentation of the Grand Palais

During the winter of 2010-11, a rescue operation conducted by the Inrap Rhône-Alpes in Châteauneuf-du-Rhône (Drôme), on the Grand Palais site, unearthed the surrounding land of an

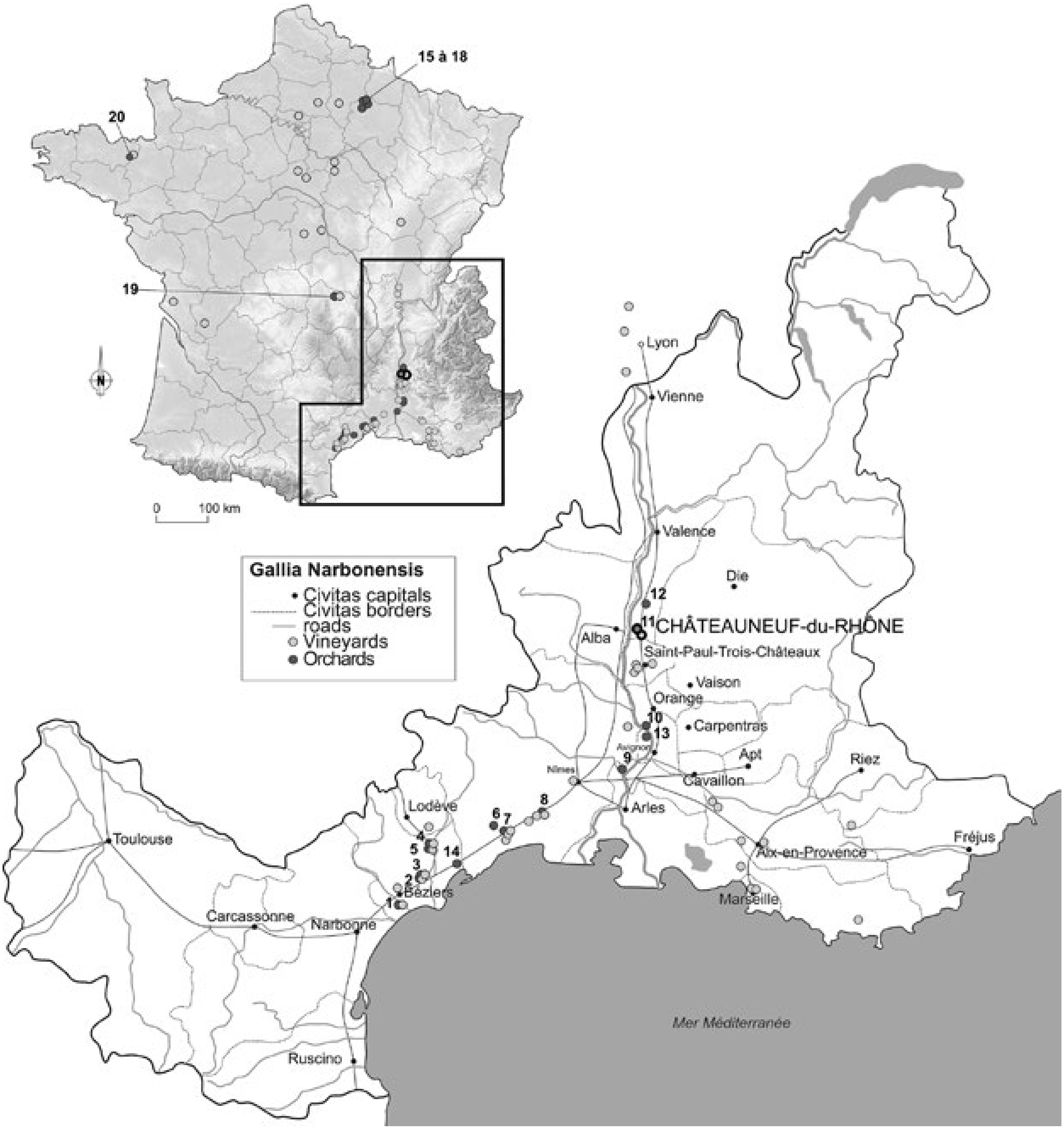

Fig. 1. Map of the main Roman sites with orchards/vine remains in Gaules (1: Sauvian (Hérault). 'La Lesse'; 2: Valros (Hérault). 'Aire de repos'; 3: Valros (Hérault). 'Champ Redon'; 4: Aspiran (Hérault). 'St-Bézard'; 5: Paulhan (Hérault). 'Vareille'; 6: Montpellier (Hérault). 'ZAC Malbosc III'; 7: Montpellier (Hérault). 'Mermoz'; 8: Lunel (Hérault). 'Mas de Fourques'; 9: Montfrin (Gard). 'Le Réal'; 10: St-Victor-la-Coste (Gard). 'Mayran'; 11: Châteauneuf-du-Rhône (Drôme). 'Le Grand Palais'; 12: Savasse (Drôme). 'La Croze'; 13: Roquemaure (Gard). 'La Ramière'; 14: Poussan (Hérault); 15: Reims (Marne). 'Rue Clovis - Îlot Capucin Hincmar'; 16: Cernay-les-Reims (Marne). 'Pelle à Four'; 17: Cernay-les-Reims (Marne). 'Les Petits Didris'; 18: Caurel (Marne). 'En droit le clocher'; 19: Les Martres-d'Artière (Puy-de-Dôme). 'Champ Chalatras'; 20: Le Quiou (Côtes-d'Armor) (Rigaud P., Landry Chr., Inrap).

antique domain and brought a new contribution to the study of arboreal traces (Landry 2012). The site is 200m to the east of the remains of the Palais area (Fig. 2), known since the 19th century, and identified as the *pars urbana* of a *villa* since the excavations conducted by J.-C. Béal from 1997 to 2001. In the Grand Palais, an opening of 1.35ha unearthed a part of the *villa*'s *pars fructaria*, composed of a plantation area of 1029 structures, within which are 779 excavated structures that can be related to the plantation pits of different tree species (Fig. 3). The evident diversity of cultures that could be seen in the Grand Palais provided an occasion to deepen the investigations into antique arboriculture as a whole.

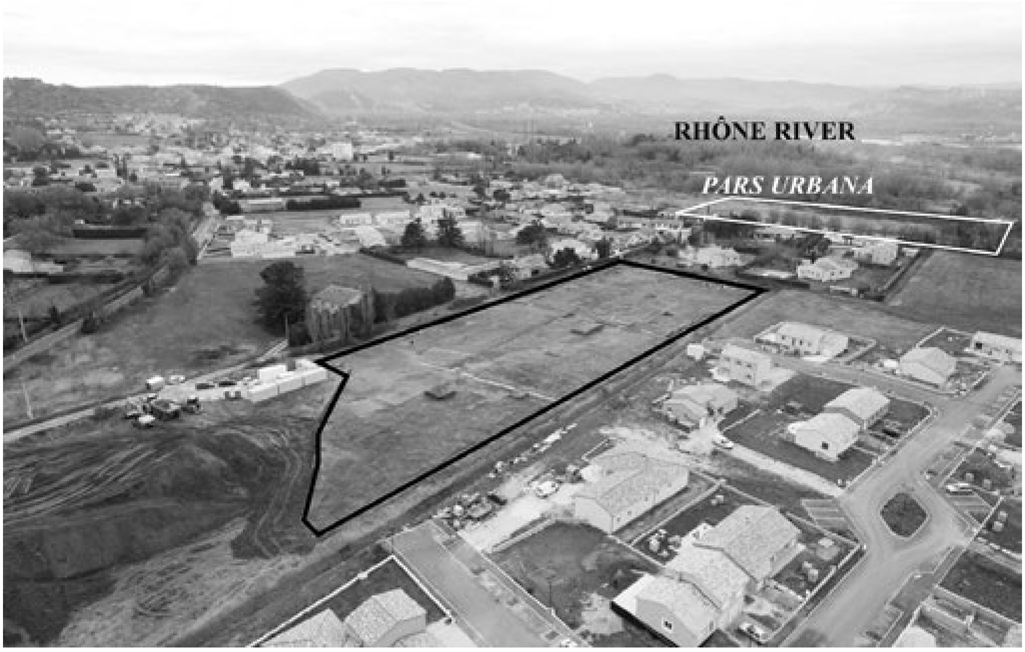

Fig. 2. Aerial view of the site (Gentil-Perret J. P., Inrap).

The main results from the Grand Palais excavations helped build a chronology of agrarian exploitation. It started during the first century BC with the setting up of a first orchard. During the Haut-Empire, what is thought likely to have been an olive grove creates a real indicator of exploitation. Later, other species replaced this plantation in increasing density, up to 1500 trees on the estimated three hectares of land exploited.

Many systems are sequential or combined, testifying to the variety of cultivated species; one of them required the implantation of an orthonormal irrigation system. The analyses of culture methods, edaphic conditions and paleobotanical spectrum enable an hypothesis for the identification of cultivated species: almond, fig or plum trees. Around the end of the third century the site was devastated by strong floods and the domain restructured. The orchards were abandoned and the field was well drained by a structured network of collecting channels. During Late Antiquity production was diversified and probably combined cereal cultivation, stock breeding and wine production – two exploited vineyard areas were, indeed, comprised within the studied region. Unfortunately, plantation pits only revealed very few artefacts, and paleoenvironemental analyses did not provide significant elements.

3 Approach

For these reasons there was a strong need for functional characterization using morphological and metrological criteria. The present article will not lay out the discussion which led to the hypothesis about the evolution of the antique plantation of the Grand Palais. Instead we will here present the metrological and statistical analyses that were used to compute the data collected during the excavation. The characterization of the plantations helped to create a typology based on both the module of excavated structures and the patterns among which the pits were distributed. The plantations that can be related to wine-growing will not be discussed as they perfectly fit into P. Boisinnot's typology (Boissinot 2001). We will thus exclude the two *scrobe* parcels that represent type 2 of this classification.

3.1 Study area

The site is on a pleistocene alluvium terrace of the Rhone, at an altitude of 75m, to the south of the Montélimar plain and at the entrance of the narrow Donzère valley that leads to the Tricastin. The Riaille, a tributary stream on the left side of the Rhone, runs to the north of the site. This river, which is dry during part of the summer, has a Mediterranean torrential nature that may bring heavy deposition or erosion. During some periods this stream significantly affects the site and creates a pronounced hydromorphic context due to the presence of an important groundwater table which certainly had much influence on cultivation in this area (Brochier *in* Landry 2012: 58).

The Grand Palais became a suitable environment for human settlement thanks to the close proximity of natural transportation routes, such as the Rhone and the Donzère valleys. For this reason the plain was densely occupied in Antiquity, within the territory of the Tricastin city. The remains that were excavated in 2010-2011 are, indeed, only 3.5km west from the estimated alignment of the *via Agrippa* (Jung 2009: 87-90).

The works of J.-C. Béal on the Palais *villa*'s *pars urbana* prove that the first construction phases began as soon as the Augustan period. The settlement saw changes during the Haut Empire and further evolved during the 4th century into a 'rural palace' (Béal 2002: 25). Many modifications, reoccupations and late scavenging took place before its assumed abandonment during the 5th century. The *pars urbana* is located north of the century DD XXXII VK III of the Orange B cadaster, and spreads onto an area of 10,000m², organized around a four-sided portico and a north-south symmetrical axis.

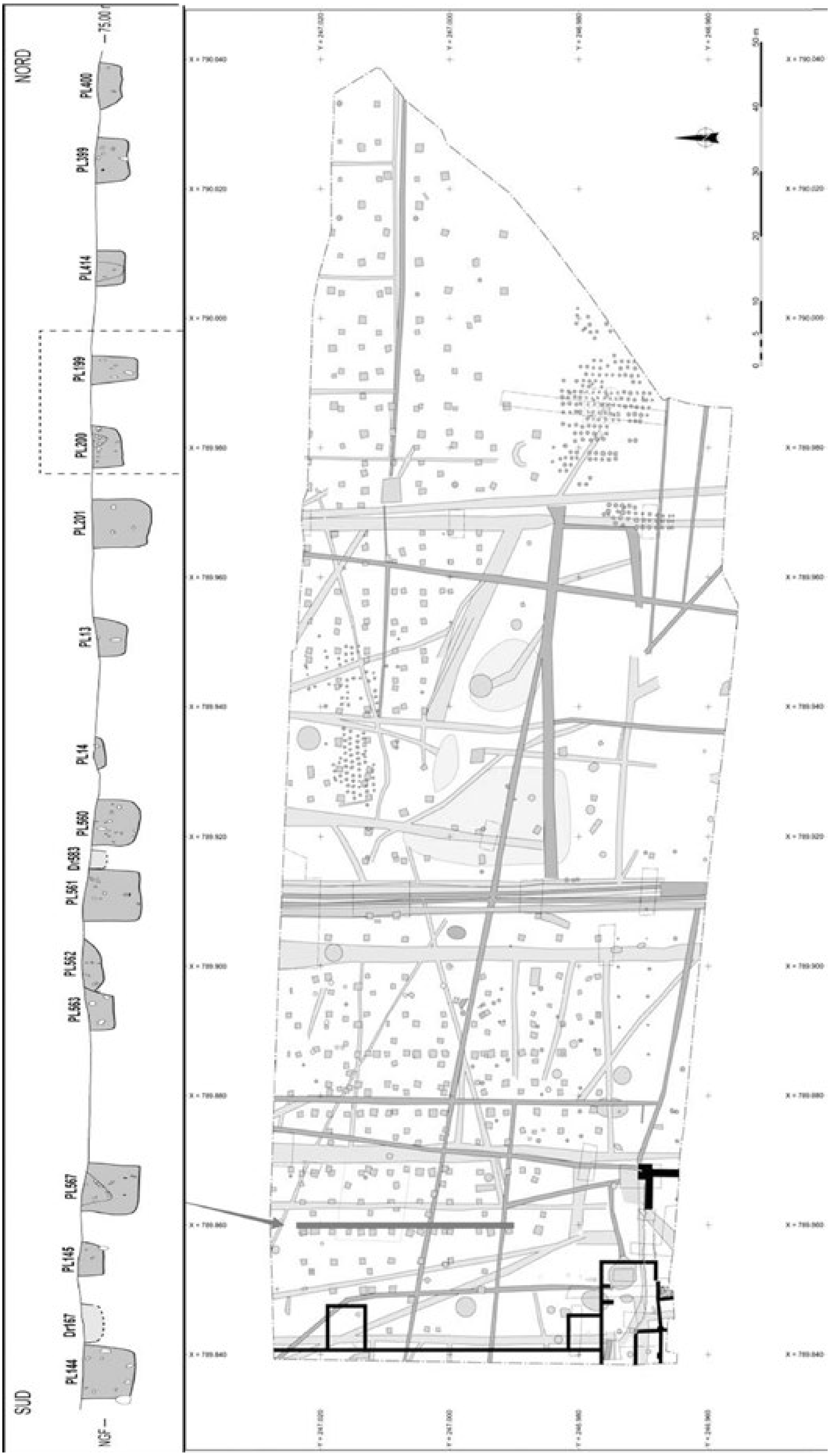

Fig. 3. General map of the Grand Palais site and an example of a section with several pits showing different states or phases (Rigaud P., Vachon V., Landry C., Inrap).

3.2 Method

3.2.1 Systems identification

Due to the multiplicity of field data and the complexity of the plantation plan, GIS turned out to be a crucial tool for understanding the organization of the cultivated domain. Indeed, statistical and geometrical analyses quickly proved incontrovertible, independently from any questioning regarding the nature of plantations.

Early observation of the plan showed that the pits followed an orthonormal logic, as prescribed by the antique agronomists (the latest being Pliny the Elder, Columelle and *Palladius*) and the techniques used by Roman surveyors (cords, stakes, *groma*...). The first statistical analysis attempted to use morphological criteria, across the whole set of structures, but it did not give sufficiently discriminatory results due to the multiplicity of variables. Hence, it seemed necessary to divide the dataset following coherent criteria that could be obtained through graphical and geometrical analysis. The aim of this first step was the definition of homogeneous patterns within the plantation. In this regard, a system is a culture set corresponding both to a plantation phase and a parcel. This precision is needed because of the overlapping of many pits and of a dense network of ditches that structures the plantation and sometimes breaks the regular alignment patterns of structures.

This systemic approach can only be supported if two tempting hypotheses are rejected. The first one considers the square pits of the Grand Palais as remains of the cubical *scrobes* mentioned by Pliny the Elder (*Histoire naturelle*, XVII, 35), measuring 3 feet in length and given over to vine planting. On this topic, P. Boissinot wrote in 2001 that 'the rare examples of this type, in Gaul, are rather tree plantation pits. In fact they are never found as series, unless they are located following great spacing' (Boissinot 2001: 51). As a matter of fact, here, a great number of quadrangular pits correspond to this module, and are aligned with sometimes very narrow spacing, close to the 'tightened' type 3 of Boissinot's typology. Therefore, one could interpret them as vineyards; but comparisons are scarce in Gaul and, most of all, are clustered into the region of the Grand Palais: the middle Rhone valley (sites of Lapalud – Les Girardes (Boissinot, Roger 2004); Dèves (Boissinot 2001: 68); Saint-Restitut (Durand 2011); Pierrelatte – Le Freyssinet (Ferber 2011). Therefore this kind of vineyard looks like a regional particularity; however, even so, the Grand Palais cannot be included with this scheme. Indeed the totality of quadrilateral pits does not show the same extreme regularity as Les Girardes and other neighbouring sites. Furthermore, the ratio length/width is much closer to 1, and thus they are not oriented in terms of length, as is the case in Lapalud. Finally the overlapping of some pits shows that their density is far less than initially estimated, implying that the spacing between the pits is wider than previously thought. Added to the fact that no traces of layering have been identified, the hypothesis of a Boissinot type-3 plantation, corresponding to a vineyard, can not be corroborated.

The second enticing assumption concerns the *alberate* training system, also known as the growing of vines on trees. The presence of pits with a 3- or 4-feet module, combined with the overlapping and interlocking of 2-feet module pits in some areas, naturally led to this idea. The technique of growing

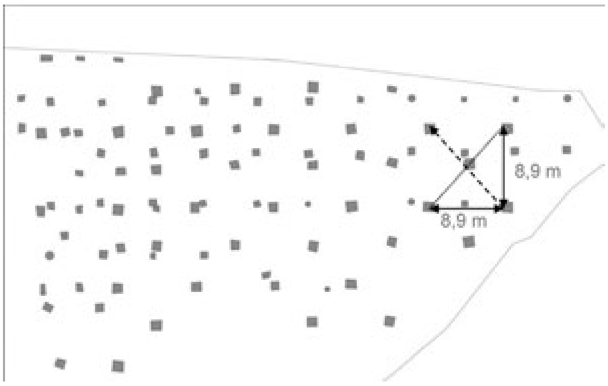

Fig. 4. Searching for regularity in an uncomplicated part of the site, using random geometric means to select a first module of 4 pits (Landry C., Inrap).

vines on trees is therefore mentioned by early agronomists, notably concerning Gaul (Columelle, *Les arbres*, XVI, et *De l'agriculture*, V, 7; Pline H.N. XVII, 35; Palladius, *L'économie rurale*, III, 10). The identification of this technique at the Grand Palais has recently been refuted, e.g. during the conference of Saint-Romain-en-Gal on wine in Antiquity (Landry forthcoming).

Thus, the premise that the overlapping of pits rather shows a succession of phases instead of one plantation type can be validated. If we consider that the structures comprise several systems, the spacing between the pits does not correspond to wine growing (Fig. 3). On the other hand, when analysed using *pes monetalis* they perfectly fit into the recommendations of early agronomists concerning arboriculture.

The geometric analysis was first tested in the eastern area, where the organization of quadrangular pits is the most legible (Fig. 4). A first pit was arbitrarily chosen, from which two lines are projected at a right angle from its centroid, and in every direction where the centroid of another pit could be crossed. The segments created by the crossed lines and quadrangles were then systematically measured and their values compared. If two perpendicular segments were of equal or very similar length, a square was drawn through a central symmetry projection. If the fourth point of this theoretical square matches with the centroid of a fourth pit, the square module is projected into the four directions using axial symmetry (Fig. 5). Then, if the eight new estimated points still match with the centroids of other quadrangles, the module is validated and expanded as a grid pattern. Every pit that coincides with the cells of the grid is associated to the system. Afterwards the operation is reiterated for the remaining pits until every quadrangle can be associated to a system (Fig. 6). The same process was applied to circular and oval structures, using ellipses centroids and point reflection projections.

The three first systems were defined for quadrangular pits of the northern part of the East area. The measures of the modules' sides were then compared to the traditionally admitted value of the classical Roman foot, or *pes monetalis*, of 0.2957m (Boissinot 2001: 62; Barthèlemy, Dubois 2007: 374). It implies here that we do not suppose the existence of a parallel local measurement system. The resulting values are very close

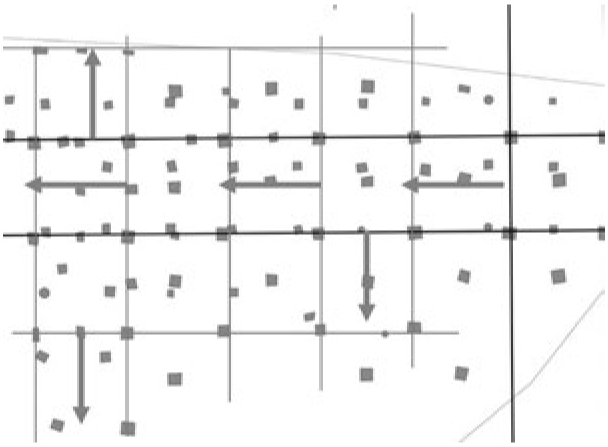

Fig. 5. The module can be repeated in all directions, so as to validate a first grid pattern (Landry C., Inrap).

to integers: 30 for the first two systems, and 20 for the third system. In these three cases the sides of the modules were then smoothed towards the integer values. Even so, every structure still fitted to its system, which corroborates the viability of this method. From this point statistical analysis could be applied to each system, in order to validate the systemic hypotheses. This was undertaken with no assumption of the interlocking or contemporaneity of the systems.

The following step was made using GIS tools by B. Moulin. The calculation of descriptive statistics used length (lo), width (la), depth (prof), and the bottom and sides' shapes of the structures. Mean, median and quantiles are calculated for the Grand Palais systems, and compared to the values that can be extracted from the quadrangular pits from the Lapalud vineyard (Boissinot 2001, Fig. 19: 60). In this way, 're' is the side-to-side spacing between pits of two neighbouring rows from the same system; 'rc' is the distance between the pits centroids; 'de' is the gap between the sides of two pits of the same row; and 'dc' is the spacing between the centroids of these pits (Fig. 7). For Lapalud it appeared that all the pits were included within a unique system, from which the precise standardization of pit length and width clearly showed the alignment orientation. For the Grand Palais, statistical analysis had to be made for every orientation hypothesis, before giving an absolute value for 'lo' and 'la' following Boissinot's method, and then validate one of the orientation hypothesis. However the preliminary encoding of the measurements required an arbitrary orientation shared by every system. To this end a N/S orientation was used – this N/S segments correspond to 'lo', and E/W segments to 'la'. For the statistical analysis, 'lo' is however attributed to the longer segment. Once the values have been calculated for each system their proportions were calculated to estimate the exact length of the foot unity used on the site, given that this value could only differ marginally from the *pes monetalis*.

3.2.2 Spatial analysis

The extraction of data related to the geometry of plantation systems, which were identified using the method previously described, was made using GIS tools of ArcGIS-ESRI. Measures were calculated for each system with the support of the following replicable routines:

1. Selection of a system using the topographical survey made during excavation.

2. Extraction of each plantation pit's centroid belonging to a system.

3. Double coding of the centroid, following N/S and E/W axes.

4. Polylines creation using centroids of the previous step; each portion of a polyline is enclosed between two points that are the centroids of a pit.

5. Intersection of N/S and E/W axes; calculation of distance N/S (dc) and E/W (rc) between each plantation pit's centroid belonging to a system (Fig. 8).

6. Extraction of polylines (rc, dc) portion's azimuth regarding true north for each system.

7. Splitting of N/S and E/W axes using the polygons corresponding to the plantation pits of a system and calculation of the length of the lines that fall inside the polygons (lo, la). The orientation of the pit according to north is calculated with Excel spreadsheet and an IF formula.

8. Selection of line portions that fall outside plantation pits and calculation of their lengths (re, de).

This processing generated a table collecting the following values for each identified plantation system: lo, la, re, de, rc, dc, az_rc, and az_dc. Descriptive statistics of each measured system were then made using this new data table (Fig. 9 and 10).

3.2.3 Statistical analysis

Following a correspondence analysis, hierarchical clustering was performed using Excel and XLstat software in order to aggregate structures given their accordance, using a similarity and dissimilarity coefficient. The algorithm, given by Ward's Method, starts collecting the most similar pairs, and gradually aggregates other structures or groups regarding their similarities, until the whole set of structures comprises a unique group. Hierarchical clustering creates a classification binary tree (dendrogram) (Fig. 11), of which roots correspond to the class including the whole data; it represents a partition hierarchy, these partitions being separable at given similarity levels. In this manner, the limits are under the first node (each class has only one structure), and above the last level (one class containing all the structures) of the tree.

Euclidean metric (classical geometry space) could not be used. Indeed, the Euclidean distance increases in parallel to the number of variables; its value also depends on the scale of each variable, which means that by changing the observation scale the results may greatly differ. This problem can be avoided by standardizing the variables or using the Chi² distance; in the case of this last processing, each line value is reported to its sum and the distance is calculated using the inverse weight of the column value. In other words the Chi² distance is the calculation of the Euclidean distance on data converted following: $X_{ij} \rightarrow X_{ij} / (X_{i}.vx.j)$, given that X_i is the sum of

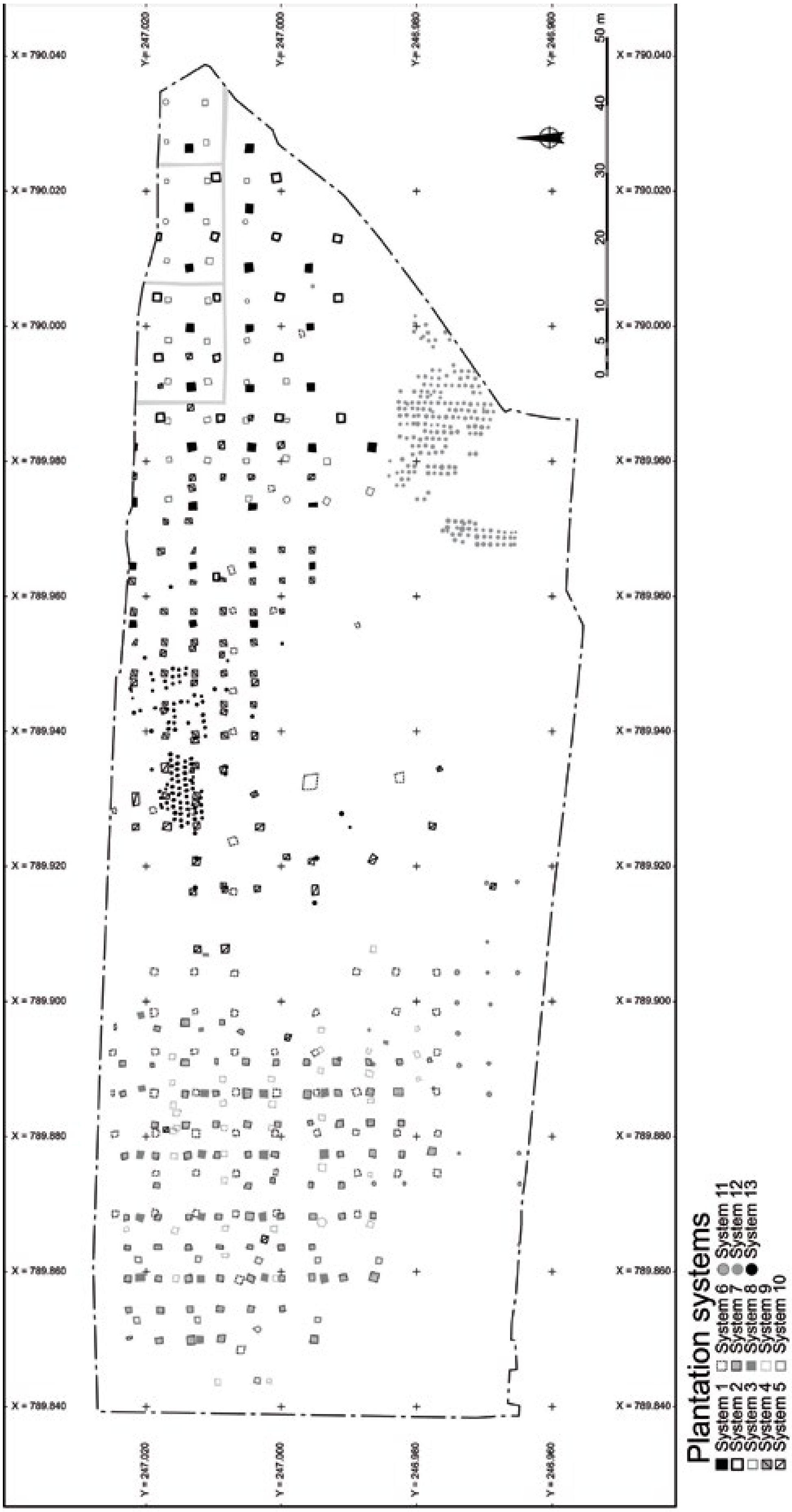

Fig. 6. Map of the 13 different systems determined by geometric method (Landry C., Inrap).

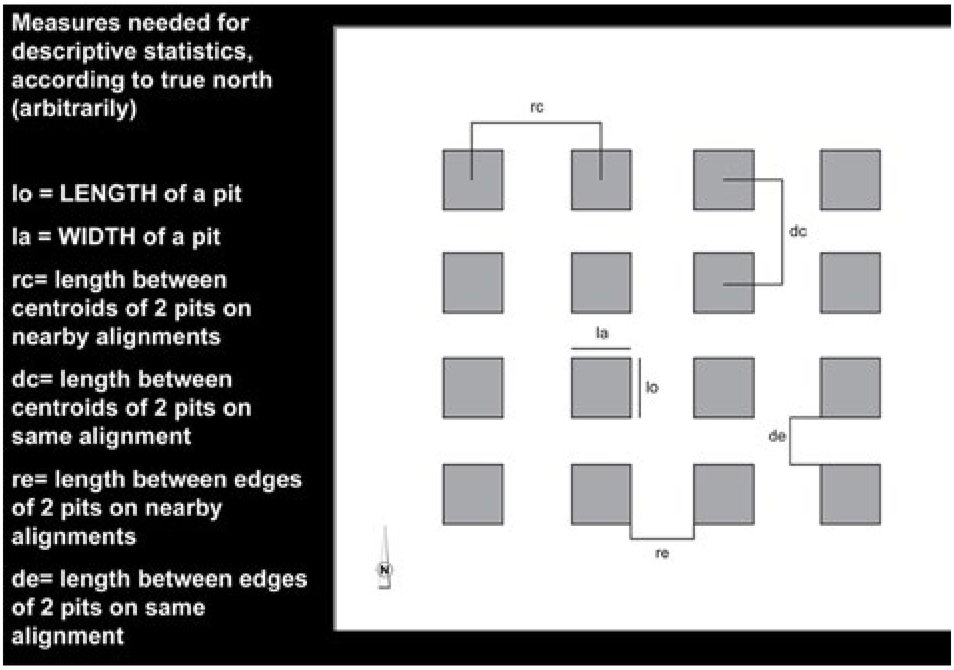

Fig. 7. Recording norms for studying the plantation pits (Bioul C., Landry C., Inrap, after Boissinot 2001).

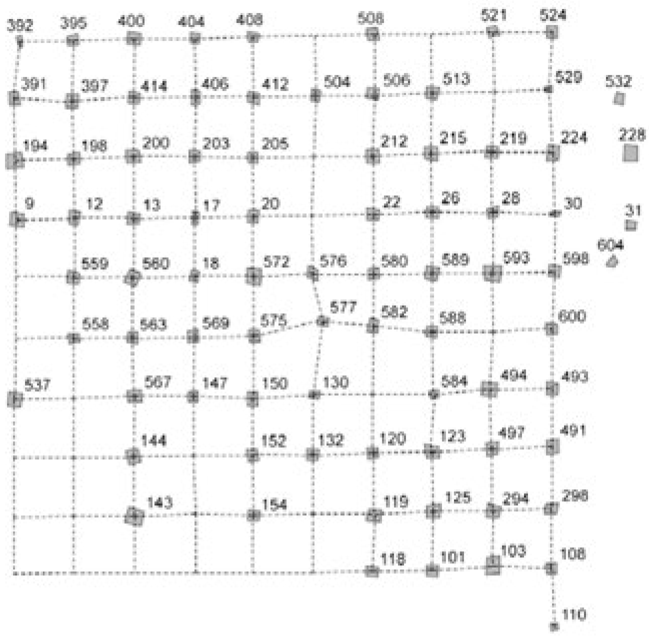

Fig. 8. Results of the work on ArcGis for system 7 (Moulin B., Inrap).

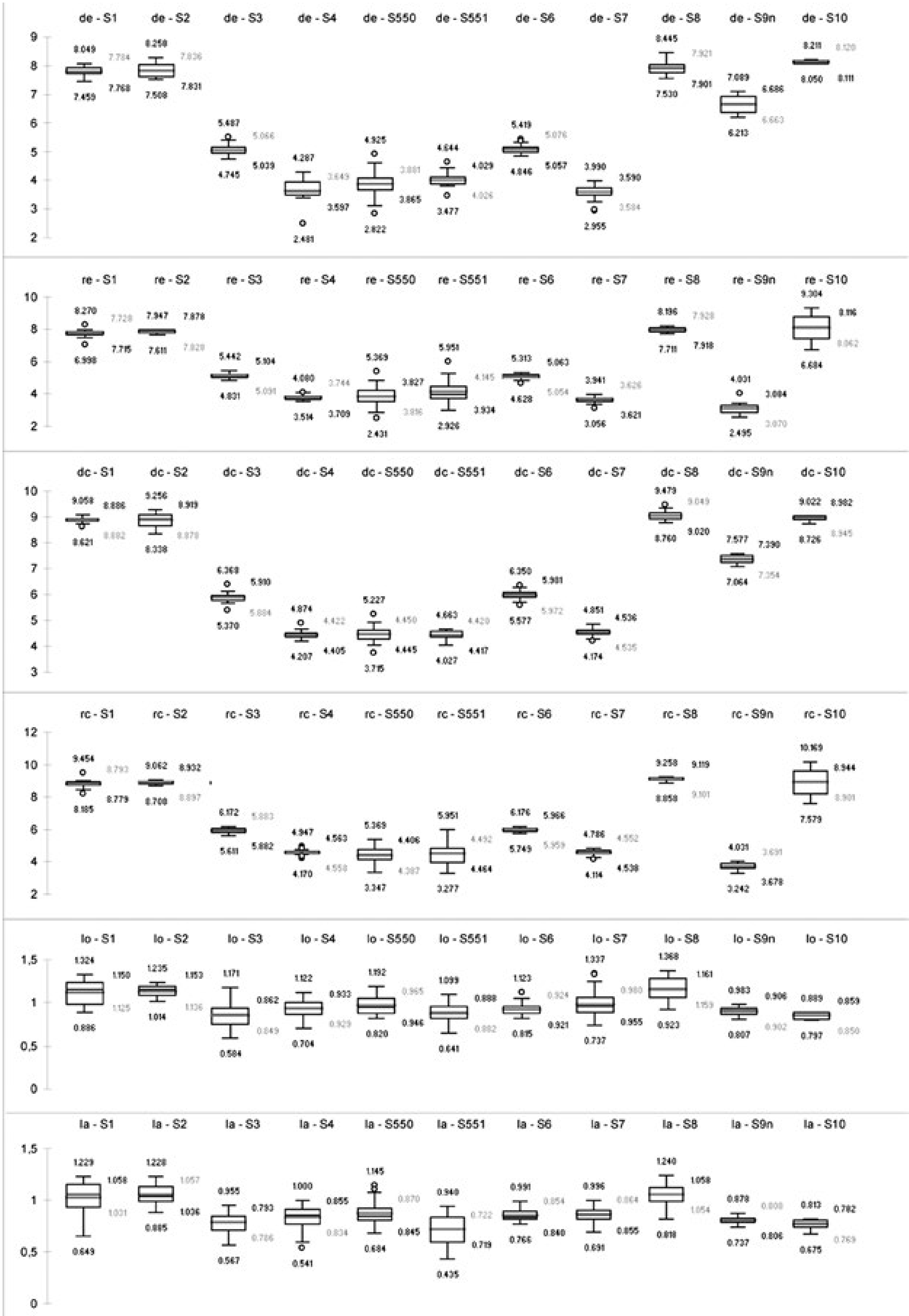

Fig. 9. Statistical results for measurements of all the systems (lo, la, dc, rc, de, re) (Moulin B., Inrap).

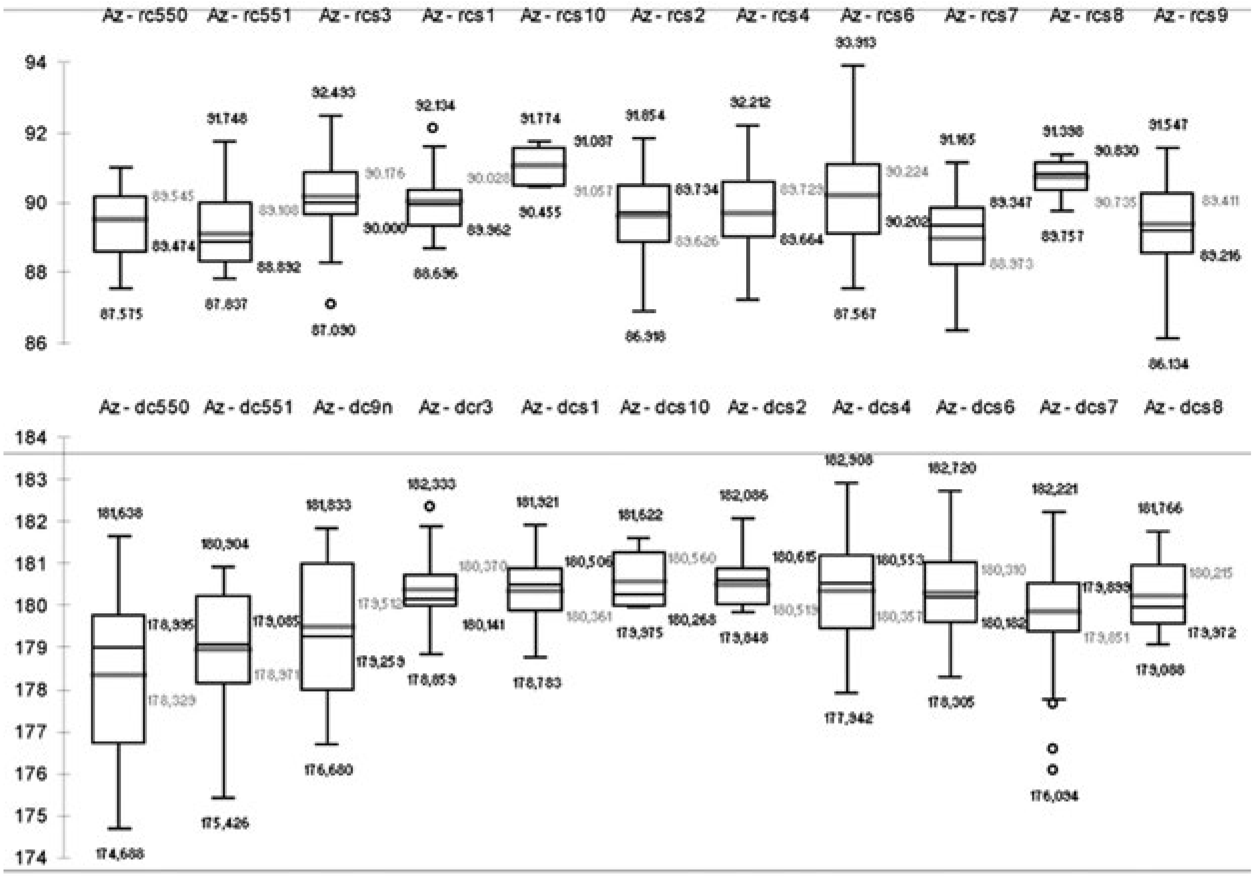

Fig. 10. Statistical results for azimuths of all systems (Moulin B., Inrap).

columns for row i, and X_j the sum of row for column j. The Chi² distance fulfils the distributional equivalence requirement, namely that the distance between rows and columns will not change if the value of two rows or two columns with the same profile is replaced by their sum. Finally, the Chi² distance is well adapted to homogeneous counting tables or extensive measures (weights, distances, percentages).

3.3 Results

The preliminary geometric analysis shows 13 coherent systems (Fig. 6). Three of them are composed of circular and oval pits, corresponding to two system types that do not need the complete statistical processing to be interpreted. The ten remaining systems were analysed through the complete spatial and statistical protocol. It must be specified that all measures were processed; the occasional spread of values within a system (in particular for lo, la, de and re) is due to taphonomical phenomena; indeed, the loss of the original opening layers and the varying levelling of structures may have a certain influence on the structure's shape – and, therefore, its associated measures. Despite this, these data are still necessary for comparisons because of the non-preservation of contemporary floor layers at other sites. It also must be remembered that the number of structures varies for each measure, following the exclusion of structures with low-quality data recording.

3.3.1 System descriptions

Descriptive statistics of each quadrangular pit system are presented in Figure 9. The 13 systems can be defined regarding the following characteristics:

- System 1

29 quadrangular pits over 2837m², in the north-east of the excavation area. Structures follow an orthonormal pattern perceptible by nine N/S and five E/W oriented lines. The observed density is 102 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 128 structures per hectare (Dmt = 10,000 / (rc moy x dc moy)).

- System 2

18 quadrangular pits over 1948m² , in the north-east of the excavation area. Structures follow an orthonormal pattern perceptible by seven N/S and four E/W oriented lines. Observed density is 92 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 127 structures per hectare.

- System 3

36 pits over 1975m², in the north-east of the excavation area. Structures follow an orthonormal pattern perceptible by eleven N/S and six E/W oriented lines. An orthonormal irrigation ditches network has been dug especially for this system. Observed density is 182 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 289 structures per hectare.

- System 4

39 quadrangular pits over 1713m² in the centre of the excavation area. Structures follow an orthonormal pattern perceptible by fourteen N/S and seven E/W oriented lines. Observed density is 227 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 517 structures per hectare.

- System 5

48 quadrangular pits over 7384m², 71% of the structures being in the central area. Three pits from the western area follow this system and eleven structures in the eastern area (System 5bis). Due to the many gaps and some offsets in the central area, it seems logical to associate Systems 5 and 5bis. This system could have been less rigorously implanted; gaps could also be explained by its creation prior to other systems, which would have overlapped – and partly destroyed – System 5, while the loss of the southern part can be related to erosive processes. The offset between Systems 5 and 5bis can also be an argument in favour of plot demarcation. Taking all the 48 structures into account the structures follow an orthonormal pattern perceptible by twenty-nine N/S and thirteen E/W oriented lines. Observed density is 65 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 517 structures per hectare.

- System 6

68 quadrangular pits over 7879m² and extending into the three areas of the plantation. Structures follow an orthonormal pattern perceptible by twenty-seven N/S and nine E/W oriented lines. This system was apparently altered by destructive phenomena which took place, in particular, in the central and eastern parts. This observation can also support the combination of System 6 with another contemporary system. Given this, the analysis concerned the western area where the pattern seems more homogeneous and shows border effects that might be related to plot demarcation. Observed density is 86 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 281 structures per hectare.

- System 7

83 quadrangular pits over 2391m², west of the excavation area. Structures follow an orthonormal pattern perceptible by nine N/S and five E/W oriented lines. Observed density is 347 structures per hectare; if we restore the complete set by filling the gaps then theoretical mean density increases to 484 structures per hectare.

- System 8

20 quadrangular pits over 2358m², west of the excavation area. Structures follow an orthonormal pattern perceptible by seven N/S and five E/W oriented lines. Observed density is 85 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 119 structures per hectare.

- System 9

37 quadrangular pits and a circular pits over 8516m², west of the plantation area. The organization does not correspond to a pattern and follows a E/W alignment; no N/S lines are perceptible. The spacing between the structures of the same row (de, dc) is fixed for the whole system, as well as the distance rc. Observed density is 45 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 381 structures per hectare.

- System 10

10 quadrangular pits over 820m², west of the excavation area. Structures follow an orthonormal pattern perceptible by three N/S and five E/W oriented lines. Observed density is 122 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 126 structures per hectare.

- System 11

22 quadrangular pits over 1369m², west of the excavation area. Structures follow an orthonormal pattern perceptible by thirteen N/S and seven E/W oriented lines. Observed density is 160 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 479 structures per hectare.

- System 12

202 quadrangular pits over 702m², east of the excavation area. 37 pits were fully excavated, of which 40% are circular and 60% oval; structures are oriented on a N/S axis. Observed density is 2877 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 10,878 structures per hectare.

- System 13

110 pits over 1625m², in the central area of the excavation. 59% of the pits are circular and 41% oval; structures are oriented on an E/W axis. 35 pits are visible but only six were sufficiently well preserved for the density calculation. Thus the observed density is 4539 structures per hectare; if we restore the complete set by filling the gaps then the theoretical mean density increases to 11,708 structures per hectare.

3.3.2 System orientation

The largest length of 56% of quadrangular pits of Systems 1, 2 and 6 is oriented N/S, and 55.9% of Systems 3, 7 and 8 is oriented E/W. This random distribution seems to demonstrate that no alignments were preferred, in favour of the global orientation of the pattern. In this manner the azimuth calculations (Fig. 10) show that each system is related to true north, with a quasi perfect N/S and E/W orientation. In the end,

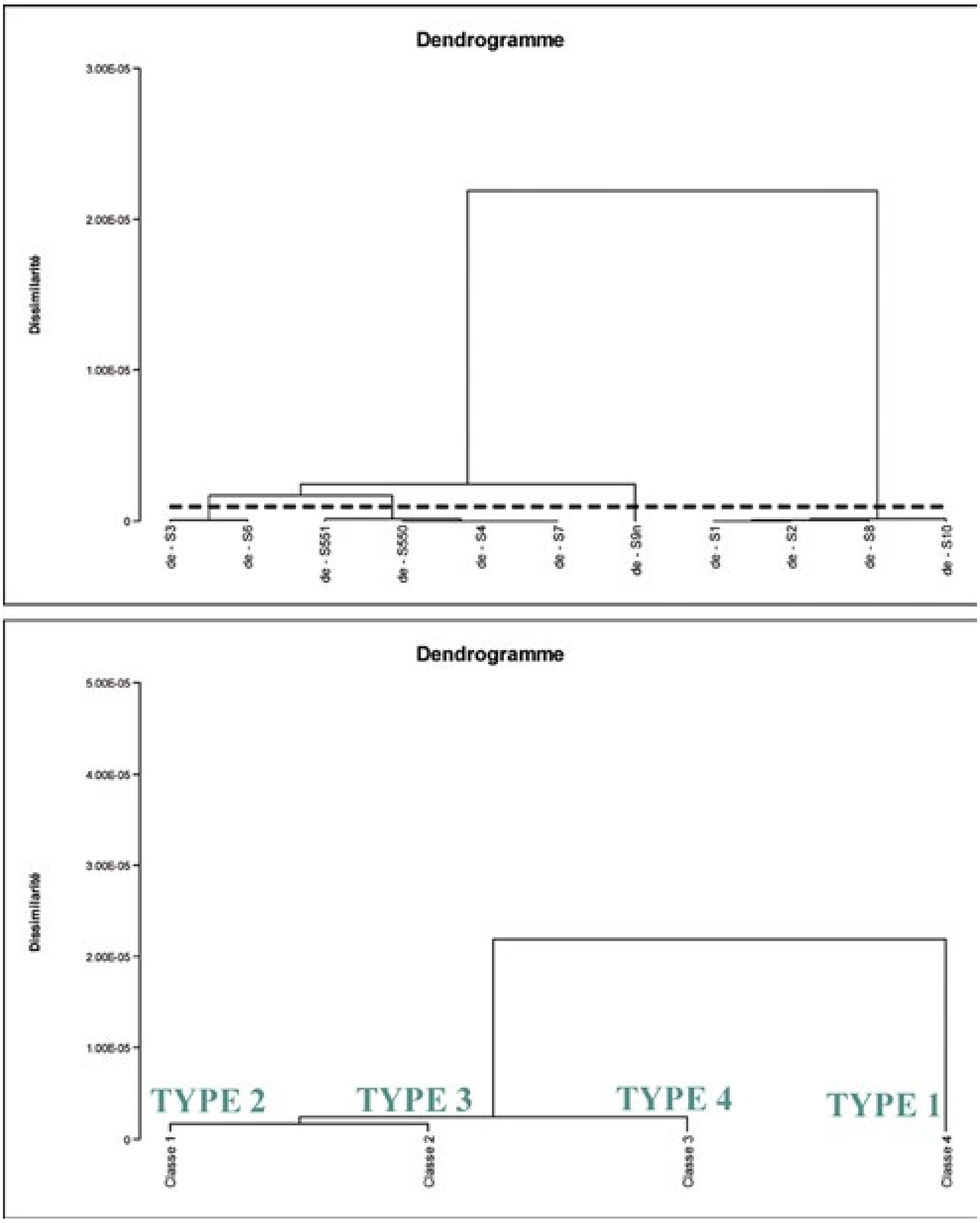

Fig. 11. Results of correspondence analysis and hierarchical cluster analysis, leading to a typology of systems (Moulin B., Inrap).

the difference between the length and width of quadrangular pits seems not of much importance (mean difference of 10cm and median value of 6.5cm). Moreover, given the asymmetry of the erosion process it is plausible that the pits were initially square-shaped.

3.3.3 Typology of quadrangular pit systems

Hierarchical clustering creates a dendrogram distributing 390 quadrangular pits, composing ten systems, into four types (Fig. 11). Type 1 includes systems 1, 2, 8 and 10, type 2 the systems 3 and 6, type 3 the systems 4, 5 and 7, and type 4 corresponds to system 9. In order to define these system types, it is necessary to convert the metric measurements to *pes monetalis* standard values (1 foot = 0.2957m). Following this it appears that dc and rc values are closer to integers, and are a multiple of 10, and sometimes 5. These results confirm that each system was indeed planted using an orthonormal pattern. Other measurements seem strongly influenced by taphonomical conditions; this is supported by the remoteness of lo and la to integers. They must therefore be rounded to the closest upper foot or half-foot. This leads to four morphological plantation types:

Type 1: orthonormal pattern module of 30 feet; pit modules of 4 feet.

Type 2: orthonormal pattern module of 20 feet; pit modules of 3 feet.

Type 3: orthonormal pattern module of 15 feet; pit modules of 3 feet.

Type 4: offset alignments; patterns with variable modules, where rc is 24 feet and dc 12.5 feet; pit modules of 3 feet.[1]

[1] The use of a non-orthonomal pattern, half-foot (or two palms) and spacing that are not multiples of 10 or 5, breaks with the arrangements of the other quadrangular pit plantation systems.

3.3.4 Typology of circular pit systems

The three other systems, composed of circular pits, were not taken in account within the hierarchical clustering. System 11 is Type 6[2] with an orthonormal pattern module of 15 feet and a circular pit module of 2 feet. According to the relative chronology of plantations this type is the oldest; for this reason it was discussed separately at the Saint-Romain-en-Gal conference (Landry, forthcoming). Its interpretation is still debated.

Systems 12 and 13 comprise Type 7, with a spacing of 3 feet between both the rows and the pit centroids of a same row; the pits are circular and have a 2 feet module. They fit Boissinot type 2, leading to the identification of these systems as vineyard types that are frequently found in Narbonnaise; as for the previous Type 6, we will not present here the detailed arguments for this assumption. When converted into Roman measurement units[3] the density corresponds to 273 trees per *jugerum* for System 12[4] and 2946 trees per *jugerum* for System 13.

3.3.5 Standard values for the Grand Palais plantations

The value of the foot used for each system can be more precisely estimated when taking into account every measurement. By calculating the mean of every measurement of the whole systems, the foot appears to be 0.2959m long; when decreasing the margin of error by using only values related to centroids, it changes slightly to a length of 0.296m. In both cases, the difference with the commonly acknowledged value of the *pes monetalis* is extremely small (0.2 or 0.3mm). This tiny variability attests, once more, to the precision of the techniques used by Roman surveyors.

This precision is confirmed by the standard deviation that shows the variance of recorded measures. The mean standard deviation of all the systems does not exceed 0.20m for values calculated from centroids, and 0.14m for dimensional values of the pits. When considering the four most coherent systems (1, 2, 3 and 6), the mean standard variation does not go beyond 0.16m. This variability is thus minimal regarding the width of the studied area; it shows the coherence of employed plantation techniques, and the rigour of their application.

4 The results

4.1 Interpretations and comparisons

Study of the digging of the pits, their filling process and root system traces give indications of the species cultivated. Likewise, the results of malacological studies depict the edaphic conditions of the site before and during the exploitation of the plantation. Palaeobotanical studies give some information regarding families, however the markers are not of a sufficient number and do not correspond to other culture indicators of the site. So, in the end, spatial analysis gives the greatest indications about tree plantations.

The results from spatial analysis have been compared to the writings of antique agronomists, in the first instance Pliny the Elder (*Histoire Naturelle*, XVI; *H.N.* XVII, 16, 17 et 19), Columelle (*Des arbres*, XVII et XIX; *De l'agriculture*, V, 9 et 10) and Palladius (*L'économie rurale*, II, 15; III, 18 et 19). It turns out from these writings that the spacing between trees depends more on the nature of the soil and climate than on the planted tree type. It seems that Type 1 systems correspond better to olive tree culture, while other system types are more related to other fruit trees.

Then, the results were compared to the data from sites where remains of antique orchards have been discovered. Many alignments are imputed to hedges, and are thus essentially studied in terms of their pit modules. According to the data, twelve square pit systems from nine sites can be used for discussion, and are suitable for comparing rc and dc values: Roquemaure – La Ramière (Gard) (Barberan *et al.* 1997; Barberan *et al.* 2002), Montfrin – Le Réal (Gard) (Le Meur *et al.* 1997), Caurel – En Droit le Clocher (Marne), Cernay-les-Reims – Les Petits Didris (Marne), Reims – L' îlot Clovis-Capucin-Hincmar (Marne) (Koehler 2003), Valros – l'Aire de Repos (Jung, Bel 2010) and Champ Redon (Jung 2011) (Hérault), Sauvian – La Lesse (Gard) (Pomarèdes 2011), Savasse (Drôme) (Ronco 2012) and the italian site of Passo di Corvo (Tinè 1983) (Fig. 12).

The comparison between the results of the Grand Palais with those from other sites of the Gaul shows some regular trends. We should remember, therefore, that the greatest contribution comes from Narbonnaise Gaul, due to the earlier agrarian archaeological studies undertaken over the last twenty years during large infrastructure projects such as the TGV and highway A75. The patterns are almost always orthonormal; only a few follow a quincunx organisation, or have a wider spacing between rows; it also seems that most of modules have a width of 3 or 4 feet. But, even so, the metrological typology of the systems must be extended.

A first group is composed of systems with a loose pattern, like the Grand Palais Type 1, and other systems with 50 feet spacing. In Narbonnaise, these orchards extend over very wide areas, mostly into the vicinity of a *villa*. The second group includes orchards with 10 to 25 feet spacing, generally associated to 3-feet pit modules, such as Types 2 and 3. They can be found in small enclosures on the outskirts of a settlement (Reims) (Fig. 12), on small plots linked to mid-range rural settlements (Sauvian), and on extensive exploitations managed by a great *villa* (Grand Palais). These two groups can be found as early as the first century BC and the Augustan era in Languedoc, and they then seem to multiply during the Haut-Empire. To this day, the leading study concerns the orchards of the first group, thanks to the research performed at the Valros site (Fig. 12). The range of cultivated species points towards extensive and relatively dry cultivations, such as olive, almond and plum trees, possibly associated with relay cropping (forage or cereals) and, perhaps, sylvo-pastoralism – as can still be observed in the Spanish and Portugese *dehesa* (Jung 2010: 156; Jung 2011: 166). For the second orchard group our assumptions are less precise. In fact only the site of Sauvian-La Lesse can be interpreted as a peach

[2] Type 5 originally corresponded to System 10, which was finally included into Type 1 due to its restricted extension and its proximity to System 8; for this reason we can assume that System 10 is an offset part of System 8.

[3] Based on the *pes monetalis*, where 1 *jugerum* = 2 *actus simplex* = 28,800 *pes quadratus* = 2516.525568 m².

[4] D = (Dmt x 2516.525568) / 10,000.

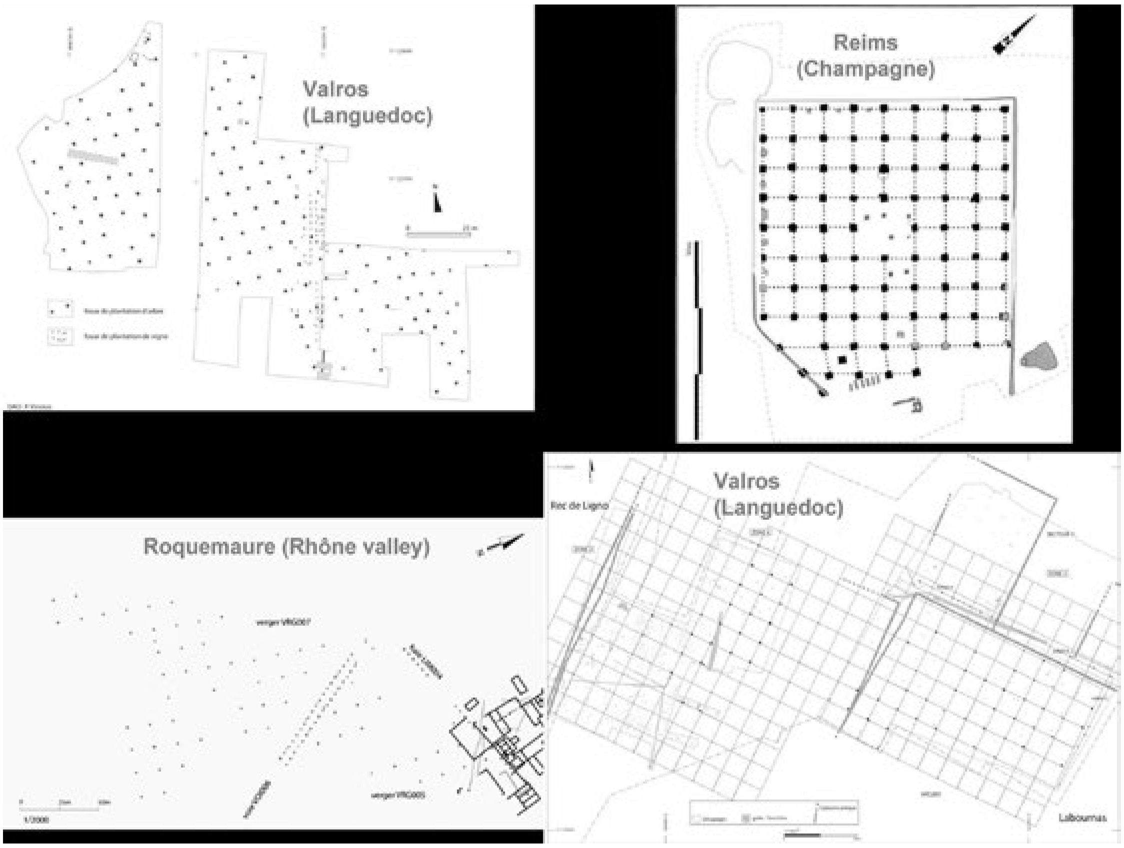

Fig. 12. Examples of maps of Roman orchards remains (from Jung, Bel 2010; Jung 2011; Koehler 2003; Barberan *et al.* 1997 and 2002).

plantation by comparing the eventual irrigation ditch network to the small, narrow-spaced pits (Jung 2010: 156).

In the Grand Palais, the plantation area can be estimated at 4 ha. Given the widths and regarding each system type, we can propose from 500 to 2,000 trees by phase, which corresponds to intensive and efficient cultivation. It was demonstrated that Type 1 systems can be related to the agronomists' specifications for olive trees. Other system types may correspond to various species cultivation; but, if we take into account the production volumes implied by such extensive planting, then the crops must be processed or dried to be stocked, and this points towards nut, plum and fig production. The root system of the almond tree would also account for the absence of holes at the bottom of the pits. However the harvested tree does was always the one that was planted. Indeed all the early agronomists write about sophisticated grafting techniques used during their respective periods. Analysis of root systems can therefore lead to the identification of the rootstock and, indirectly, to the potential species that can be grafted to it.

Following these discussions, and before the arrival of new studies that could provide more answers, some hypotheses can be proposed for the Grand Palais orchards. The Type 1 systems correspond to the first two phases of the quadrangular pit orchards, where the whole area would be dedicated to olive culture (Fig. 13). The discovery of what might be an oil mill inside the *pars fructaria* of the *villa* validates this assumption, even if a greater part of the agrarian domain is still unearthed and might provide new equipment and installations. Type 2 is posterior; the restored irrigation network of system 3 implies an estimated culture over 2300m², which can be related to a specie that need constant watering; due to its limited width, the drying or transformation of the production might not be necessary. Peach, apple and pear cultivation are all plausible (Fig. 13). In parallel, on the western part of the plantation, the system 6 might correspond to the cultivation of almond trees because of its 20 feet spacing (Fig. 14). Types 3 and 4 follow on and have very narrow spacings. This apparent reduction might be related to some quantitative exploitation logic at the expense of production quality and tree lifespan, but could still be possible with an increase of the water supply. Efficiency multiplies and fruit drying are necessary. We may thus propose the successive or combined culture of almond, fig and prune trees (Fig. 14). The orchards seem to have been abandoned around or shortly after the end of the third century.

4.2 The limitations of the comparative method: proposition of standardized field data recording and spatial analysis

The protocol created for the Grand Palais site permits the spatial characterization of antique orchards, while the state of documentation (antique texts, excavated sites) lead to some interpretations. However, available data concerning orchards studied by rescue archaeology is still too limited to establish an extended typology to the whole of Gaul and, therefore, to the

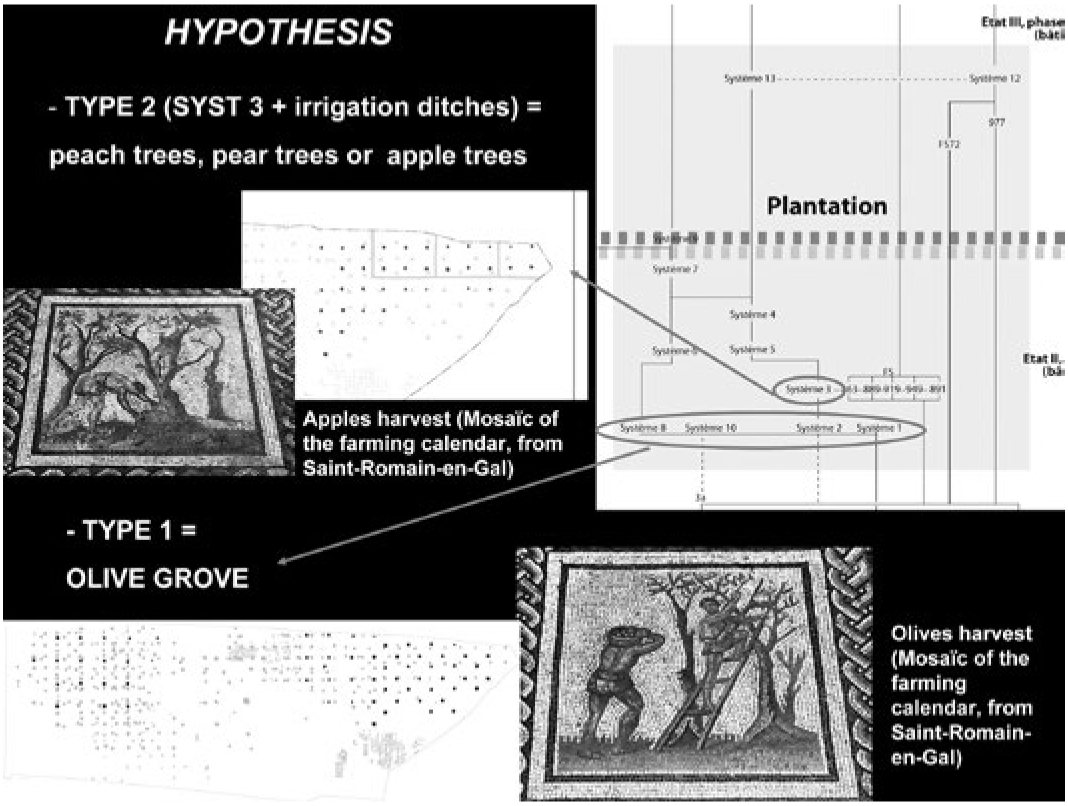

Fig. 13. Hypothesis of identification of tree species according to Grand Palais typology: Types 1 and 2 (Landry C. Inrap).

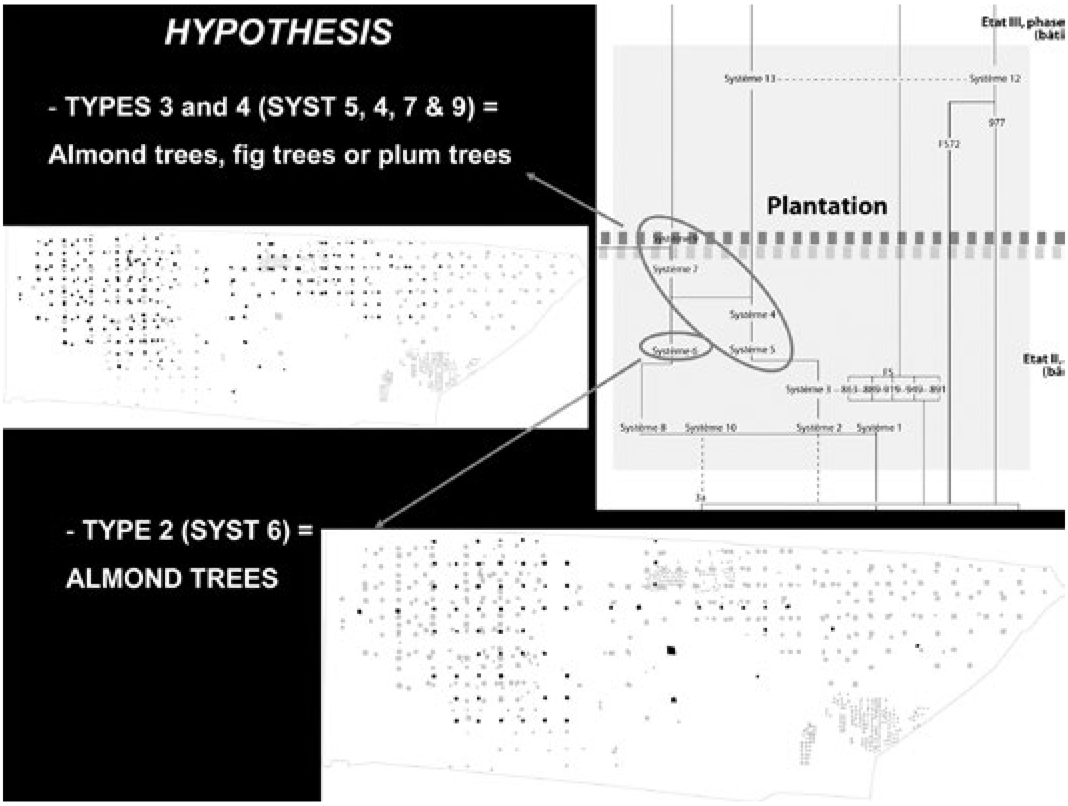

Fig. 14. Hypothesis of identification of tree species according to Grand Palais typology: Types 2, 3 and 4 (Landry C. Inrap).

Roman Empire. Statistical methods need to take into account all kinds of measurements, as was the case at the Grand Palais.

In this regard, it is necessary to combine a high-precision topographical survey that can be processed by GIS tools, with detailed excavations of a statistically sufficient number of structures. The standardization of this method should lead to a more substantial typology. Moreover, spatial analysis must include the whole range of palaeoenvironmental studies, from a root system study to the eventual product storage and transformation installations. Let us hope that the increasing number of sites yielding information on the preservation condition of ecofacts (wells, marshes, hearths...) and material remains (infrastructures, objects...) will lead to more sustained correlations between vegetal species and plantation pits.

5 Conclusion

The methods used to spatially characterize antique orchards of the Grand Palais follow, finally, a quite simple process: centroid extraction using GIS and hierarchical clustering. Nevertheless, they are well adapted to the very specialized research field of orchard exploitation by early farmers who were influenced by Roman culture and traditions. The writings of antique agronomists, as well as plantation remains studied during excavations, attest to extremely precise and standardised methods of implantation, as can be observed in many other aspects of Roman spatial planning (city, transportation, architecture...). Thus, in the case of sites where the overlapping of plantations makes the plan of the remains unreadable, other spatial analysis methods are used to search for patterns, such as the automated search for the nearest neighbour, are not relevant and do not bring more reliable results. The simple method presented in this article is justified by the fortunate preservation of early texts and the increasing number of sites where a unique orchard pattern can be identified. But these analytical tools must be completed by a standardization of metrological data recording and the systematization of paleoenvironemental analyses on antique rural sites in order to provide more answers.

Bibliography

Arramond, J. C., Requi, C. 2012. Arboriculture ou viticulture ? Le cas de la *villa* gallo-romaine du Quiou, *Archéopages* 34: 6-9. Campagnes, Inrap, Paris.

Barberan, S. *et al.* 1997. *La Ramière - Roc de Peillet (Roquemaure, Gard). L'espace agraire et les établissements ruraux gallo-romains. L'établissement moderne du Roc de Peillet. Archéologie rurale sur la rive droite du Rhône*, Document final de synthèse, TGV Sud-est Ligne nouvelle 5 - Lot 22, SRA Languedoc-Roussillon, Montpellier, 4.

Barberan, S., Fabre, L., Maufras, O., Petitot, H., Pomaredes, H., Sauvage, L., Thernot, R. 2002. Les *villae* de La Ramière à Roquemaure, Gard, In *Archéologie du TGV Méditerranée, Fiches de synthèse*, Tome 3, Monographies d'Archéologie Méditerranéenne: 889-919.

Barthelemy, D., Dubois, S. 2007. Métrologie antique, une tige métallique graduée découverte à Mâcon (Saône-et-Loire), *Revue Archéologique de l'Est* 56: 371-9.

Beal, J. C. 2002. Agglomérations, sanctuaires ou villae à l'entrée du défilé de Donzère, *Revue Archéologique de Narbonnaise* 35: 281-8. Université Paul Valéry Montpellier 3, Montpellier.

Boissinot, P. 2001. Archéologie des vignobles antiques du sud de la Gaule. In J. P. Brun, F. Laubenheimer (eds.), La viticulture en Gaule, *Gallia*, 58: 45-68.

Boissinot, P., Roger, K. 2004. Le domaine viticole des Girardes a Lapalud. In F. Favory, A. Vignot (eds.), *Actualité de la recherche en Histoire et Archéologie agraires* (Actes du colloque AGER de Besancon 2000): 225-40. Presses Universitaires Franc-Comtoises, Besançon.

Bourgaut, R. 2010. *Poussan, ZAE Les Clachs 1, Tranche 1*, BSR 2008 Languedoc-Roussillon, Montpellier: 154-7.

Brun, J. P. 2005. *Archéologie du vin et de l'huile en Gaule romaine*, Errance, Paris.

Brun, J. P., Laubenheimer, F. (eds.) 2001. La viticulture en Gaule, *Gallia*, 58.

Cribellier, C. 2011. Nouvelles données sur la viticulture chez les Senons autour de Beaune-la-Rolande (Loiret), In M. Poux, J. P. Brun, M. L. Herve-Monteil (eds.), La vigne et le vin dans les Trois Gaules, *Gallia*, 68/1: 151-62.

Columelle, *De l'agriculture,* Livres I à XII, trad. par M. Louis Du Bois, C. L. F. Panckoucke, Bibliothèque latine-française, Seconde série, 1844, Available from: http://remacle.org/.

Columelle, *Les arbres*, Texte établi, traduit et commenté par Raoul Goujard, Ed. Les Belles Lettres, Paris, 1987.

Durand, E. 2011. *Saint-Restitut (Drôme), Glairas et Grand-Faron, création d'un parc photovoltaïque et de quatre bâtiments*, Rapport de diagnostic, SRA Rhône-Alpes, Lyon.

Ferber, E. 2011. *Pierrelatte (Drôme), Quartier du Freyssinet, Chemin du Freyssinet*, Rapport de diagnostic, SRA Rhône-Alpes, Lyon.

Garcia, J. P., Chevrier, S., Dufraisse, A., Foucher, M., Steinmann, R. 2010. Le vignoble gallo-romain de Gevrey-Chambertin 'Au-dessus-de Bergis', Côte-d'Or (Ier-IIe s. ap. J. C.): modes de plantation et de conduite de vignes antiques en Bourgogne, *Revue archéologique de l'Est*, Tome 59-2: 505-37.

Jung, C. 2009. Le réseau viaire antique du Tricastin et de la Valdaine: relecture des travaux anciens et données nouvelles, *Revue Archéologique de Narbonnaise*, n° 42: 85-113. Université Paul Valéry Montpellier 3, Montpellier.

Jung, C. 2011. *Autoroute A75 – Section Béziers-Pézenas. Hérault, Montblanc et Valros. Renaussas et Champ Redon. Installations agricoles et espace funéraire antiques autour d'un carrefour de voies*, Rapport final d'opération, SRA Montpellier, 2 vol.

Jung, C., Bel, V. 2010. *Autoroute A75 - Section Béziers-Pézenas. Hérault, Montblanc et Valros. Aire de Repos de Valros. Occupations d'un espace rural antique dans le territoire de la cité de Béziers*, Rapport final d'opération, SRA Montpellier, 4 vol.

Jung, C., Compan, M., Figueiral, I. 2009. Les cultures et les pratiques agricoles antiques dans la cité de Béziers: L'exemple de la viticulture et de l'arboriculture sur l'autoroute A75 (Pézenas-Béziers, Hérault). Viticulture et arboriculture antique sur le tracé de l'autoroute A75 Béziers-Pézenas. Résultats préliminaires, Nov 2008, Girona, France. Universitat de Girona, *Studies on the rural world in the Roman period*, 2009: 85-97.

Koehler, A. 2003. Vergers antiques dans les campagnes péri-urbaines: le cas de Reims, In: *Revue archéologique de Picardie, 1-2, Cultivateurs, éleveurs et artisans dans les campagnes de Gaule romaine*: 37-46.

Landry, C. 2012. *Châteauneuf-du-Rhône, Le Grand-Palais, Lotissement* '*Les Résidences du Ponant*', Rapport final d'opération de fouille préventive, Inrap, Service Régional de l'Archéologie Rhône-Alpes, Lyon, 3 vol.

Landry, C. (forthcoming). La question de la conduite de la vigne en hautain en Gaule. Le cas des premières traces de culture à Châteauneuf-du-Rhône, In *Actes de la table ronde sur le vin et la viticulture antiques 'Vinalia' du musée de Saint-Romain-en-Gal, 27 septembre 2014*.

Le Meur, N., Noret, C., Sauvage, L. 1997. *Montfrin 'Le Réal' (Gard),* AFAN-TGV Ligne 5 - Secteur III - Lot 41, Rapport de fouille, SRA Languedoc-Roussillon, Montpellier.

Maune, S. 2003. La villa gallo-romaine de 'Vareilles' à Paulhan (Hérault; fouille de l'autoroute A75). Un centre domanial du Haut-Empire spécialisé dans la viticulture ? In: *Revue archéologique de Picardie 1-2, Cultivateurs, éleveurs et artisans dans les campagnes de Gaule romaine*: 309-37.

Monteil, M., Barberan, S., Piskorz, M., Vidal L. 1999. Culture de la vigne et traces de plantation des IIe-Ier s. av. J. C. dans la proche campagne de Nîmes (Gard), *Revue archéologique de Narbonnaise* 32: 67-123.

Ott, M., Pancin, S. 2006. *Mas de Fourques II à Lunel (Hérault)*, Rapport final d'opération de fouille archéologique, SRA Montpellier.

Palladius, *L'économie rurale*, Livres I à XIV, trad. par M. Cabaret-Dupaty,C. L. F. Panckoucke, Bibliothèque latine-française, Seconde série, 1843, Available from: http://remacle.org/.

Pline L'Ancien, *Histoire Naturelle*, Livres XIV à XVIII, Available from: http://remacle.org/.

Pomaredes, H. 2008. With collaboration of Compan, M., Ginouvez, O., Jung, C., Viticulture et équipements de production dans la cité de Lodève durant le haut Empire: apport des découvertes récentes autour de Clermont-L'Hérault, In: *Revue archéologique de Narbonnaise* 41: 7-41.

Pomaredes, H. 2011. *Hérault, Sauvian, La Lesse. Implantation d'une ferme pré-augustéenne et développement d'une petite* villa *de la cité de Béziers (fin Ier s. av. / IIIe s. ap. J. C.)*, Rapport final d'opération, SRA Montpellier.

Poux, M. 2011. With collaboration of Debize, T., Clement, B., Collet, A., Gilles A., Guillaud, L., Latour-Argant, C., Prioux, F., Tripier, A. et Carrato, C. Le vin du Triumvir. Témoignages archéologiques et littéraires d'une production de vin sur le territoire colonial de Lugdunum, In M. Poux, J. P. Brun, M. L. Herve-Monteil (eds.), La vigne et le vin dans les Trois Gaules, *Gallia*, 68/1: 13-91.

Poux, M., Brun, J. P., Herve-Monteil, M. L. 2011. La vigne et le vin dans les Trois Gaules, *Gallia*, 68/1.

Ronco, C. 2012. *Savasse, Croze – Lotissement Les Terrasses de Savasse II*, Rapport final d'opération de fouille préventive, Inrap, Service Régional de l'Archéologie Rhône-Alpes, Lyon.

Ruas, M. P. 2006. Cultures des fruits et lieux de culture de l'Antiquité, du Moyen Âge et de l'époque moderne. Des savoirs en pratiques, des mots et des images. *Actes du séminaire tenu à Toulouse les 31 mars et 1er avril 2005, Archéologie du Midi médiéval* 23-24, 2005-2006: 5-206. Carcassonne.

Tine, S. 1983. *Passo di Corvo e la civilta neolithica del Tavoliere*, Genova, SAGEP (ed.)

Toupet, C., Lemaitre, P. 2003. Vignobles et modes d'exploitation viticoles antiques dans le nord de la Gaule: l'exemple de Bruyères-sur-Oise (Val-d'Oise): une relecture, *Revue Archéologique de Picardie 1-2*: 209-26.

Vallat, P., Cabanis, M. 2009. Le site de ' Champ Chalatras ' aux Martres-d'Artière (Puy-de-Dôme) et les premiers témoins archéologiques de la viticulture gallo-romaine dans le bassin de Clermont-Ferrand (Auvergne), *Revue archéologique du Centre de la France*, Tome 48, Available from: http://racf.revues.org/index1325.html [Accessed: 24 February 2010].

GIS Applications and Spatial Analysis for the Survey of the Prehistoric Northern Apennine Context: the Case Study of the Mugello in Tuscany

Andrea Capecchi(1)
arc.capecchi.andrea@gmail.com

Michele De Silva(1)
michele.desilva@unifi.it

Fabio Martini(1)
fabio.martini@unifi.it

Lucia Sarti(2)
lucia.sarti@unisi.it

[1] Dipartimento di Storia, Archeologia, Geografia, Arte e Spettacolo (SAGAS), University of Florence, Italy
[2] Dipartimento di ScienzeStoriche e dei BeniCulturali, University of Siena, Italy

Abstract: This research is a study of territorial archaeology that takes advantage of information technology methods to examine the rich Tuscan context of Mugello area (156km^2), on the Apennines mountains in the Florence province, from the lower Paleolithic to the final Bronze Age. This work intends to define a profile of the prehistoric settlement strategies by the use of GIS based spatial analysis on a total of 114 occupations scattered in 95 sites. The focal goal is to highlight the different dwelling choices diachronically and relating them with the physiography of the area, the geological features and the environmental influences. This study shows his originalities about the methodology and the application of the spatial analysis of the territorial data, especially relating with the use of the settlement typology as an intermediate reclass and synthesis phase in the workflow, the expected frequencies analysis and the integration between quantitative and qualitative data.

Keywords: Mugello, Survey, Settlements, GIS, Spatial analysis

Foreword

This work has been carried out in full collaboration by the authors. In particular the authors developed some given aspects of the present research as follows:

F. Martini and L. Sarti, archaeological review of the findings, chronological attributions, typology; M. De Silva, methodology regarding physiographic themes and dataset structure; A. Capecchi data acquisition, spatial analysis, statistical analysis, diagrams, charts and map editing.

1 Context

The present work correlates physiographic and archaeological data in order to disclose possible hidden settlement patterns in the Mugello area, taking advantage of GIS spatial analysis. The case study is located in Italy, in the northern Tuscan Apennines of the Florence province and consists of 114 different occupations, referred to 21 chrono-cultural horizons, set into 95 sites, starting from the lower Paleolithic to the Final Bronze Age. The surveyed area is divided into higher Mugello, lower Mugello and the Sieve River Valley, for a total extension of 156 Km^2, within the following municipalities: Barberino di Mugello, Borgo S. Lorenzo, Dicomano, Firenzuola, Londa, Marradi, Pelago, Pontassieve, Palazzuolo sul Senio, Scarperia, San Godenzo, San Piero a Sieve, Vicchio di Mugello.

2 Territorial framework and objectives

The archaeological attractiveness of this area is due to four primary peculiarities and, although apparently unrelated to each other, they make GIS spatial analysis the most suitable tool to examine this variable and rich context, thanks to the possibility of gathering and processing a lot of data coming from different sources. The first element involves the Mugello's geographical position as a link between Central and Northern Italy, between the Adriatic and the Tyrrhenian contexts. A second important feature is related to the physiographic variety of the Mugello, making this area potentially ideal for hosting many different settlement strategies throughout the passage of prehistory. The third aspect is the large amount of archaeological data coming from different sources, with different data collection contexts (museums, documentation centres, cartography, unpublished researches, archaeological groups, surveys, etc.). On the other hand, this high number of findings was lacking a combined interpretation able to outline a diachronic and territorial understanding of the archaeological context.

Considering these four elements and the great diversity of the physiographic and archaeological data, the accumulation of the geographic data within a single archive allowed for the application of spatial analysis within a single interface and the management of the data, which leads towards the two main objectives of this research. The first objective is defining the

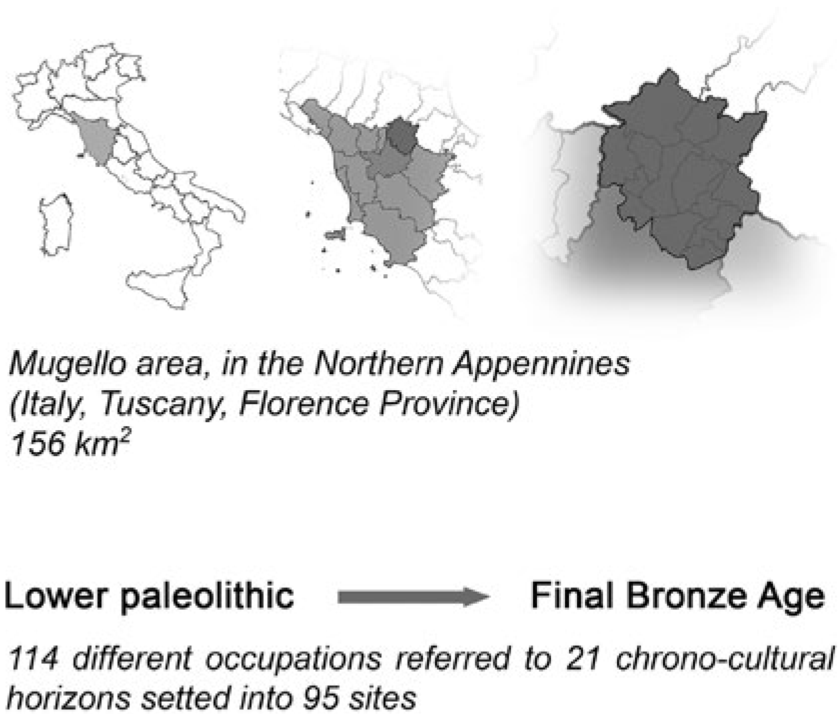

Fig. 1. Study area, chronological range and evidence overview.

overall features of the prehistoric settlement strategies in the ancient Mugello region, highlighting the different dwelling choices diachronically and relating them with the climatic and environmental influences, the economic factors and the practical needs. The second goal is to build a first interpretive framework able to draw guidelines for further studies on this area.

3 Steps and method

The first two phases of the research involved the accumulation of a vast quantity of data about physiographic and archaeological respects. The archaeological evidence was subsequently divided by occupation phases and chronologically classified. Simultaneously the context analysis has pointed out a group of physiographic themes able to describe the ancient settlement strategies by means of a quantitative description. Afterward, archaeological sites and physiographic layers were overlaid in order to give a thematic and quantitative description of each specific occupation. The next step concerned a reclassification of the output data through the application of a settlement typology to each occupation. Each typology is built to express and recap groups of values related to the physiographic themes in a more simple, manageable and concise manner, while being more qualitative. The last step was the interpretation of the overlay output supported by the settlement typology and integrated by qualitative data in order to define dwelling patterns and highlight factors able to influence them.

3.1 Archaeological data

A literature review was conducted of the study area as a preliminary step, including previous fortuitous findings from

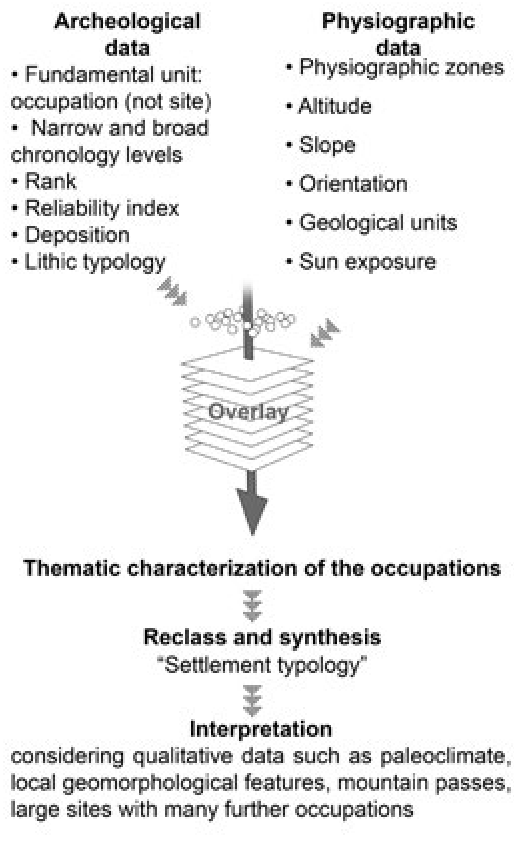

Fig. 2. Steps and method.

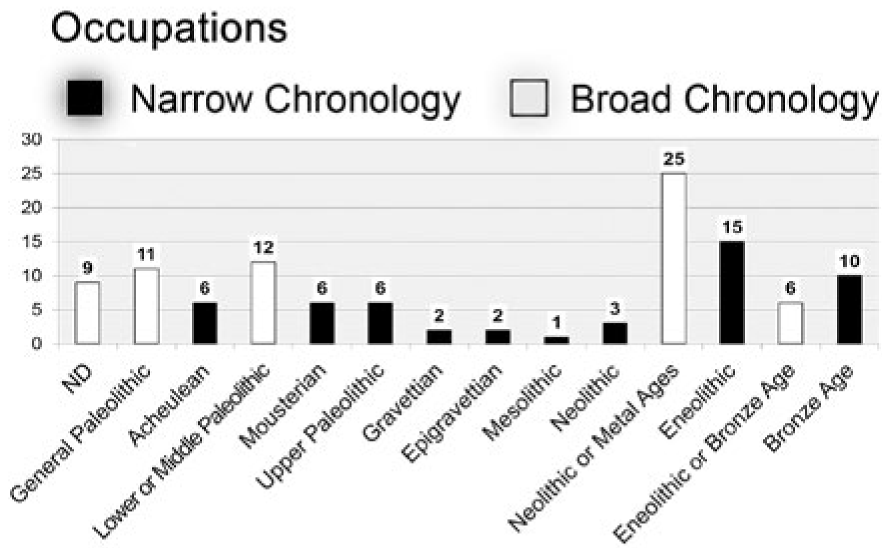

FIG. 3. OCCUPATION CHRONOLOGY.

the end of XIX century, the present archaeological cartography (Co. Idra 1995; Spaterna 1992) and latest report from surveys and excavations. The acquired data was integrated with an unpublished archive[1] of evidence known on the territory. After that, a direct review of the archaeological materials was accomplished, in total 114 occupations, comprised of 79 single-phase sites, 13 double-phase sites, 3 triple-phase sites.

Considering this ensemble of sources, the sites have been georeferenced in a GIS environment, using the 1:10,000 C.T.R. and the 1:25,000 I.G.M. cartography. After the sites positioning, the occupation was considered the basic archiving unit for the archaeological data. Considering this, a chrono-cultural attribution for each occupation has been provided. Thanking to this attribution the occupations have turned out to be divided into two groups: one with a more detailed chronology called 'Narrow chronology' (defined attribution, such as 'Mousterian', 'Acheulean', etc.) and one with a less detailed chronology called 'Broad Chronology' (uncertain attribution, such as 'Lower or middle Palaeolithic', 'Eneolithic or Bronze Age', etc.).

The Narrow and the Broad Chronology will be considered and treated separately, while being brought together during the interpretation step, giving priority to the former because of the greater precision of the dating.

Subsequently, the two sets of occupations were characterized by four main attributes coming from the archaeological review:

- Deposition: Primary, sub-primary, secondary, n/a.

According to Leonardi (1992: 30) sub-primary deposition (or sub-in-place) is defined as 'all the cases in which, although the material is slightly displaced, it is still possible to deductively evaluate a direct genetic link with its original layer'. This type of deposition is very common in the surface archaeology results and very often it represents the best depositional condition observed in this kind of surveys. Since the larger part of the data comes from surface findings given as secondary deposition without the sub-primary option, all the occupations recorded as secondary deposition have been reviewed in order to modify their attribution to sub-primary, where possible. This has permitted to raise the number of occupations to be treated in the statistical analysis to 94.

- Rank: site, off-site, n/a.

- Lithotype: a qualitative description of the flint, jasper, quartzite or other materials used for the tools production, indicating features that can be related with corresponding geological formation. (e.g. Marches red flint).

- Typology: lithic classification following G. Laplace typology, pottery forms, structures types.

3.2 Physiographic data

- Altitude -

The base for the elaboration of this informative layer has been a DTM (Fig. 13) of Tuscany, clipped on the investigated area and having a resolution of 10m on the ground. For the statistical study, the altitude has been subdivided into 50m ranged classes, from the lower (100-150m) to the highest one (1650-1700m).

- Slope -

The slope layer is originated by the DTM and, in order to arrange data on a linear scale, it displays inclines in sexagesimal degrees. The floating information has been classified into 5° classes, starting from the 0-5° class (approximated as 'flat') to the >75° one.

[1] Compiled by Riccardo Barbi (member of the Archaeological Group of Scarperia) on behalf of the University of Siena (the contribution and collaboration of the local archaeological groups have been very useful for the present work).

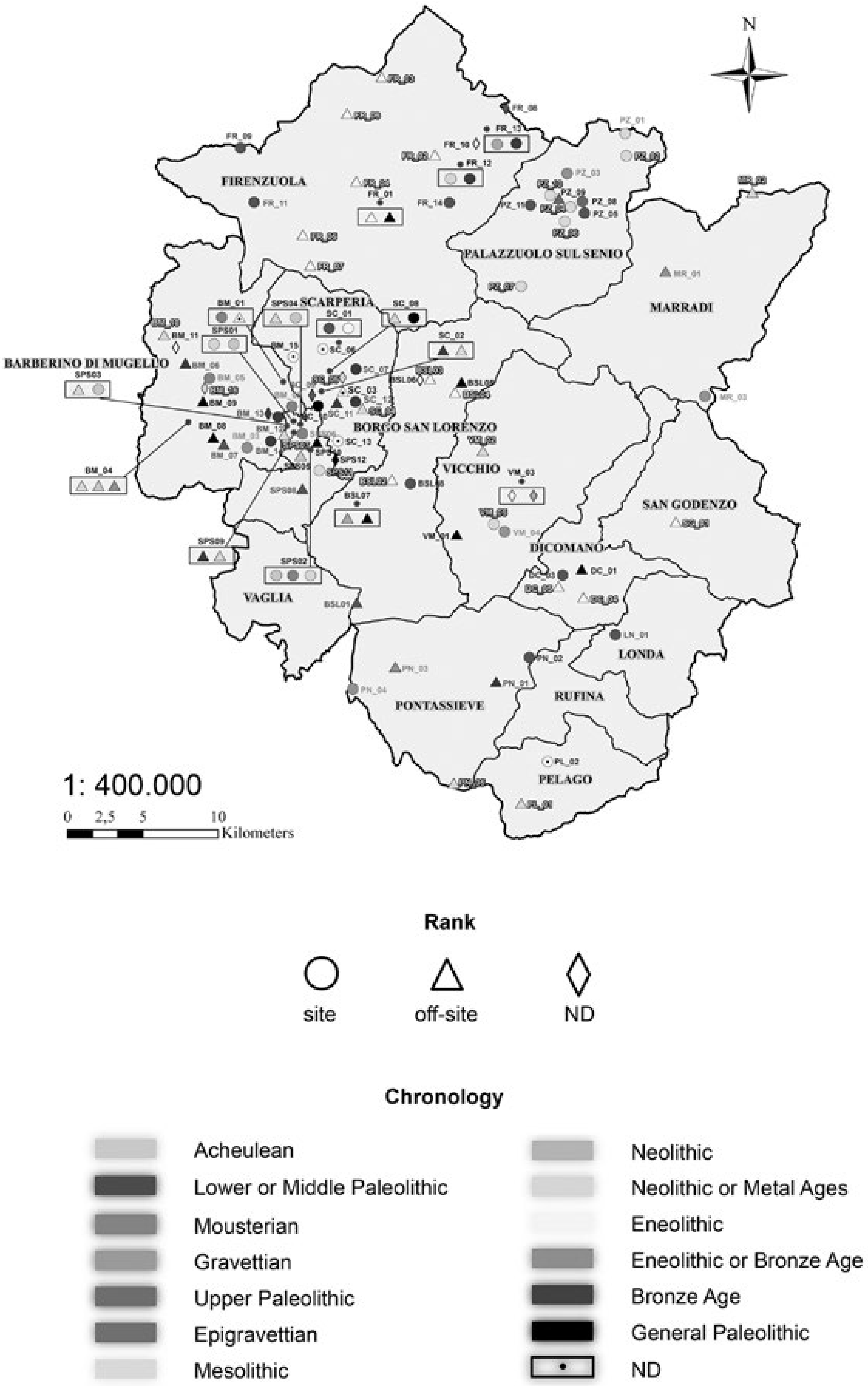

Fig. 4. Territorial framework of findings (occupations displayed).

- Orientation -

Starting from the same dataset, the orientation map (aspect layer) was calculated, deleting all the pixels showing a flat value or belonging to the first slope class (0-5°). This apparent loss of accuracy was performed to get the computer data closer to the real perception of the landscape. The remaining data was classified by the main and intermediate cardinal points (45° wedges).

- Physiographic zones -

Gathering all the previous data, 8 physiographic zones have been identified. Every zone is defined as a territorial unit showing generally consistent features of altitude, slope, orientation and geology. This analytic theme, developed mainly by means of qualitative methods, goes further than the single quantitative information and allows one to consider multiple aspects in a single class. This investigation tool has turned out to be very important during the spatial analysis, thanks to the possibility of taking in account of multiple simultaneous characteristics affecting the dwelling patterns.

- Geological units -

The classification follows the Carta Geologica della Toscana 1:100,000.

- Sun yearly exposure -

The value for each site was calculated by using the GIS tool on the DTM dataset. The punctual output data, related to the single sites, was extended to the related occupations and it expresses yearly sun radiation in W/m^2 per year. This data was kept as punctual information without classification.

3.3 Overlay and thematic characterization of the occupations

Once all informative layers have been organized and gathered in the GIS along with the georeferenced sites' level, an overlay was executed. Then, a data extraction was performed in order to apply all the values and the characterizations deriving from the archaeological and physiographic data to each occupation. The whole dataset has been stored into the relational database 'Preistoria Mugello', gathering all the information from the steps above. The following are the final output of this step:

- Territorial framework map.
- Orographic map.
- Slope map.
- Orientation map.
- Physiographic zone chart.
- Altitude class chart.
- Slope class chart.
- Orientation class chart.
- Geologic unit chart.
- Altitude dot plot.
- Slope dot plot.
- Yearly sun exposure dot plot.

3.4 Reclass and synthesis

This step has provided an interpretive analysis through the creation of a typology. This typology integrates geomorphological data and recaps all the previous physiographic themes in six types: every type corresponds to a certain settlement arrangement. This phase represents an intermediate interpretive characterization between the pure analysis and the interpretation phase. The typology, which is a complex classification, is different from the altitude or the slope single data and it had an important role during the final step. Indeed, being a cross-category theme, it is representative of a lot of information packed together in every typological class. This reclass introduces a geomorphological interpretation embedding altitude, slope and geology aspects. In the present work, referring to the prehistoric population, the settlement typologies are defined as classes of inhabited places identified by specific geomorphological features. The types have been determined following the criterions of the 'Archeologia Globale del Territorio', widely applied by L. De Marchi for the investigation of the Northern Apennines in the Modena and Reggio Emilia provinces (De Marchi 2003). The types have been identified using the GIS with quantitative and qualitative methods, initially applying the typology to the sites and then extending it to the related occupations. The fluvial terrace type has been applied automatically extracting the data from the Carta Geologica della Toscana 1:100,000. The other types have been assigned by a qualitative examination of the sites' distribution on the 3D model coming from the DTM, textured with the slope pixels' values. Finally, the following settlement types have been found: wide ridge with little slope, mid-slope terrace, ridge saddle, upland site, ridge ending, fluvial terrace. The settlement typology charts (Fig. 9) don't show any expected frequency because of the point data and the non-automatic identification procedure. Indeed by definition, the settlement typology is not based on general areas, which can be inhabited or not, but only on verified dwelling events.

The complex of meanings expressed by the settlement typology, once connected to the environmental factors and to the archaeological features, can disclose interpretive glimpses about the dwelling patterns and the sites' purpose in the overall territorial framework. The surface archaeology results can take the greatest advantage of this method, going beyond the simple analysis of evidence, highlighting links and analogies between territorial data, with a general improving of the interpretation efficacy.

3.5 Interpretation

Considering all the data gathered in the charts and connecting them with each other, an interpretive framework was performed for the narrow chronology. This output was compared with the broad chronology tendencies in order to verify the data and to suppose possible contributions within the broad chronology itself. The final result relates the different dwelling patterns

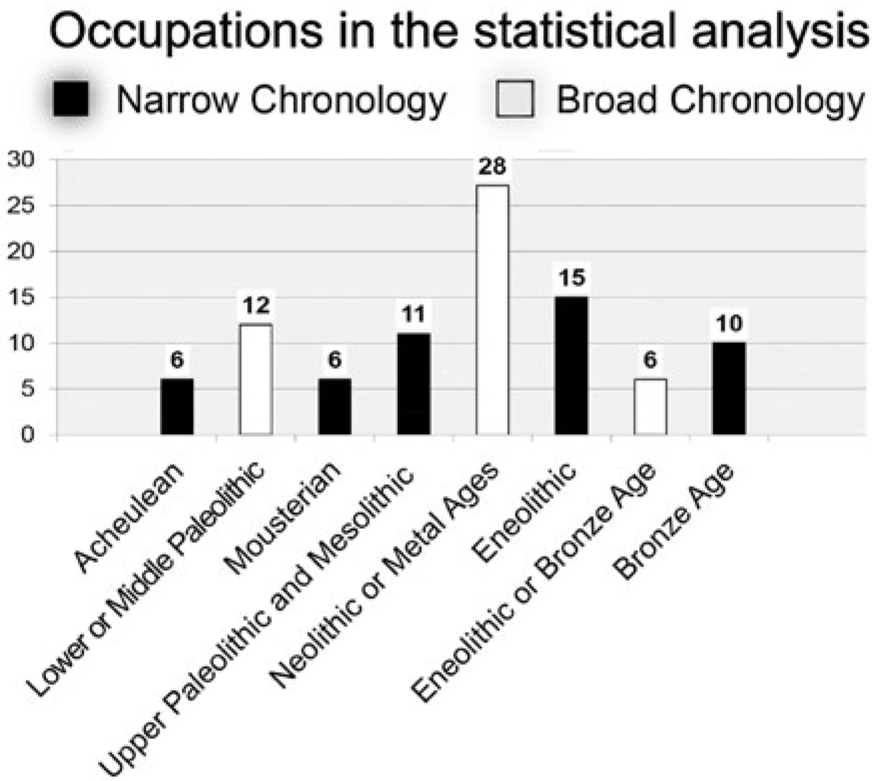

Fig. 5. Occupations in the statistical analysis.

with factors able to affect them (such as palaeoclimate, local geomorphological features, mountain passes, large sites with many further occupations, etc.) and infers possible connections between them and the variation of the settlement strategies.

4 Chart and map analysis

The territorial framework (Fig. 4) and the charts show the occupations rather than the sites. The findings with an undetermined chronology or with the attribution of 'generic Paleolithic' have been removed from the statistical analysis. In order to achieve a more representative sample, Gravettian, Epigravettian, Mesolithic and general Upper Paleolithic occupations have been unified and treated together in the Upper Paleolithic and Mesolithic class (11 occupations in total). Neolithic occupations (counting 3) have been considered in the Neolithic and Metal Age class.

Expected frequencies shown in the charts are for a qualitative evaluation in case of a big divergence with the data, because χ^2 test was not possible since the number of sites were too small. For a quick evaluation, order 2 polynomial trendlines are displayed for the floating data.

The following analysis shows the result of the integration between the narrow and the broad chronology data.

4.1 Lower and Middle Paleolithic

- All the occupations are located at a very low altitude, between 200m and 400m.a.s.l.
- Nearly every site is on flat ground or has a southward orientation.
- No settlements on the Adriatic (northern) side of the area. Almost exclusive distribution in the Palaeolake basin physiographic zone.
- All of the above elements are strongly divergent from the expected frequencies.
- The evidence shows the highest yearly sun exposure values, displaying a concentrated distribution.
- The fluvial terrace settlement typology is almost the unique typology for this period.
- 4.2 Upper Paleolithic and Mesolithic
- Occupations are still at a low altitude, with a remarkable presence beyond the expected frequencies. No occupation over the 550m.a.s.l.
- Orientation and slope charts do not reveal remarkable significance.
- New physiographic zones are populated, first settlements on the Adriatic side of the Mugello.
- In addition to fluvial terrace sites, new settlement typologies begin to appear in this period: 'steep ridge ending' and 'wide ridge with little slope'.

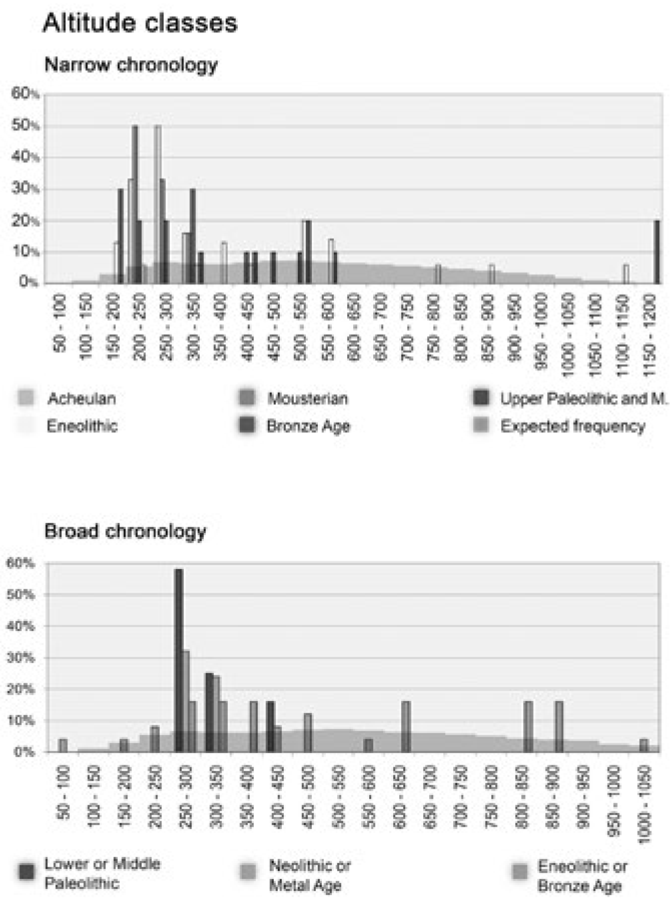

Fig. 6. Altitude classes.

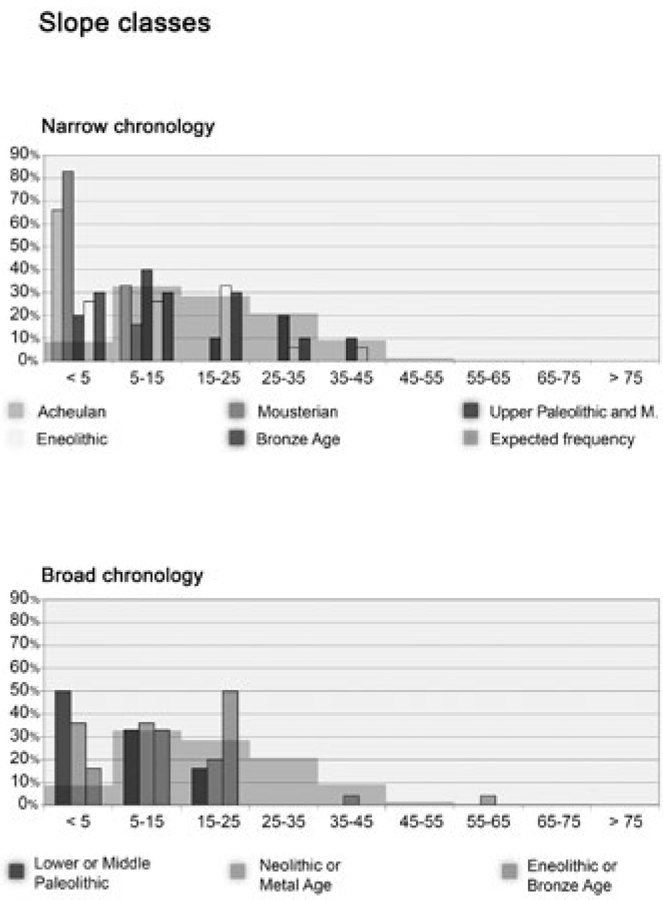

Fig. 7. Slope classes.

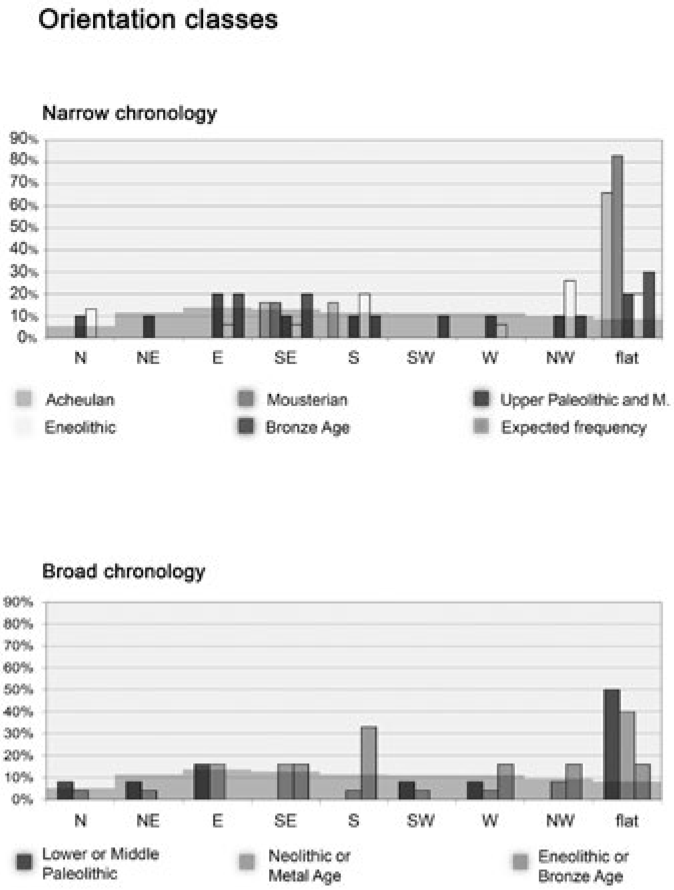

Fig. 8. Orientation classes.

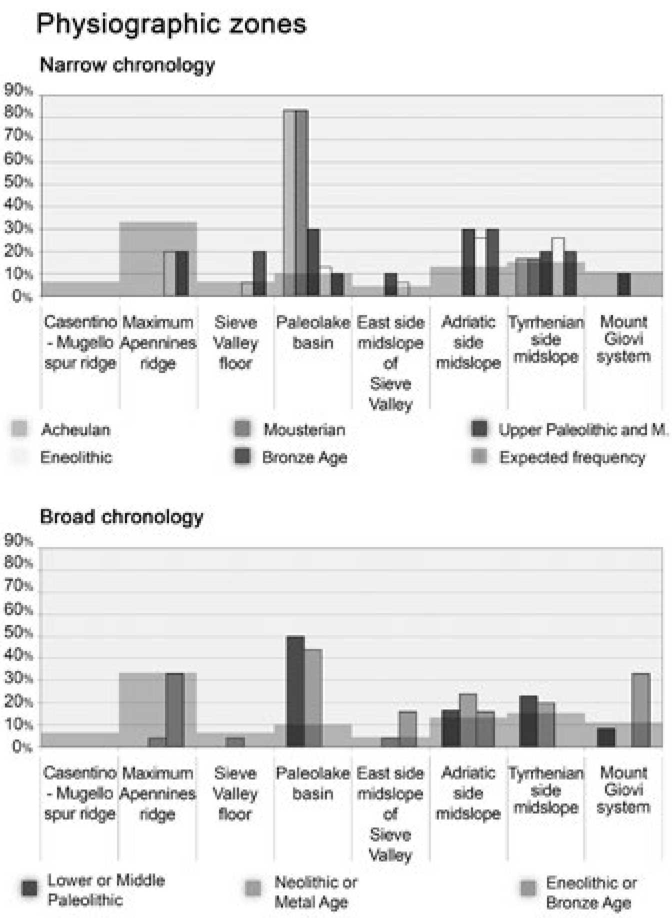

Fig. 9. Physiographic zones.

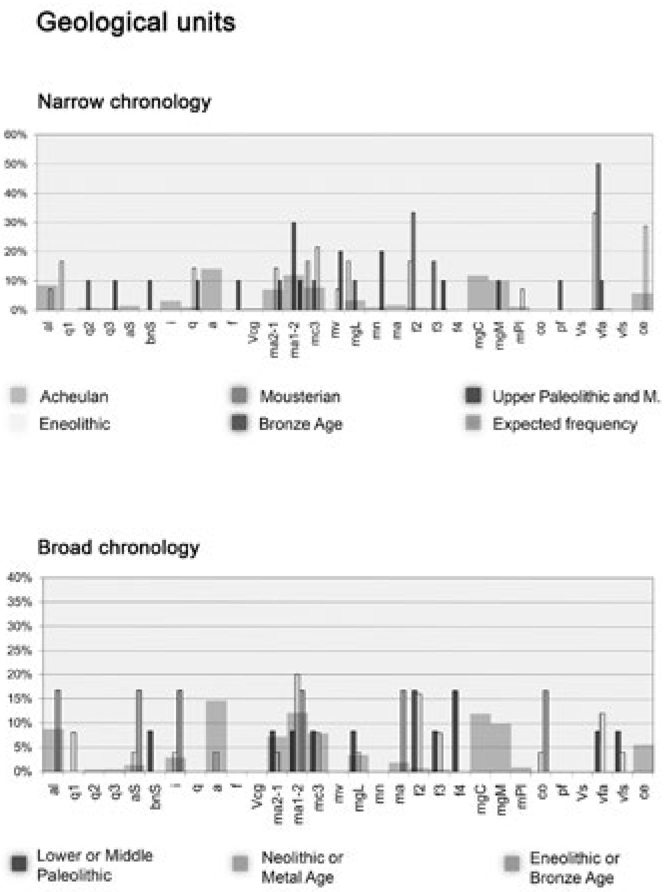

Fig. 10. Geological units.

4.3 Neolithic

- Due to the small amount of Neolithic occupations in the narrow chronology, a strict statistical analysis was avoided, but it has been possible for the broad chronology.
- The occupations took place in low altitude sites, max. 350m.a.s.l. with a very low slope.
- Both Adriatic and Tyrrhenian side reveal Neolithic presence.
- Decreasing level of yearly sun exposure compared with the previous periods.
- The fluvial terrace is the characteristic settlement typology for this period in this area.

4.4 Eneolithic

- In the Eneolithic period human peopling spread all over the Mugello area reaching all the physiographic zones uniformly from North to South.
- Eneolithic sites reveal no significance in altitude, slope and orientation analysis reaching the highest altitude up to this period.
- Appearance of new settlement typologies: 'upland site' and 'mid-slope terrace'. No fluvial terrace sites found.

4.5 Bronze Age

- No significance for altitude apart from the lower range that displays a divergence from expected frequency. The presence of high altitude sites up to 1.200m.a.s.l. is remarkable.
- Preference for flat or low-sloped sites. This is due to the position on top of the elevations.
- Site rank for every occupations of this period, no off-site evidence found.
- Only two settlement typologies attested: fluvial terrace and Upland site.

5 Settlement strategies in the prehistoric Mugello

During the Lower and Middle Paleolithic, environment factors probably had a primary influence, thus we can suppose the glaciation climate as a limiting factor for the settlement spread over the 400m.a.s.l. as well as the lack of northward expansion. Especially during the Mousterian, the effects of the first Würmian Pleniglacial, like the spreading of snowfields, prevented the ancient Neanderthals from dwelling at an high altitude (Palma di Cesnola 1965; Grifoni Cremonesi 1971; Ceccanti *et al.* 1982; Martini 1992; Galiberti 1997; Bellandi 2000). This environmental influence could even explain the lack of occupations on the northern side of the Apennines (Adriatic side), affected by a more continental climate. This

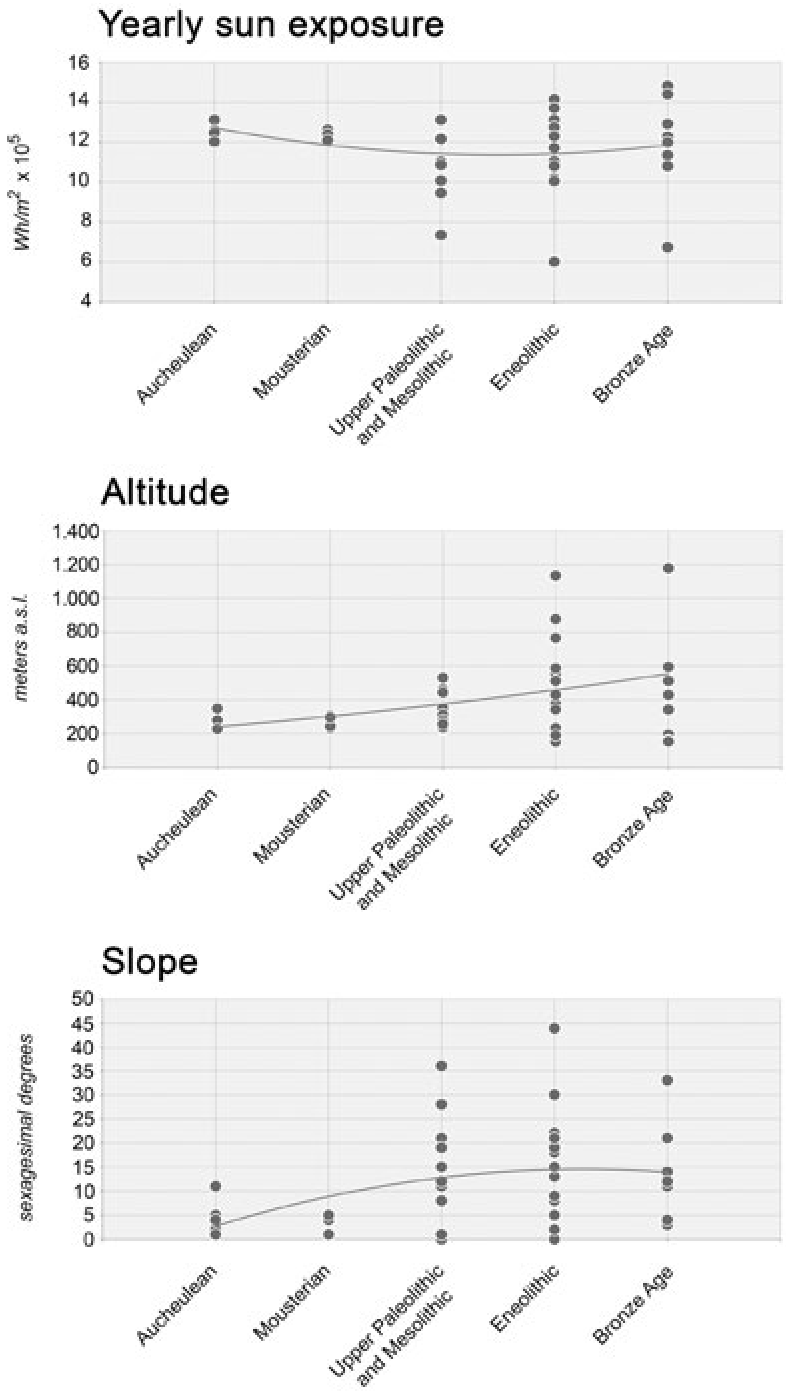

Fig. 11. Point data (only for the narrow chronology).

way, the preference for south-oriented sites with a high level of yearly sun exposure could be connected with this factor as well. In this period, the most suitable location for settlement appears to be on the fluvial terrace.

During the second pleniglacial, fluvial terrace are still preferred and no settlement are located on the northern side of the area. Starting from the Epigravettian, occupations begin to raise their altitude and to spread northbound, reaching the Adriatic side. We can assume that the better climate condition along with the new hunting techniques affected these dwelling choices toward an expansion of the inhabited zones.

During the Neolithic, the return of the low altitude sites on fluvial terraces can be connected with the new relationship between population and the territory, due to the introduction of agriculture and breeding, along with the decreasing of hunting activity. In search of fertile and flat grounds, fluvial terraces could have been an old solution to the new requirements.

The Eneolithic constitutes a breaking-point in the dwelling strategies of the prehistoric Mugello and a starting point for the further periods. A spread direction is revealed from the South-East to the North-West following the ridges, primarily due to off-site evidence (95%). The absence of fluvial terrace sites can

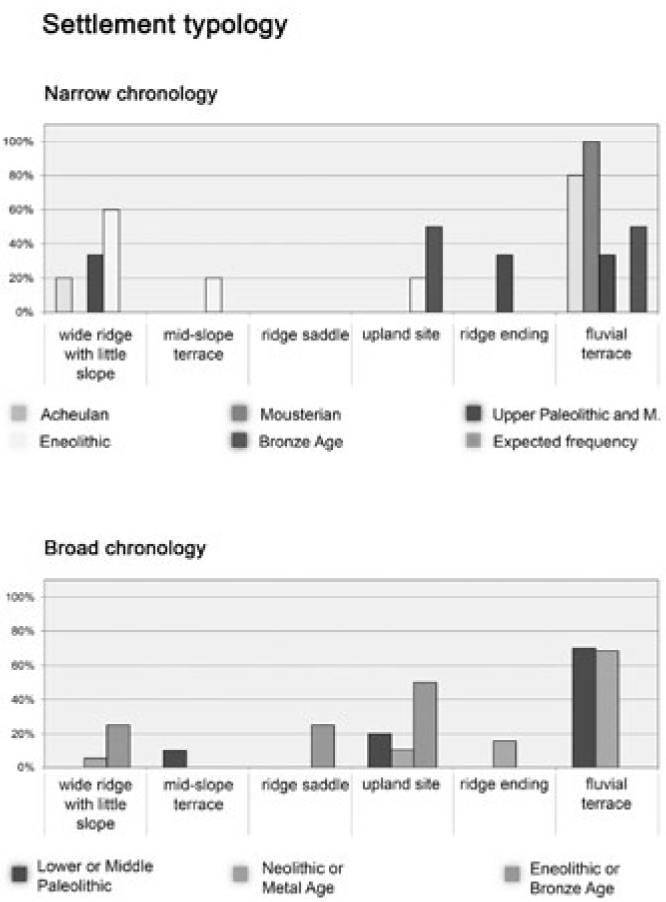

Fig. 12. Settlement typology.

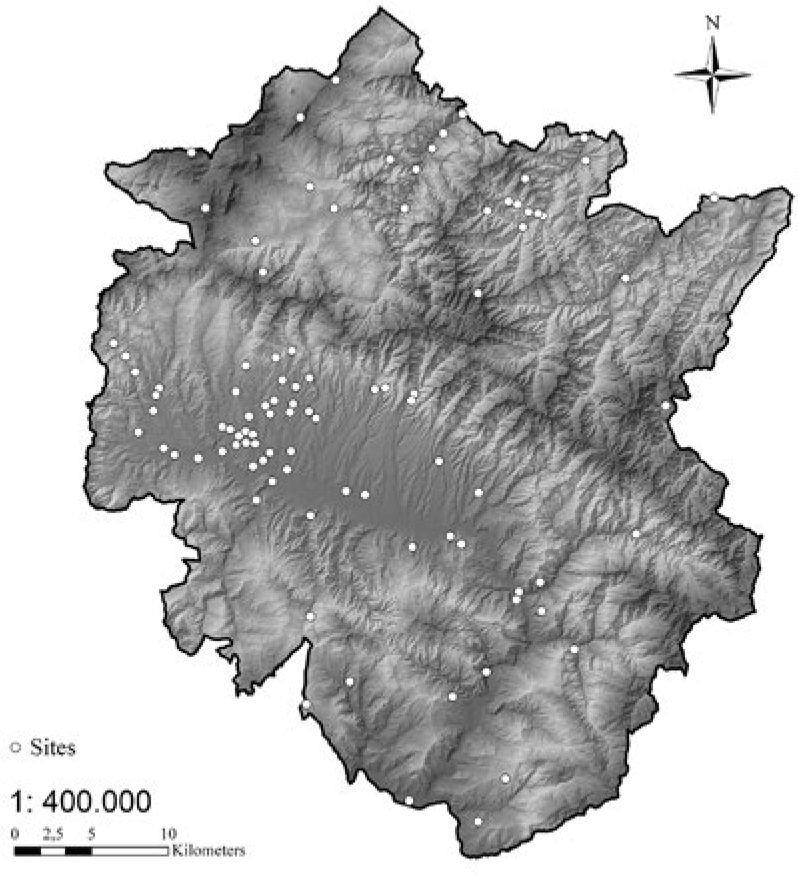

Fig. 13. DTM (sites displayed).

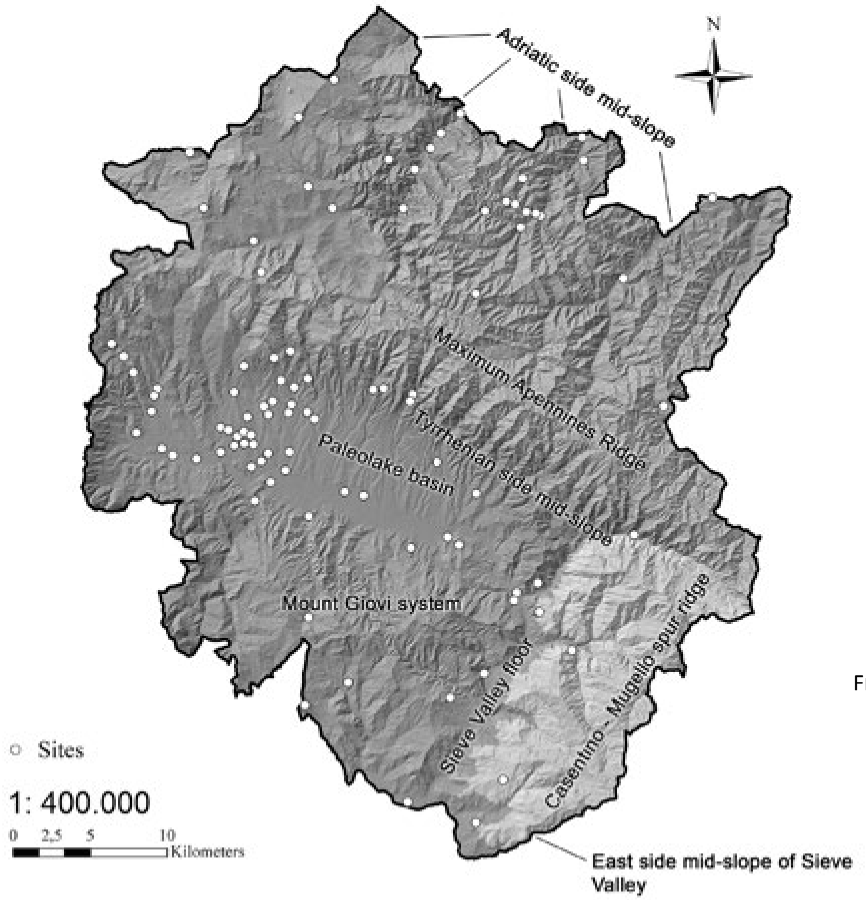

Fig. 14. Physiographic zones (sites displayed).

be connected with the development of the mountain ranges and the increasing requirement of territory control.

The Bronze Age settlement pattern has his base on the Eneolithic one and, starting from it, an overall strengthening is remarkable. Effectively, many sites reveal a continuous occupation, getting their rank from off-site to site. Some sites are reoccupied in a little distance, pointing out bigger evidences. The settlement typology indicates the establishment of a well-defined dwelling strategy with two main factors: lower settlements with fertile ground and water availability, and higher upland ones with the possibility of mountain ranges and land control.

Bibliography

Agostini, C. and Santi, F. 1994. Un insediamento del Gravettiano nell'area dell'invaso del Bilancino in loc. Il Piano (Barberino di Mugello). In *Archeologia in Alto Mugello - Mugello - Val di Sieve e il caso di S. Piero a Sieve*, *Firenze 22 gennaio 1994*.

Agostini, C. and Santi, F. 2000. *La strada Bologna-Fiesole del II secolo a.C. (Flaminia Militare). Storia e testimonianze archeologiche di una ricerca sull'Appennino Tosco-emiliano*, Bologna, Clueb.

Aranguren, B., Baglioni, L. and Revedin, A. 2001. Nuclei a morfologia bulinoide: Prime osservazioni sulla produzione lamellare gravettiana di Bilancino (Firenze). *Rivista di Scienze Preistoriche* 53: 569-80.

Aranguren, B., Becattini, R., Mariotti Lippi, M., Revedin, A. 2007. Grinding flour in Upper Paleolithic Europe (25,000 bp). *Antiquity* 81, 12: 845-55.

Aranguren, B., Bracco, J., Le Brun-Ricalens, F., Longo, L., Pallecchi, P., Revedin, A. 2006. Éléments de la chaine opératoire fonctionnelle des burins de Noailles de Bilancino (Florence, Italy). In *ArcheLogiques 2*. *Papers from Actes de la Table ronde internationale d'Aix-en-Provence, Aix-en-Provence, 3-5 march 2003*: 142-63. Luxembourg, Musée National d'Histoire et d'Art.

Aranguren, B. and Revedin, A. 2008. Un accampamento di 30,000 anni fa a Bilancino (Mugello,Firenze). Origines. Firenze: Istituto Italiano di Preistoria e Protostoria.

Baccini, G. 1911a. Il bel Mugello. *Messaggero del Mugello*. 11th June.

Baccini, G. 1911b. Il bel Mugello. *Messaggero del Mugello*. 18th June.

Baccini, G. 1911c. Il bel Mugello. *Messaggero del Mugello*. 30th July.

Baccini, G. 1911d. Il bel Mugello. *Messaggero del Mugello*. 13th August.

Baccini, G. 1911e. Il bel Mugello. *Messaggero del Mugello*. 20th August.

Bachechi, L. 2009. Nella storia della preistoria: il dolmen di Montesassi (Vicchio, Firenze). *Studi per l'ecologia del Quaternario*. 31: 73-76.

Baldi, F. 1877. *Considerazioni paleontologiche intorno agli antichi abitanti del Mugello*. Firenze.

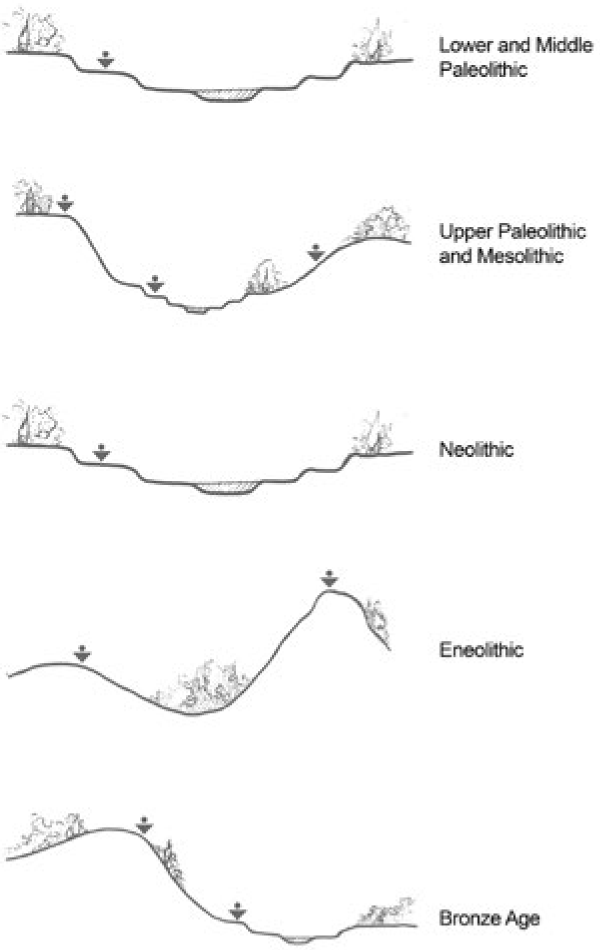

Fig. 15. Schematic sections of the settlement types.

Bandini, C., Gucci, P., Perrone, C. and Servi G. 1984. Il Musteriano di Lucigliano (Scarperia - Firenze). *Studi per l'Ecologia del Quaternario*. 6: 51-63.

Barbi, R. and Volante, N. 2003. Marroneta Tonda (Scarperia, Prov. Firenze). *Rivista di Scienze Preistoriche,* Notiziario 53.

Bellandi, F. 1993. *Preistoria e storia antica del Mugello, Alto Mugello e Val di Sieve attraverso le testimonianze archeologiche*. Scarperia.

Bellandi, F. 2000. *Preistoria e storia antica. Un viaggio attraverso le testimonianze archeologiche del Mugello, Alto Mugello e Val di Sieve*. Scarperia.

Bentini, L. 1981. Rinvenimenti di età pre-protostorica nei dintorni di Palazzuolo sul Senio. *Studi Romagnoli* 32: 15-51.

Benvenuti, M. 1992. L'evoluzione geologicae le faune fossili del Mugello. In *Atti della giornata di studio Archeolologia e Ambiente in Alto Mugello 28 giugno 1992*: 7-8. Firenze.

Benvenuti, M. 1997. Physical stratigraphy of the fluvio-lacustrine Mugello Basin (Plio.Pleistocene, northern Appennines, Italy). *Giornale di Geologia* 59/1-2 (s 3): 91-111.

Benvenuti, M. and Papini, M. 1997. Depositi continentali Plio-Pleistocenici nell'area di Monte Giovi. Relazione tra l'evoluzione idrografica e la neotettonica della Valdisieve (Firenze). *Il Quaternario* 10, 1: 105-20.

Cambi, F., Terrenato, N. 1994. *Introduzione all' Archeologia dei paesaggi*. Roma, Carocci

Capecchi, G. L., Maggiani, A., Sarti, L., Nicosia, F. 1974. *Reperti archeologici del territorio di Dicomano*. Firenze.

Capecchi, A., De Silva, M., Martini, F., Sarti, L. 2008 Indagini sulle strategie insediative preistoriche in *Mugello. Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 4: 122-6.

Capecchi, A., De Silva, M., Martini, F., Sarti, L. 2009. Indagini sulle strategie insediative preistoriche in Mugello. *Rivista di Scienze Preistoriche,* Notiziario 59: 369-72.

Cappuccini, L., Ducci, C., Gori, S., Paoli, L. 2009. *Museo archeologico comprensoriale del Mugello e della Val di Sieve. Catalogo dell'esposizione*. Firenze, Aska Edizioni.

Carocci, G. 1882. Lettera a S.E. il Ministro della Pubblica istruzione. *Arte e Storia* I, 10, 8: 73-4.

Regione Toscana 2014. *Cartografia tecnica regionale e scarico dati geografici*. [Online] Available from: http://www.regione.toscana.it/-/cartografia-tecnica-regionale-e-scarico-dati-geografici [Accessed: 30 June 2014].

Regione Toscana 2014. *Geoscopio*. [Online] Available from: http://www502.regione.toscana.it/geoscopio/cartoteca.html [Accessed: 30 June 2014

Castiglioni, G. B. 1986. *Geomorfologia*. Torino, Utet.

Ceccanti, M. 1980. Scopeti. *Rivista di Scienze Preistoriche* 35: 383.

Ceccanti, M., Martini F., Mazzini Menotti Rodolfi, G., Sanesi, G., Sarti, L. 1982. *Testimonianze preistoriche nel Mugello e nella Val di Sieve. Catalogo della mostra itinerante Maggio '82- Febbraio '83*. Roma, Edizioni Viella.

Cenni, E. 1992. Aspetti vegetazionali del Mugello. In *Atti della giornata di studio Archeolologia e Ambiente in Alto Mugello 28 giugno 1992*: 9, 16. Firenze.

Chini, L. 1886. Ancora dell'antichità mugellane. *Il messaggero del Mugello*, *14 September*: 1-2.

Ciampoltrini, G. and Notini, P. 1986-87. Nuovi documenti del Bronzo finale dalla Capriola di Camporgiano (Lucca). *Rassegna di Archeologia.* 6.

Cipriani, N., Dini, M., Ghinassi, M., Martini, F., Tozzi, C. 2001. L'approvvigionamento della materia prima in alcuni tecnocomplessi della Toscana appenninica. *Rivista di Scienze Preistoriche*. 51: 337-88.

CO. IDRA 1995. *Carta Archeologica della Provincia di Firenze*. 1:50,000. Firenze.

Cocchi, D. 1982. La preistoria del Valdarno superiore. *La Storia del Valdarno*. 2: 432-540.

Cocchi, I. 1871. *Raccolta degli oggetti de' così detti tempi preistorici*. Cataloghi della Collezione centrale italiana di paleontologia. Firenze, Civelli.

Cocchi Genick, D. 1989. Elenco delle stazioni. In D. Cocchi Genick, R. Grifoni Cremonesi (eds.), *L'Età del Rame in Toscana*: 9-83. Viareggio.

Colini, G. A. 1892. Martelli o mazzuoli litici con foro rinvenuti in Italia. *BPI* 18: 149-235.

Colini, G. A. 1896. Martelli o mazzuoli litici con foro rinvenuti in Italia. *BPI* 22: 1-18, 73-93, 257-76.

Curri, C. B. 1976. *Vicchio di Mugello (Firenze). Saggi esplorativi nell'acropoli etrusca di Poggio Colla*. Notizie degli scavi di antichità: 93-112.

D'amato, M., Fedeli, L., Iardella, R. 2001. Materiali dell'età del bronzo da Podere Parpiotto (Firenzuola-Firenze). In *Preistoria e Protostoria della Toscana, Atti della XXXIV Riunione Scientifica I.I.P.P dedicata ad Antonio Mario*

Radmilli (Firenze, 29 settembre - 2 ottobre 1999): 654-6. Firenze.

D'amato, M. and Iardella, R. 2003. Podere Parpiotto (loc. San Pellegrino-Firenzuola-FI): i materiali. In G. Roncaglia, A. Donati, G. Pinto (eds.), *Appennino tra antichità e Medioevo*: 317-9. Città di Castello, Petruzzi

De Marchi, L. 2003. *Archeologia della Preistoria tra Parmense e Reggiano, l'Età del Bronzo nelle Valli Parma, Enza e Baganza*. Parma, Graphital Edizioni.

De Marinis, G. 1981. Gli insediamenti etruschi nel Mugello e nella Val di Sieve. In G. Rodolfi (ed.), *Evoluzione storica del territorio del Mugello: insediamenti, viabilità, agricoltura*: 1-8. Firenze, Centro documentazione del Mugello.

Di Cesare, V. 1992. Novità documentarie e topografiche sulla riva sinistra del Savena tra Bologna e il Passo della Futa. In *Atti del convegno 'la Viabilità tra Bologna e Firenze nel tempo' tenutosi a Firenzuola - S. Benedetto Val di Sambro, 28 september-1 october 1989*: 45-50. Bologna.

Di Cesare, V., Agostini, C., Santi, F. 1989. *La strada Flaminia Militare: Testimonianze archeologiche sulla dorsale sinistra del Savena tra Bologna e il Passo della Futa alla ricerca della strada del 187 a.C*. Bologna.

Diringer, D. 1929. Edizione Archeologica della Carta d'Italia al 100,000. Foglio 107 (Monte Falterona). Firenze.

Fedeli, L. 1992. Campagna di scavi 1989 presso i tratti stradali della Dorsale transappenninica fra il Setta, il Savena e il Santerno. In *La viabilità tra Bologna e Firenze nel tempo: problemi generali e nuove acquisizioni. Atti del convegno tenutosi a Firenzuola - S. Benedetto Val di Sambro, 28 september-1 october 1989*: 59-90. Firenze.

Fedeli, L. 2003. Falde appenniniche. In G. Roncaglia, A. Donati, G. Pinto (eds.), *Appennino tra antichità e Medioevo*: 293-315. Città di Castello, Petruzzi.

Fedeli, L., Bigagli, C., D'aquino, C., Iardella, R., Mennuti, F. and Palchetti, A. 2005. Borgo San Lorenzo (FI). Viale fratelli Kennedy: campagna di scavo 2005. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 1: 122-6.

Fedeli, L. and De Stefani, M. 2007. Pontassieve (FI). Località Molino di Vico, vocabolo Il Campone: scavi 2007. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 3: 158-62.

Fedeli L., Filippi, O., Martini, F. 2006. Firenzuola (FI). Frazione Cercetola, località Cialdino: campagna di scavo 2006. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 2: 107-9.

Fedeli, L., Filippi, O., Martini, F. and SARTI, L. 2007. Firenzuola (FI). Frazione Cercetola, località Cialdino: campagna di scavo 2006. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 3: 139-40.

Fedeli, L. and Paci, S. 2006. Palazzuolo sul Senio (FI). Frazione Mantigno: campagna di scavo 2006. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 2: 113-4.

Fedeli, L., Sarti, L., Volante , N. 2005. Scarperia (FI). Vocabolo Marroneta Tonda: campagna di scavi 2005. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 1: 119-21.

Fedeli, L., Sarti, L., Volante, N. 2006. Scarperia (FI). Vocabolo Marroneta Tonda: campagna di scavo 2006. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 2: 115-6.

Ferrini, V. 1988. La presenza umana dall'antichità al medioevo. In I. Moretti (ed.), *Antiche Leghe*: 87-140.

Foresi, R. 1870. *Nota di oggetti preistorici inviata al Prof. Luigi Pigorini per l'Annuario Italiano del 1870*, Firenze.

Forte, M. 2002. *I Sistemi Informativi Geografici in archeologia*. I Quaderni di MondoGIS. Roma.

Fugazzola Delpino, M. A., Lattanzi, V., Pessina, A. and Tinè,V. 2004. *Il Neolitico in Italia, ricognizione, catalogazione e pubblicazione dei dati bibliografici, archivistici, bibliografici e monumentali. Origines* I-III. Roma.

Galiberti, A. 1997. *Il Paleolitico e il Mesolitico della Toscana. Catologo Mostra Materiali*. Poggibonsi.

Giglioli Hillyer, E. 1912. *La collezione etnografica del Prof. Enrico Hillyer Giglioli, geograficamente classificata* I-II. Città di Castello.

Grifoni Cremonesi, R. 1964. La collezione di oggetti preistorici della Toscana esistente al museo L. Pigorini di Roma. *Atti della Società Toscana di Scienze Naturali* 71 (series A): 51-82 .

Grifoni Cremonesi, R. 1971. Revisione e studio dei materiali preistorici della Toscana. *Atti della Società Toscana di Scienze Naturali* 78 (series A): 170-300.

Inglis, B. 1985. L'industria Epipaleolitica di S. Apollinare (Valle del Senio). *Studi per l' Ecologia del Quaternario* 7: 41-51.

Inglis, B. 1985a. Il Bronzo tardo di Monte Battaglia sull'Appennino Tosco-Emiliano (Casola Valsenio). *Studi per l'Ecologia del Quaternario* 7. Firenze.

Laplace, G. 1964. Essai de typologie systématique. Annali dell'Università di Ferrara 15, 1: 1-85.

Leonardi, G. 1992. Assunzione e analisi dei dati territoriali in funzione della valutazione della diacronia e delle modalità del popolamento. In M. Bernardi (ed.), *Archeologia del paesaggio, 4° Ciclo di lezioni sulla ricerca applicata in archeologia, Certosa di Pontignano 14-26 gennaio 1991*: 25-66. Firenze.

Magi, F. 1929. Edizione Archeologica della Carta d'Italia al 100,000. Foglio 106 (Firenze). Firenze.

Magi, M. 1979. Figline Valdarno - loc. Poggerina (Firenze) e Figline Valdarno - C. Madonna (Firenze). *Studi per l'Ecologia del Quaternario* 1: 184.

Martini, F. 1992. Il popolamento umano dell'Alto Mugello in età preistorica. In *Atti della giornata di studio Archeolologia e Ambiente in Alto Mugello 28 giugno 1992*. Firenze: 17-26.

Martini, F. 1994. Prime ricerche stratigrafiche a Certola - Cialdino (Firenzuola - Firenze). In *Atti della giornata di studio 'Archeologia in Alto Mugello - Mugello - Val di Sieve e il caso di S. Piero a Sieve', 22 gennaio 1994*: 87-90. Firenze.

Martini, F. 2009a. Preistoria dell'aretino: documenti, problemi e ipotesi nel quadro dell'archeologia delle origini in Toscana. *Arezzo nell'antichità*. Roma: 35-48.

Martini, F. 2009b. Pieve di Ca'Maggiore (Firenzuola, FI). In L. Cappuccini, C. Ducci, S. Gori, L. Paoli (eds.), *Museo archeologico comprensoriale del Mugello e della Val di Sieve. Catalogo dell'esposizione*: 12,13,16-18. Firenze.

Martini, F. 2009c. Lucigliano (S. Piero a Sieve, FI) p. 10. In L. Cappuccini, C. Ducci, S. Gori, L. Paoli (eds.), *Museo archeologico comprensoriale del Mugello e della Val di Sieve. Catalogo dell'esposizione*: 10. Firenze.

Martini, F. 2009d. Loc. Tre Vie (S. Piero a Sieve, FI). In L. Cappuccini, C. Ducci, S. Gori, L. Paoli (eds.), *Museo archeologico comprensoriale del Mugello e della Val di Sieve. Catalogo dell'esposizione*: 11, 12. Firenze.

Martini, F. and Filippi, O. 2007. Cialdino (Firenzuola, Prov. Di Firenze. *Rivista di Scienze Preistoriche,* Notiziario 57: 451-2.

Martini, F., Ghinassi, M., Moranduzzo, B. 2004. Caratterizzazione degli areali e modalità di raccolta della materia prima litica in area fiorentina dal Paleolitico all'Età del bronzo. In *Atti della XXXIX riunione scientifica dell'I.I.P.P. 'materie prime e scambi nella preistoria italiana'.* Firenze.

Martini, F., Pallecchi, P., Sarti, L. 1996. *La ceramica preistorica in Toscana: artigianati e materie prime dal Neolitico all'Età del Bronzo*. Firenze.

Martini, F., Sarti, L. and Filippi, O. 2008. Cialdino (Firenzuola, Prov. di Firenze). *Rivista di Scienze Preistoriche*, Notiziario 58: 424.

Mastrelli, C. A. 1969. Sul nome del Mugello. *Studi Etruschi* 37.

Morselli, E. 1875. Scoperta di una stazione dell'epoca della pietra presso Barberino di Mugello. *Archivio per l'Antropologia e la Etnologia* 5: 305-7.

Matthews, A. J. 1985. *Metodologia statistica per la ricerca geografica.* Geografia e società. Milano, F. Angeli.

Morelli, M. 2002. *La storia geologica dell'Area protetta del Monteferrato.* Prato: 77-86.

Morico, G. 1983. *Catalogo della mostra Monterenzio* 1983: 399.

Niccolai, F. 1914. *Guida del Mugello e della Val di Sieve*. Borgo San Lorenzo.

Nieri, N. 1930. *Edizione Archeologica della Carta d'Italia al 100,000*. Foglio 98 (Vergato). Firenze.

Nieri, N. 1931. *Edizione Archeologica della Carta d'Italia al 100,000*. Foglio 99 (Faenza). Firenze.

Palchetti, A. and Sozzi, M. 1999. L'industria litica del sito preistorico 'V. Visani' a Pieve di Camaggiore (Firenzuola-Firenze). *Studi per l'Ecologia del Quaternario.* 21: 49-66.

Palma Di Cesnola A. 1957. *Rivista di Scienze Preistoriche*, Notiziario 12: 270.

Palma Di Cesnola, A. 1965. Industria litica dei terrazzi sul lacustre di Galliano. In: Sanesi G. (ed.) *Geologia e morfologia dell'antico bacino lacustre del Mugello*. *Bollettino della Società Geologica Italiana* 84 (fasc. 3).

Perazzi, P. and Poggesi, P. 2005. La carta archeologica della Provincia di Prato. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 1: 66-71.

Pigorini, L. 1875. Ricerche Paletnologiche nel Veronese ed in Toscana. *BPI* 1: 179-82.

Pigorini, L. 1882. Notizie diverse. *BPI* 8: 86.

Pizziolo, G. 2000. L'uso dei GIS per la valutazione dell'attendibilità dei dati archeologici ai fini di un'analisi distributiva. Bias analysis nella valle del Biferno. In M. Panzeri, G. Gastaldo (eds.), *Sistemi Informativi Geografici e Beni Culturali*: 101-7. Torino.

Sarti, L. 1980. L'insediamento dell'età del Bronzo di Dicomano, *Rivista di Scienze Preistoriche* 35, 1-2: 183-247.

Sarti, L. 2009. Cantiere Rosselli (Dicomano, FI). In L. Cappuccini L., C. Ducci, S. Gori, L. Paoli (eds.), *Museo archeologico comprensoriale del Mugello e della Val di Sieve. Catalogo dell'esposizione*: 18-20. Firenze.

Sarti, L. and Volante, N. 2006. Marroneta Tonda (Scarperia, Prov. Di Firenze) campagna di scavo 2006. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 2: 115-116.

Sarti, L. and Volante, N. 2007. Marroneta Tonda (Scarperia, Prov. Di Firenze). *Rivista di Scienze Preistoriche.* Notiziario 57: 451.

Spaterna, G. 1992. Foglio 98 Vergato, Foglio 99 Faenza, Foglio 106 Firenze, Foglio 107 Monte Falterona. In M. Torelli, M. Masseria (eds.) *Atlante dei siti archeologici della Toscana*. Biblioteca di studi e materiali: 31-33, 35, 107-123, 149-159. Roma.

Tracchi, A. 1978. *Dal Chianti al Valdarno*. Roma.

Valsini, F. 1882. Antichità mugellane (lettera a Guido Carocci). *Arte e Storia* I, 12 (8): 91.

Visani, V. 1985. Testimonianze preistoriche ed archeologiche nella Valle del Senio. *Studi per l'Ecologia del Quaternario* 7: 175-93.

Visani, V. 1988. Valle del Senio (Palazzuolo). *Studi per l'Ecologia del Quaternario* 10: 145.

Visani V. 2002. Palazzuolo sul Senio. *Studi per l'Ecologia del Quaternario* 24: 127-8.

Visani, V., Borzatti Von Löwestern, E. 1987. Valle del Santerno (Toscana). *Studi per l'Ecologia del Quaternario* 9: 127.

The Statistics of Time-to-Event. Integrating the Bayesian Analysis of Radiocarbon Data and Event History Analysis Methods

Juan Antonio Barceló
juanantonio.barcelo@uab.cat

Giacomo Capuzzo, Berta Morell, Katia Francesca Achino, Agueda Lozano
Quantitative Archaeology Lab, Department of Prehistory,
Autonomous University of Barcelona, Faculty of Philosophy and Letters, Bellaterra (Barcelona), Spain

Abstract: Survival or Event History Analysis is a set of statistical methods for examining not only event occurrence but also the timing of events. These methods were developed for studying death – hence the name 'survival' analysis – and have been used extensively for that purpose in the social sciences and ecology; however, they can also be successfully applied to archaeology. The underlying idea is pretty basic but fundamental for archaeological and historical purposes: understanding the pattern of events in time and what factors are associated with when those events occurred. In this paper we have used some of these methods to study of the survival of Bronze Age cultural practices in Western Europe (from the Alps to the Mediterranean). We have used radiocarbon data from culturally homogenous geographical areas to discover how the duration spent in one cultural state affected the probability some entity will make a transition to another social state.

Keywords: Event History Analysis, Survival Analysis, Radiocarbon, Cultural Change, Late Bronze Age

Introduction

It has for some time been accepted that the question 'How long did this activity last?' cannot adequately be addressed by simply calibrating single radiocarbon determinations. It is critical for the archaeologist to have a theoretically sound reason for hypothesizing when a social process could have begun. Consequently, the first step in any historical study is not just to 'measure' *time*, but to define particular events in terms of discrete states.

An event is a transition from one state to another, that is, from an origin state to a destination state. Any change or 'innovation' in the social, cultural, political, economic domain can be considered as a *transition* from one state to another (Andersen and Keiding 2002; Strang 1991; Singer and Willett 2003). In archaeology and other historical sciences, the simplest hypothesis of a *transition* is a two-state model for cultural change with one transient state '0: old' and one absorbing state '1: new' (Fig. 1). In general, an *absorbing* state is a state from which further transitions cannot occur while a *transient* state is a state that is not absorbing. In our case, the observation for a given region will here consist of a random variable, say *T*, representing the time from a given origin (time 0) to the occurrence of the event ('first occurrence of a new cultural feature').

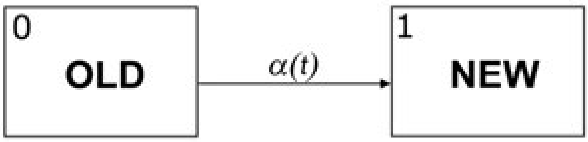

Fig. 1. Simplest hypothesis of a transition in archaeology.

We shall start by focusing on the time elapsed from an initial time 0 step to the first occurrence of the innovation at different places and regions. As a generic term, the time from the initiating event to the event of interest is usually denoted a *survival time*, also when the end-point is something different from death (Kleinbaum and Klein, 2011; Aalen, Borgan and Gjessing, 2008; Abbot, 1995). In archaeology, it is referred as *duration* (Buck *et al.* 1994; Nicolucci and Hermon 2015) or 'period of validity' (Mestres and Martin 2002; Barceló 2008). We are interested in knowing how the duration spent in one cultural state affects the probability some entity will make a transition to another social state. In other words, we intend to estimate the conditional probability of exiting a state given that the state has been occupied for some length *t*. The dependent variable, the duration, is the length of time that has elapsed from the beginning of the state until its end or until measurement is taken and therefore truncates the observation.

1 A probabilistic model of temporal duration

Our approach can be defined as the analysis of the duration of the occurrence of an event during a hazard or risk period. In this paper we define a *hazard* as any source of potential change on something or someone under certain conditions at work. The period that a particular cultural feature is at risk of change is called the 'hazard period'. For example, let us imagine a human group experiences some form of cultural change because it has maintained some degree of interaction with another group. In general, we can assume that any interacting group can be at risk of a particular cultural change for the shake of cultural transmission/imposition between them. It does not mean that the only source of change is social interaction, but in general historians have empirical support for the hypothesis of the higher risk of cultural change in presence of sufficient channels for social interaction than in its absence. Although isolated groups may also change, the probability and frequency of cultural change is higher in the situation of contact and cultural transmission with other groups. It is in this sense that we can assume that the most relevant part of the hazard period(s) for a cultural change are the period(s) that a social agent is interacting with other social agents. The hazard or 'risk set' is the set of social agents –in our case 'settlements' or 'sets of settlements= regions' in some time interval that are at risk of experiencing the adoption of a cultural innovation, and hence a cultural change. Once the event is experienced, that is, the people living at that settlement or region abandons the traditional feature and adopts a new one, the settlement or region exits the risk set. Hence, at each observation period, hazard progressively dwindles until, by the end of the observation plan, no units are at risk (as each has experienced the event).

The definition of the hazard (or 'transition') rate is always conditional with respect to the event of interest not having occurred *before* time *t*. It therefore makes an assumption about how information on the past influences the present and the future. It is usually expressed as the following:

(1)

Thus, α*(t)* is the *transition intensity* from state 0 (tradition) to state 1 (innovation, cultural change), i.e. the instantaneous probability per time unit of going from state 0 to state 1. The hazard rate measures the propensity of a particular cultural feature to change at any given time, if and only if it has survived up to that time. The propensity of an event ending at some time point, given that the event has lasted to that time point, is the critical feature of a hazard rate. According to a substantive perspective we can ask 'what is the risk a cultural feature will fall out of use?', or 'how long do cultural features stay in use?'. Such questions beckon a time dimension; and by modeling the hazard rate, we gain substantial leverage on answering such questions.

We define a survivor function, *S(t)*, as the proportion of the population that is still at risk of change at time *t*. The survival function, *S(t),* gives the expected proportion of regions or sites for which the new cultural feature has not yet happened by time *t*. If the random variable *T* denotes the survival time, one may write more formally:

(2)

It is seen that *S(t)* corresponds to the probabilities of being in state 0 or 1 at time *t*. If every group of social agents is assumed to be in state 0 at time 0 then *S(t)* is also the *transition probability* from state 0 ('before change') to state 1 ('first occurrence of change') for the time interval from 0 to *t*. Remember that we use the term 'survival time' in a quite general sense, and hence the same applies to the term survival function. Thus the survival function gives the probability that the cultural feature of interest still survives by time *t* (in the study time scale), and no cultural change is documented.

We should also consider the probability density function of each event of innovation:

(3)

The term *f(t)* represents the probability density function of the duration ("duration density") and it may be interpreted as the instantaneous probability of the occurrence of an event *T* at time *t*. As suggested by Strang (1991) it can be also interpreted as the limiting probability that settlements, in a particular culturally homogeneous geographical area, moves from non-adoption to adoption between two points of time.

2 Temporal data

Let us consider the case of the survival of Bronze Age cultural practices. From the end of the Middle Bronze Age onwards, human communities across Western Europe and the northern basin of Mediterranean began to adopt a new funerary practice characterized by the burial of cremated body parts, frequently inside an urn (see Capuzzo and Barcelo 2015 for earlier references). Why do some geographical regions adopted such a new cultural feature at this precise historical moment ('Late Bronze Age', ca. 1350-750 BC), while other regions do not or adopted later? The answer probably lies in the way the predominant ritual practice at a local level was related to the odds of economic, social and cultural change at a more global level. We strongly reject the classical idea of 'archaeological culture'. There was not any prehistoric 'culture' of Inhumation Graves in European Bronze Age, substituted by a 'new one' characterized by cremation burials, but some groups of people that *changed* the way they buried their dead people. We assume that the rate of leaving a traditional practice was related with the intensity of adopting a cultural innovation. That means that we are considering a global social and cultural change, and not simply the entry of new populations in an environment peopled by social agents with alternative cultural practices.

When modeling the duration of time a cultural practice was in use, each practice still in use at some particular moment of time can be considered a 'survivor'. In our case, it means the 'survival' of traditional cultural features: a burial practice (inhumation), a technique of burial construction (tumulus), a tool type (pottery with vertical expansion handles), etc. The historical event of interest is here the 'adoption of cremation in urn as a new burial practice'. Therefore, our analysis concerns the 'duration' of non-occurrence of inhumation and the delays in adopting new cultural features.

Ideal data for carrying on this study would be radiocarbon estimates for archaeological contexts with clear evidence of both events of interest (Barceló, Bogdanovic and Capuzzo 2012). In those circumstances, survival time (or duration) would be described by two independent parameters, a start event t_a and a finish event t_b (Buck *et al.* 1991; 1992; Zeidler *et al.* 1998; Bronk Ramsey 2009 and 2015). However, we are far from such ideal data. Cremation burials are not spatially associated with inhumation ones, and hence we cannot measure the temporal difference or the degree of contemporaneity between both practices at the same site. Properly dated archaeological contexts are also irregularly selected and it is seldom impossible to date the beginning of the occupation *and* the date of the cultural feature of interest. The adoption of cultural innovations in those historical circumstances is assumed to be a continuous process over time and space but we only observe the event at selected discrete times as dictated by the limited availability of archaeological well excavated data. The lack of proper data makes impossible measuring survival times of cultural features at a local scale. Consequently, we are

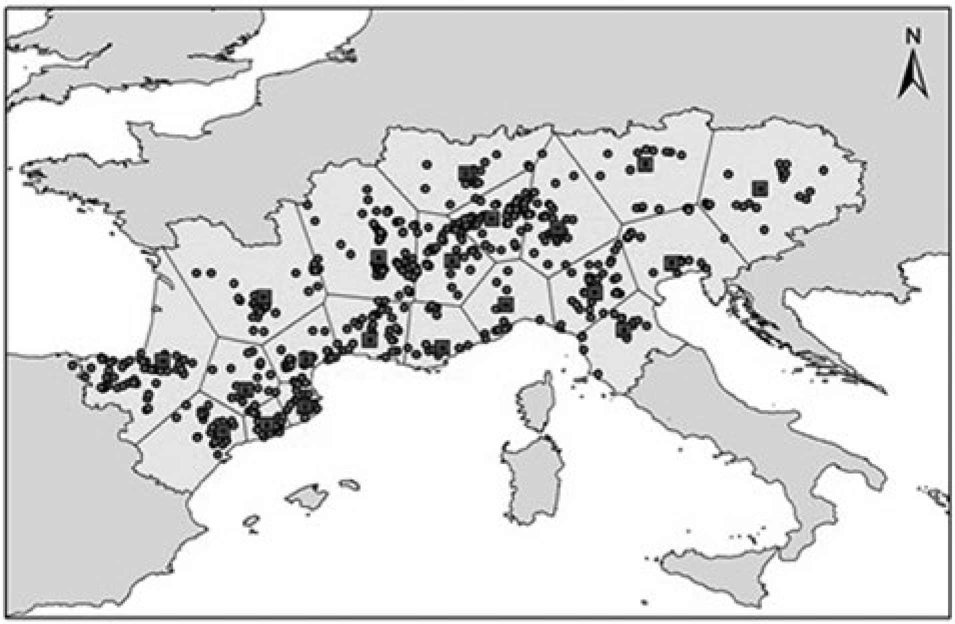

FIG. 2. MAP SHOWING ^{14}C-DATED ARCHAEOLOGICAL SITES INCLUDED IN THE EUBAR DATABASE. DOTS CORRESPOND TO TWENTY DIFFERENT GEOGRAPHICAL REGIONS IDENTIFIED WITH THIESSEN POLYGONS (SOFTWARE: ESRI 2011. ARCGIS DESKTOP: RELEASE 10. REDLANDS, CA: ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE).

constrained to adopt a macro-spatial approach where the unit of study is a geographical region assumed to have been culturally homogenous during the most part of the period under study. We have considered 20 natural regions, from the Alps to the Mediterranean (Fig. 2).

To estimate the survival time of the traditional Bronze Age cultural package and the timing of the adoption of new cultural features we have used data from the EUBAR Database (Capuzzo *et al.* 2014; Capuzzo 2014; Capuzzo and Barceló 2015). The EUBAR database contains radiocarbon 1700 radiocarbon dates associated to details about archaeological contextual associations from a wide territory between the Ebro and the middle course of the Danube Rivers. The analyzed time span goes from 1800 to 750 BC, the end date is determined by the 'Hallstatt plateau': a plane form on the calibration curve, caused by variations in solar activity. Therefore we have not taken into account dates between 750 and 400, because the results would be characterized by too large a time span, and so would not be useful for a statistical analysis.

We have used OxCal 4.2 to model a Bayesian estimation of the most probable timing for the lowest and uppest boundary events for inhumation and cremation burial practices, assuming a simple boundary (Tab. 1).

From this we have created two survival time tables, one for measuring the survival of a traditional cultural feature (inhumation) (Tab. 2), and the second to estimate the temporal delay in adopting the cultural change (cremation and the related cultural package) (Tab. 3). In both cases t_i is a positive number indicating the number of calendar years. In the first case, the survival of Bronze Age traditions has been calculated as the difference between time 0 (1800 BC) and the median of the Bayesian interval for the last occurrences of inhumations in a region within the studied period. It is important to take into account that this is not the median of the confidence interval of the most probable date, but the meadian of the boundary. As an estimation of the middle point of a probability interval, medians can generate misleading results. However, we can use medians to distinguish the most probable lowest boundary from a comparison of the oldest dates, and the most probable highest boundary from the comparison of the most recent ones. Bronk Ramsey (2009, 2015) has argued that the lowest and highest boundaries of a time period are Gaussian distributed, consequently we can estimate the duration of the periods in terms of the difference between the medians of lowest and highest boundaries.

Available temporal data are, however, incomplete and partially truncated. In some cases we have not found any properly dated inhumation or cremation burial. The lack of properly dated inhumation burials is an instance of *left-truncation* or *delayed entry*. The left-truncation problem occurs when observations of individual cases begin after the case has already entered the risk set. This implies that the risk set will not only decline over time, but will also increase when another individual comes into the study. Fixing a Time 0 as 1800 BC, a time where inhumation was present everywhere in the area of study, we avoid such problems. The case of *right-censoring* is more relevant in our analysis because we cannot fix the end or finishing moment of the tradition whose survival we are interested in. As a partial solution to this problem in data coherence we have introduced a dichotomous indicator denoting whether or not a region experienced the event within the time frame of the analysis. This solution belies the logic of studying time dependency in the first place (Box-Steffensmeier and Jones 1997), although we are conscious that an indicator variable cannot capture the variability in duration time the inhabitants of a particular region spended prior to adoption.

Tab. 1. Median values calculated with OxCal 4.2 software for the lower and upper simple boundaries of the phenomena of adoption of both inhumation and cremation rites in twenty European regions.

Region	Funerary ritual	Lower Boundary	Upper Boundary
Ebro Valley	Inhumation	*1800*	*1519*
Ebro Valley	Cremation	*821*	*800*
Barcelona	Inhumation	*1800*	*1334*
Barcelona	Cremation	*997*	*800*
W. Pyrenees	Inhumation	*1800*	*1517*
W. Pyrenees	Cremation	*896*	*800*
C. Pyrenees	Inhumation	*1800*	*744*
C. Pyrenees	Cremation	*1358*	*800*
E. Pyrenees	Inhumation	*1800*	*890*
E. Pyrenees	Cremation	*960*	*800*
Languedoc	Inhumation	*1800*	*1435*
Languedoc	Cremation	*985*	*800*
Massif Central	Inhumation	*1800*	*1149*
Massif Central	Cremation	*1040*	*800*
Provence	Inhumation	*1800*	*726*
Provence	Cremation	*1516*	*800*
Lower Rhone	Inhumation	*1800*	*760*
Lower Rhone	Cremation	*1200*	*800*
Upper Rhone	Inhumation	*1800*	*888*
Upper Rhone	Cremation	*1323*	*800*
Alsace	Inhumation	*1800*	*822*
Alsace	Cremation	*1253*	*800*
W. Alps	Inhumation	*1800*	*1293*
W. Alps	Cremation	*958*	*800*
Swiss Plateau	Inhumation	*1800*	*923*
Swiss Plateau	Cremation	*1675*	*800*
C. Alps	Inhumation	-	-
C. Alps	Cremation	-	-
Bavaria	Inhumation	*1800*	*1128*
Bavaria	Cremation	*976*	*800*
Piedmont	Inhumation	*1800*	*1381*
Piedmont	Cremation	*1575*	*800*
Po Valley	Inhumation	*1800*	*1765*
Po Valley	Cremation	*1600*	*800*
Apennines	Inhumation	-	-
Apennines	Cremation	-	-
N. Adriatic	Inhumation	*1800*	*1496*
N. Adriatic	Cremation	*1380*	*800*
Vienna Basin	Inhumation	*1800*	*782*
Vienna Basin	Cremation	*1255*	*800*

3 The survival of inhumation in Bronze Age europe

We use survival probabilities to test hypotheses concerning the effect of temporal duration on the hazard of cultural change. When the event of interest is 'survival of inhumation burial as a traditional burial practice', the analysis concerns the duration of the last archaeological evidences of inhumation. We have used the Kaplan-Meier estimator of the survival function:

(4)

Let $0 < t_1 < t_2 < t_l < ... < t_k$ be the ordered (continuous) time points at which events occur, n_l is the number of cases at the risk right after t_{l-1} and d_l the number of events at time point t_l. Note that n_k equals n_{l-1} minus the number of events and the number of censored cases in time interval k. Values are plotted using a 95% confidence interval.

Tab. 2. Survival of BA traditions has been calculated as the difference between time 0 (1800 BC) and the median of Bayesian interval for the last occurrences of inhumations in a region within the studied period. Missing values are due to the lack of reliable radiocarbon-dated archaeological contexts in those regions.

REGION	INHUMATION SURVIVAL TIME (number of calendar years since 1800 BC until the last occurrence)
Ebro Valley	281
Barcelona	466
W. Pyrenees	283
C. Pyrenees	1056
E. Pyrenees	910
Languedoc	365
Massif Central	651
Provence Alps	253
Lower Rhone	1040
Upper Rhone	912
Alsace	978
W. Alps	507
Swiss Plateau	877
C. Alps	-
Bavaria	672
Piedmont	419
Po Valley	35
Apennines	-
N. Adriatic	304
Vienna Basin	1018

Tab. 3. The delay in adopting the funerary ritual has been calculated as the difference between time o (1800 BC) and the median of the Bayesian interval for the first occurrence of cremations in a region within the studied period. (Missing values are due to the lack of reliable radiocarbon-dated archaeological contexts in those regions).

REGION	CREMATION ADOPTION (number of calendar years since 1800 BC until the first occurrence)
Ebro Valley	979
Barcelona	803
W. Pyrenees	904
C. Pyrenees	442
E. Pyrenees	840
Languedoc	815
Massif Central	760
Provence Alps	284
Lower Rhone	600
Upper Rhone	477
Alsace	547
W. Alps	842
Swiss Plateau	125
C. Alps	-
Bavaria	824
Piedmont	225
Po Valley	200
Apennines	-
N. Adriatic	420
Vienna Basin	545

The resulting cumulative survival curve represents the proportion of regions where a traditional cultural feature survived at least a given period of time (Fig. 3). The lengths of the horizontal lines along the X-axis of serial times represent the survival duration for that interval. The interval is terminated by the last occurrence of an inhumation burial, that is, the burial with the most recent radiocarbon date. Medians of the Bayesian interval for each region have been considered and not raw radiocarbon data. The vertical distances between horizontals express the change in cumulative probability as the curve advances (Rich *et al.* 2010). Intervals (horizontal lines in the K-M curve) and the attendant probabilities are only constructed for events of interest and not for censored subjects –regions for which no proper radiocarbon dated context is available. Because an event ends one interval and begins another interval, there should be more intervals than events; in other words, there is one event between two intervals.

A horizontal gap means that it took longer for one region to experience a certain fraction of cultural changes at this particular time interval. In other words, there are two period of relevant 'survival'. The first one (in the graph from time 0 to 450, that is, from 1800 BC to 1450 BC) is quite obvious, the very beginning of the period under study, when survival probability is 1 because there are inhumation burials everywhere. This initial interval represents the 'floruit' of the cultural tradition, that is, the period of maximum popularity of this cultural feature. From that date onwards, the probability of this particular tradition surveying began to decrease. In this case, interval durations are variable, but in most cases, except in the first, at the beginning of the period under study, the length of the intervals is relatively short, if compared with the initial interval. In 150 years, probability decrease 20%. After a quite short period without further changes (from 1230 to 1120 BC), the curve records a sudden decrease of additional 20 %. That is, around 1120 BC, inhumation survived in 60% of natural regions from the Alps to the Mediterranean. Up to 950 BC

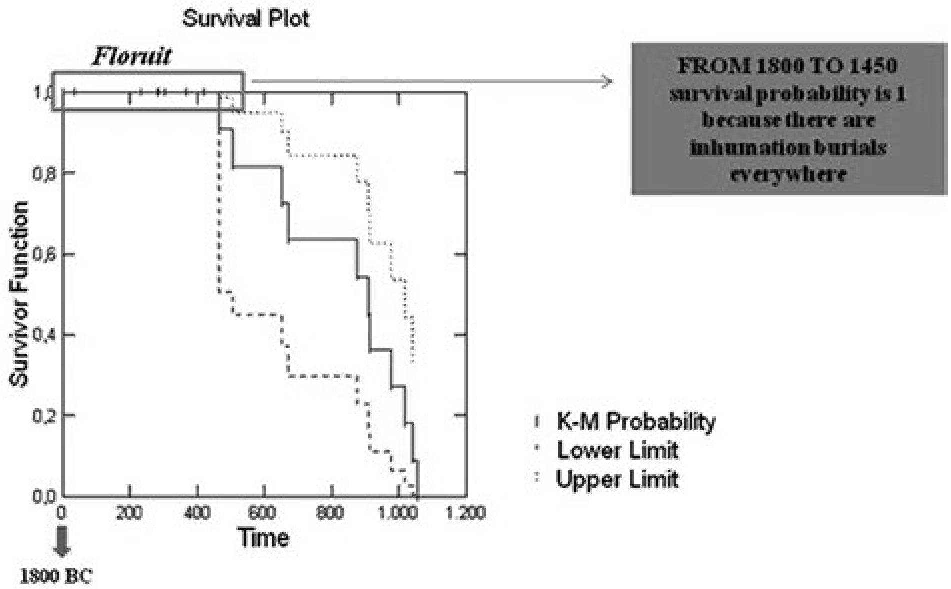

Fig. 3. The survival of inhumation in Bronze Age europe. From 1450 onwards, the probability of this particular tradition surveying begins to decrease. Around 1120 BC inhumation survived in 60% of regions from the Alps to the Mediterranean. From 950 BC on, in 100 years the probability of inhumation survival decreases more than a 50%.

we cannot determine further changes in survival probabilities. However from this last date on, decrease is very fast: in 100 years, the probability of inhumation survival decreases more than a 50%. Right-censoring does not allow determining with precision the very end of this process.

The estimated median period of inhumation survival, that is, the period in which inhumation survived in more than 50 % of regions can be established between 1800 BC and 890 BC.

4 The delay of cremation burials in Bronze Age Europe

When the event of interest is 'adoption of cremation as a new burial practice', the analysis concerns the duration of non-occurrence of inhumation; in other words, the time that individuals remained in the state of never cremating their deads. There are no right-censored data in this case. Using the Kaplan-Meier estimates, we obtain the following survival curve (Fig. 4)

The resulting cumulative survival curve represents the proportion of regions that will resist cultural change at least a given period of time (delay). In this case the horizontal gap at the beginning is quite short, just 100 years (until 1700 BC) where the probability of delay is higher. In this period, resistance to cultural change is maximum because inhumation not only survives, but it is at its 'floruit'. The first occurrence of cremation appears can be understood as a sequence of fast but relatively unimportant occurrences of the new ritual. At 1500 BC, cultural delay was high enough (80 %). The probability of cultural change resistance maintains for another 100 years, after which decreases quickly, 40 % in 200 years, indicating that a majority of regions have adopted the new cultural practice at 1200 BC. From 1000 BC onwards, the dynamics of cultural change increase, so that at 750 BC all regions from the Alps to the Mediterranean have changed one of the most relevant cultural features for the identity of human groups.

The estimated median for the adoption of cremation funerary practices from the Alps to the Mediterranean can be established between 1380 and 985 BC.

5 The relationship between the survival of traditions and the adoption of new cultural features.

Is there any relationship between the low chances of survival of traditional practices and the higher chances of adopting a new cultural package? We have cross checked both cumulative survival probabilities plot and we have tested the statistical hypothesis of correlation (Fig. 5)

In theory, the probability of delaying the adoption of the new ritual should be the same as the probability of maintaining the use of the traditional practice. The graph shows that this was not the case in Western Europe at the end of Bronze Age. We have used a Log-Rank test using Mantel and Haenszel statistic to compare both curves. With a *p-value* of 0.000, the test suggests that there are relevant differences between both curves, indicating that survival of old traditions and resistance to adopt innovations were not temporally correlated in a linear way.

The overlaying of survival function curves in the figure shows that the probability of survival of the tradition was always higher than the probability of resistance to change. After all, cremation was adopted but in no case substituted entirely the previous ritual. The moment at which 50 % of studied regions maintained the old tradition (1000 BC) is more recent than the moment at which 50 % of regions adopted the new funerary ritual (1200 BC). Part of the explanation lies in the quality of data used, and the relevance of right-censoring in the case of inhumation burials. It has not been possible in all cases to distinguish the most probable date of the last inhumation burial from the date of the floruit of this phenomenon, because we had only one radiocarbon estimate. In any case, when a

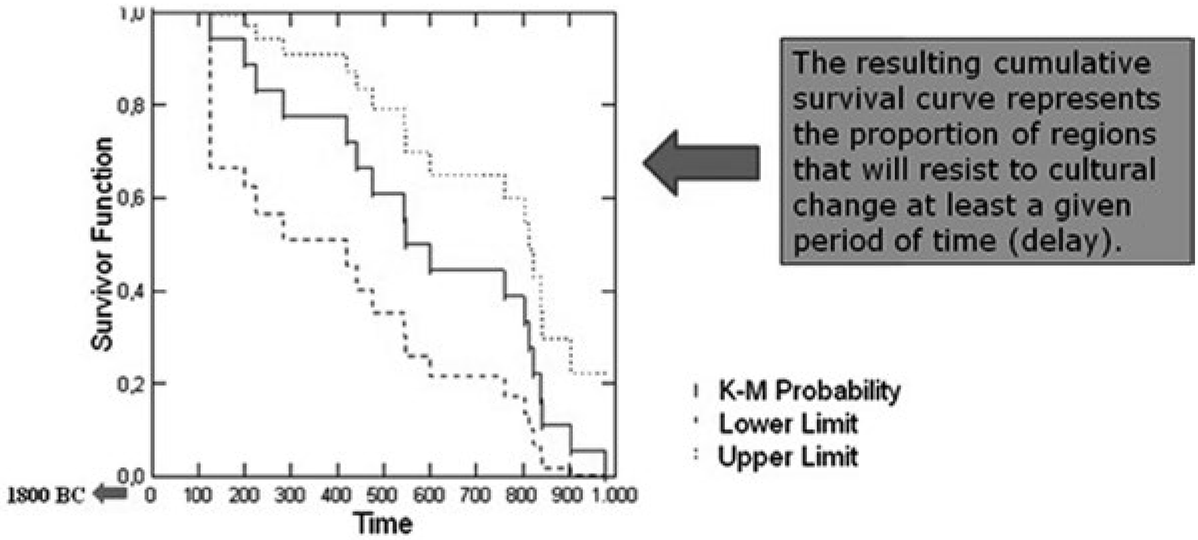

Fig. 4. The delay of cremation burials in Bronze Age Europe. At 1200 BC a majority of regions have adopted the new cultural practice.

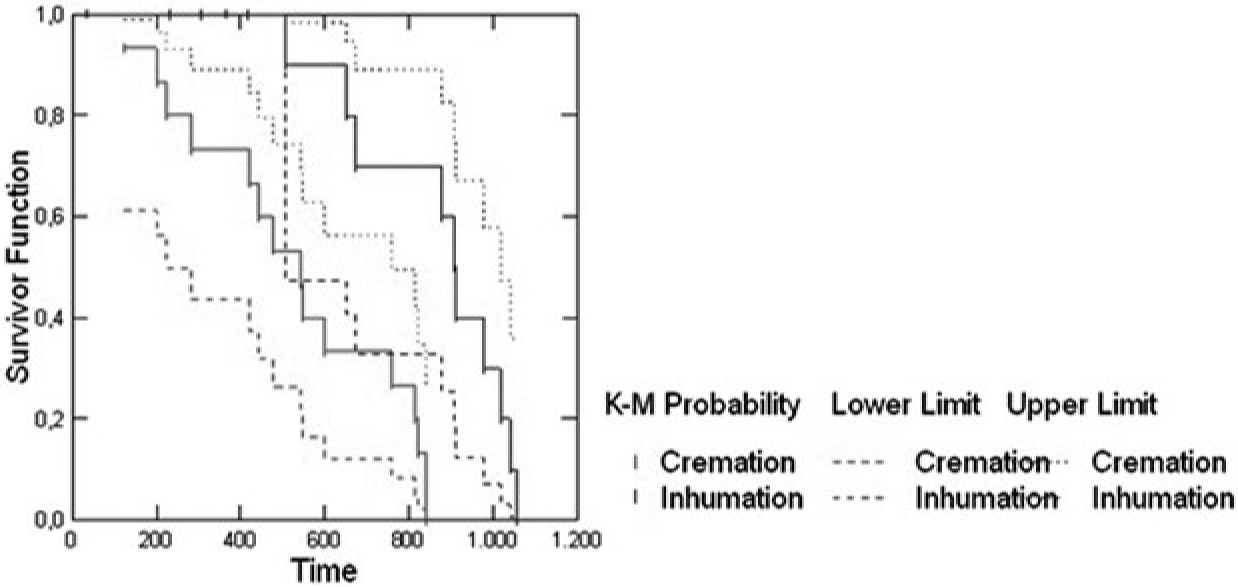

Fig. 5. The relationship between the survival of traditions and the adoption of new cultural features. The probability of survival of the tradition was always higher that the probability of resistance to change. Cremation in no case substituted entirely the previous ritual.

majority of regions (50 %) adopted the new ritual (1200 BC), 90 % of regions still used the traditional practice. That means that both ritual practice coincided along time, and the end of the older was neither a cause nor a requisite for the adoption of the younger.

The graph shows also that turn points in both curves were different and unrelated. The most relevant turn point in the case of inhumation survival has been fixed at 950 BC, when the probability of inhumation survival drops from 70 % to 0 % in only 150 years. 950 BC is a moment in the progression of the adoption of cremation when all regions had adopted the new ritual. That is, although there is no linear correlation between both phenomena, they were in some way related: once the innovation was adopted at all regions, the survival of inhumation began a very fast decline. With more and better data for the chronology of last inhumations we could give more details about it.

6 The probabilities of cultural change at the end of Bronze Age

It is hard to think about the survivor function for cultural features. However it is easier to think about their hazard

Region	N. Region	Time from 0 (Swiss Plateau)
Ebro Valley	1	854
Barcelona	2	678
W. Pyrenees	3	779
C. Pyrenees	4	317
E. Pyrenees	5	715
Languedoc	6	690
Massif Central	7	635
Provence	8	159
Lower Rhone	9	475
Upper Rhone	10	352
Alsace	11	422
W. Alps	12	717
Swiss Plateau	13	0
C. Alps	14	-
Bavaria	15	699
Piedmont	16	100
Po Valley	17	75
Apennines	18	-
N. Adriatic	19	295
Vienna Basin	20	420

Tab. 4. Temporal differences between the adoption of cremation burials in the twenty regions and the introduction of cremation rite in the Swiss Plateau, taken as time 0.

function. In contrast to the survivor function, which focuses on not having an event, the hazard function focuses on the event occurring. In summary, the hazard relates to the incident (current) event rate, while survival reflects the cumulative non-occurrence. It is of interest because it provides insight into the conditional failure rates and provides a vehicle for specifying a model of cultural change.

To study the hazard function of adopting a new ritual at the end of Bronze Age, we have considered a different data set. Instead of considering time 0 as the beginning of the period under study, we have fixed time 0 as the median of the Bayesian interval for the region where cremation first occurred. This is the Swiss Plateau at 1675 BC. We have calculated the difference between that year and the median of the first occurrence of a cremation burial at each of the remaining regions (Tab. 4). As in the previous case, where we do not have properly dated contexts, we have considered right-censored data.

We can plot the cumulative hazard function $H(t)$, or rather an estimate of it. We have used the Nelson-Aalen estimator:

(5)

The easiest way to think of cumulative hazard rates in the present case study is as the cumulative force of delay, or the number of events that would be expected for each individual by time t if the event were a repeatable process.

Figure 6 shows that the gradient/slope of the cumulative hazard function increases over time. However, the slopes are very different and $H(t)$ appears to be non-linear, what suggests that the rate of change in the cumulative hazard was not constant over time: indeed, during the first 300 years since the first occurrence of cremation burials it increased slowly. From 1375 BC until 1000 BC, the risk increased more quickly and from 1000 BC onwards the rate of hazard increased exponentially. The general shape of the curve suggests the expansive nature of the process of cultural change. When the new cultural feature emerged as a new distinctive part of the social identity of a human group, it was likely quite fragile and it had a very low influence on global identity. As soon as the new cultural feature survived a period of time, its chance of influencing global identity increased and the hazard rate for the abandonment of old traditions became higher. In the same way, the risk set increased as more and more regions adopt the new cultural features.

From these results we can infer that the temporality of the adoption of the new ritual followed a well defined distribution from the moment of its wide adoption. The gradient of the curve is very high indicating the fastness of cultural change at most regions. We have tested that a two-parameter Weibull distribution (a=0,17891 b=1929,7) can be fitted to our data (Kolmogorov-Smirnov test, with a *p-value* of 0.63). In this case, the probability density function would be:

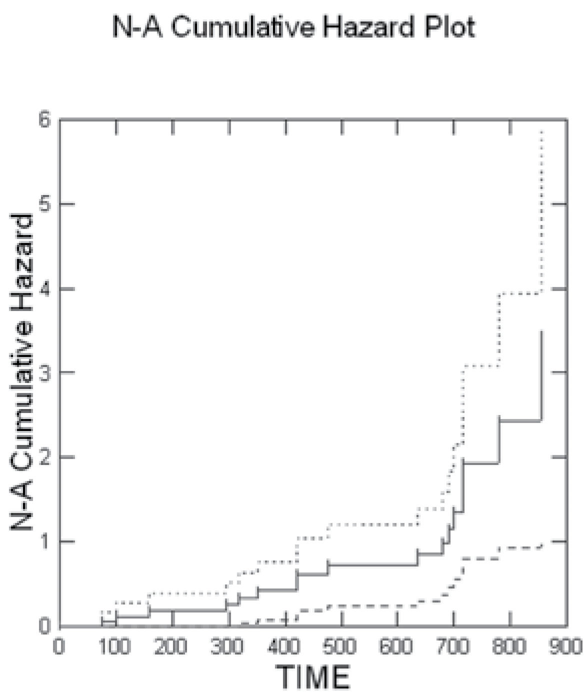

Fig. 6. Cumulative hazard function for the adoption of a new burial ritual from 1650 BC onwards (Nelson-Aalen estimator).

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right)$$

(6)

Consequently, the hazard rate at any given point in time from 1000 BC to 750 BC appears to be equivalent to the hazard rate at any other point in time within the same interval, suggesting that the probability of a cultural was the same at different regions, and hence it did not depend on how long the old tradition of inhumation had been in use. In other words, the probability of a distintive practice occurring an additional number of years would be the same, regardless of how long the older ritual has already been practiced at that geographical area. The hazard rate is simply the inverse of expected duration.

Nevertheless it is important to point to the fact that the introduction of cremation cannot be explained as the cause of the abandonment of inhumation. It is certain that a person can hardly be buried following two traditions at once, so both processes are surely not independent. However, the strict parallelism between the survival curve for both rituals, and the lack of crossing points between both suggest a probable scenario where both traditions had spatio-temporal coexistence at a certain ratio. The causation and the forces that produce the observed pattern must surely be sought in the overarching social system.

7 Conclusions

The adoption of a ritual innovation in Late Bronze Age Western Europe bears resemblance to a complex adaptive system, because the relationship between cause and effect seem to have not been smooth and proportionate. At that time, and in those historical conditions, social agents responded to changes in a non proportional way to the intensity of change: small changes in initial conditions, and later interventions of whatever size, may have resulted in disproportionately large effects. Social, Economical and Political networks connecting settled areas at the end of Bronze Age were overlapping, multiple and complex. Our results suggest that in this particular case study cultural change occurred most often in heterogeneous zones, i.e. transitional spaces where sufficient differentiation among network members emerged. Such heterogeneous network connections related different kinds of agents, the more resistant to cultural change and the more prone to the adoption of new ideas.

Our study looks at a convenient methodology for analyzing both the fine and global scales of social behaviour and the relationships between people at the aggregated level. We have intended to understand cultural change at the end of prehistory as a set of emergent behaviours and feedback, when aggregates of individual behaviour are scaled up to a similar behaviour on a system level. Beginning with the level of local interactions, the fine scale, we study how the diffusion of a new cultural consensus took place through a network consisting of macro-scale units (local and regional groups as potential adopters). As agents adopted the cremation and new pottery typologies or rejected it, their behaviour contributed to the macro system-level scale of behaviour. As the rate of cultural change accelerated and innovation diffusion took off, emergent adoptive behaviour occurred at the system level. As the new ritual practice was adopted by additional agents in the new and evolving social system, a feedback loop may have occurred in the diffusion process, as observability of the new cultural standard increased everywhere, reducing uncertainties associated with the new idea, process, or technology. Other patterns of change and innovation may have occurred elsewhere, but the empirical record of cremation at the end of Bronze Age suggests that this may have been the case.

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Bibliography

Aalen, O., Borgan, O., Gjessing, H. 2008. *Survival and event history analysis: a process point of view*. Springer Press.

Abbott, A. 1995. Sequence Analysis: New Methods for Old Ideas. *Annual Review of Sociology* 21: 93-113.

Andersen, P. K. and Keiding, N. 2002. Multi-state models for event history analysis. *Statistical Methods Medical Research* 11: 91-115.

Barceló, J. A. 2008. La incertesa de les cronologies absolutes en Arqueologia. Probabilitat i Estadística. *Cypsela* 17: 23-34.

Barceló, J. A., Bogdanovic, I., Capuzzo, G. 2012. New developments of archaeological data bases. The example of radiocarbon dating. In A. Castillo (ed.), *Proceedings of the 1st International Conference on Best Practices in World Heritage: Archaeology, Maó, 9-13April 2012*: 733-49.

Buck, C. E., Christen, J. A., Kenworthy, J. B., Litton, C. D. 1994. Estimating the duration of archaeological activity using 14C determinations. *Oxford Journal of Archaeology* 13 (2): 229-40.

Buck, C. E., Kenworthy, J. B., Litton, C. D., Smith, A. F. M. 1991. Combining archaeological and radiocarbon information: a Bayesian approach to calibration. *Antiquity* 65: 808-21.

Buck, C. E., Litton, C. D., Smith, A. F. M. 1992. Calibration of radiocarbon results pertaining to related archaeological events. *Journal of Archaeological Science*19: 497-512.

Box-Steffensmeier, J. M. and Jones, B. J. 1997. Time is of the Essence: Event History Models in Political Science. *American Journal of Political Science* 4 (41): 1414-61.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51 (1): 337-60.

Bronk Ramsey, C. 2015. Bayesian approaches to the building of Archaeological Chronologies. In J. A. Barceló and I. Bogdanovic (ed.), *Mathematics and Archaeology*: 272-92. Boca Raton-Florida, CRC Press.

Capuzzo, G. 2014. Space-temporal analysis of radiocarbon evidence and associated archaeological record: From Danube to Ebro rivers and from Bronze to Iron Ages. Unpublished PhD thesis, Autonomus University of Barcelona.

Capuzzo, G. and Barceló, J. A. 2015. Cultural changes in the 2nd millennium BC: a Bayesian examination of radiocarbon evidence from Switzerland and Catalonia. *World Archaeology*. *Special Issue: Bayesian approaches to Prehistoric Chronologies* 47(4) (in press).

Capuzzo, G. Boaretto, E., Barceló, J. A. 2014. EUBAR: a database of ^{14}C measurements for the European Bronze Age. A Bayesian analysis of 14C-dated archaeological contexts from Northern Italy and Southern France. *Radiocarbon* 56 (2): 851-69.

Kleinbaum, D. G. and Klein, M. 2011. *Survival Analysis. A Self-Learning Text*. Springer Press.

Mestres, J. S. and Martin, A. 2002. Periodització des de la Fi del neolític fins a l'Edat del Bronze a la Catalunya Sud-Pirinenca. Cronologia Relativa i Absoluta. In: *Pirineus i veïns al 3er mileni A.C. XII Col.loqui Internacional d'Arqueologia de Puigcerdà. Puigcerdà, November 2000*: 77-130. Puigcerdà, Institut d'estudis Ceretans.

Nicolucci, F., Hermon, S. 2015. Time, Chronology and Classification. In J. A. Barceló and I. Bogdanovic (ed.), *Mathematics and Archaeology*: 257-70. Boca Raton-Florida, CRC Press.

Rich, J. T., Gail, J., Paniello, R. C., Voelker, C., Nussenbaum, M., Wang, E. 2010. A practical guide to understanding Kaplan-Meier curves. *Otolaryngol Head Neck Surg* 143 (3): 331–6.

Strang, D. 1991. Adding Social Structure to Diffusion Models An Event History Framework. *Sociological Methods and Research* 19 (3): 324-53.

Singer, J. D. and Willett, J. B. 2003. Describing continuous time event occurrence data. In J. D. Singer and J. B. Willett (ed.), *Applied longitudinal data analysis: Modeling change and event occurrence*: 468-97. Oxford, Oxford University Press.

Zeidler, J. A., Buck C. E. and Litton, C. D. 1998. The integration of archaeological phase information and radiocarbon results from the Jama River Valley, Ecuador: a Bayesian approach. *Latin American Antiquity* 9: 135-59.

Hypothesis Testing and Validation in Archaeological Networks

Peter Bikoulis
(peter.bikoulis@mail.utoronto.ca),
Department of Anthropology, University of Toronto, Canada

Abstract: This paper reports a procedure for quantitative validation for the purpose of hypothesis testing between competing archaeological network models. Two ways of forming networks are compared using a case study situated in 4th-3rd millennia BC southern Turkey. The first is created using the principal of proximity that connects network actors based on their geographical distance. This is a common approach used for networks that use location to connect actors. The second is created using the principal of effort costs, and uses Least Cost pathways between sites as a means of connecting them. These are employed as idealized routes connecting sites, taking into consideration movement between sites as the primary constraint in the formation to networks. A third set of random graphs generated using bootstrapping methods (Monte Carlo) are used to assess results between these two network creation strategies. Comparison and evaluation of the real-life network models indicates that large-scale or regional scale network models based on spatial proximity may not provide the best or ideal way of creating archaeological networks.

Keywords: Archaeological Networks, Random graphs, Network science, Prehistoric Anatolia

1 Introduction and Problem

Social Network Analysis has become a significant analytical method in the Social Sciences over the past few decades (Barabási 2002; Borgatti *et al.* 2009; Buchanan 2002; Christakis and Fowler 2009; Watts 1999a, 2003). Not surprisingly, it has found numerous stimulating applications in archaeology and ancient history. Many of these have used network models and methods to visualize and explore social dynamics in the past. One area that has not been well surveyed in the archaeological literature has been the use of networks to test competing hypotheses about social relations in the past. Network theorists in other fields have explored these properties in contemporary society, and have found surprising regularities in seemingly random associations (Barabási and Albert 1999; Brandes *et al.* 2013; Newman 2005; Watts and Strogatz 1998; Watts 1999a, 2003, 2004). The dynamical processes operating in these apparently random networks has led to the coining of the now-classic phrase ‘six degrees of separation’, which colloquially describes the phenomena of a small number of global connections between individuals in our increasingly integrated world (Watts 2003). While an exciting field of research in its own right for physicists and mathematicians (e.g. Bollobás 2001), the highly regularized patterns of ostensibly random associations pose distinctive problems for behavioural scientists who seek to apply social network methods to their research.

Those studying non-human social networks have argued that observations of social relations must significantly deviate from the characteristic properties of randomness in order to be useful for hypothesis testing (Croft *et al.* 2008, 2011; James *et al.* 2009; Krause *et al.* 2007). Specifically, some have promoted the use of jack-knife or other bootstrapping methods like Monte Carlo as a means of comparing the properties of purely random networks to those based on in-the-field observations (Croft *et al.* 2011). Following these recommendations, the use of random graphs is demonstrated here as a step towards hypothesis testing and validation of network results in archaeological applications. To illustrate the method advocated here, two contrasting strategies for creating networks are compared. The first network involves the use of closest neighbours to connect sites. This is a common, even intuitive, way of connecting actors. The second is based on the use of Least-Cost pathways as simulated routes connecting the same set of sites (Bikoulis 2012). In many respects, this approach complements the work Herzog (2013), who used Least Cost pathways to connect German Medieval sites. Each network creation strategy is based on a different behavioural or economic principle, namely that 1) spatial proximity (i.e. Euclidean geometry) greatly affects social interaction, and, 2) accessibility or topographic impediments are a greater concern when determining interaction.[1] While the two networks are shown to differ significantly from random graphs based on well-established network metrics like Centrality, they also differ from each other in important ways. The results suggest that networks based on simple or Euclidean distance may not offer archaeologists the best means of representing social interaction modelling on the movement of people and goods in terrestrial or other contexts.

2 Hypothesis Testing and Validation in Archaeological Networks

2.1 Background to Social Network Analysis

Social Network Analysis is a formal (i.e. mathematical) method based on the graphical representation of actors and their relationships (see Jackson 2008; Kadushin 2012; Knoke and Yang 2008; Scott 2012; Wasserman and Faust 1994). Actors are represented as vertices or nodes in visual representations or graphs and can be defined as anything ranging from individuals to nation states. Links between network actors are dependent upon the type(s) of relationships that the analyst is investigating. Networks known as simple graphs are characterized as undirected, unweighted graphs; all the networks presented here are simple graphs. Lines labelled as *edges* represent these symmetrical relationships. However one chooses to define the actors used in a network, the primary

[1] For the sake of simplicity, those networks built using spatial proximity as the structuring principle are referred to as ‘proximity-based’ and those using accessibility as ‘effort-based’.

elements to consider are the number of actors (boundary) and how they are connected (association).

2.2 Hypothesis Testing and Validation of Archaeological Networks

Network analysis has become especially prominent in the last decade in archaeology (Bernardini 2007; Bikoulis 2012; Broodbank 2000; Davis 1982; Evans *et al.* 2009, 2012; Golitko *et al.* 2012; Gorenflo and Bell 1994; Hart and Engelbrecht 2011; Jenkins 2001; Johansen *et al.* 2004; Knappett *et al.* 2008, 2011; Larson 2013; Merrill and Read 2010; Mills *et al.* 2013; Mizoguchi 2009; Munson and Macri 2009; Peregrine 1991; Rothman 1987; Sindbæk 2007; Sosna *et al.* 2012; Terrell 2010a, 2010b) and ancient history (Alexander and Danowski 1990; Clark 1991; Isaksen 2008; Ruffini 2008; Schor 2007, 2009, 2011). Archaeological network analyses so far have focused on descriptive or exploratory levels of analysis, constructing networks to investigate general qualities rather than engaging in clearly defined hypothesis testing of archaeological phenomena using the formal methods available from network analysis; recent examples such as Brughmans *et al.* (2014) and Östborn and Gerding (2015) are strong movements in this direction.

Archaeological networks have primarily used artefactual evidence such as common ceramic types to demonstrate social ties between actors. While shared material culture traits or diagnostic types strongly point to a general social relation between sites and their inhabitants across vast regions, exactly how to assign connections between entities within such large-scale frameworks still remains problematic. Thus, there remains a great need for conjectural network reconstructions employing such disparate data to engage in explicit hypothesis testing. This contrasts with networks based on historical or archival sources, which frequently can make direct, unambiguous connections between network actors based on documented thoughts and intentions expressed by individuals concerning other network members (Clark 1991; Ruffini 2008; Schor 2007). Some have more recently begun to match specific economic or social models with network analysis in a productive manner (e.g. Sindbæk 2007), but assumptions concerning the mechanisms governing the distribution of material culture often remain implicit in the majority of studies of archaeological networks. I propose this situation be flipped. That is, network models based on clearly defined social or economic activity can be used to structure networks themselves, which can then be evaluated based on their explanatory power.

In order to carry out hypothesis testing of this sort, archaeologists need to start by building performance expectations for networked phenomena by adopting practices similar to those studying animal social networks. Ecologists have sought to ensure that the networks they produce based on in-the-field observation of animal interaction are reliable representations of social interaction (Croft *et al.* 2011; Kasper and Voelkl 2009; Lusseau 2003; C Sueur *et al.* 2011; Wey *et al.* 2008; Whitehead and Lusseau 2012). Studies have looked to social networks among marine mammals (Guimarães *et al.* 2007; Lusseau 2003, 2007; Lusseau *et al.* 2006; Wiszniewski *et al.* 2010), non-human primates (Barrett *et al.* 2012; Bradley *et al.* 2004; Brent *et al.* 2011; Henzi *et al.* 2009; Hirsch *et al.* 2012; Kasper and Voelkl 2009; C Sueur *et al.* 2011; Cédric Sueur *et al.* 2011; Sueur *et al.* 2010, 2012; Voelkl and Kasper 2009; Zhang *et al.* 2012), fish (Kelley *et al.* 2011), and ungulates (Cross *et al.* 2005; Sundaresan *et al.* 2007). Specifically, ecologists have used random graphs as part of hypothesis testing concerning non-human animal social relations in network validation. Social scientists have similarly argued for the need to set network 'benchmarks', where random network models are used to 'develop a reference point for building richer models and understanding the strengths and weaknesses of models that are tied to social and economic forces influencing individual decisions to form and maintain relationships' (Jackson 2008: 78).

The approach outlined here seeks specifically to answer recent calls for network validation in archaeology (e.g. Brughmans 2013: 650) through the demonstration of one way of conducting such a study. The approach presented here is similar to Mills *et al.* (2013), who performed a comparable probabilistic sampling in their study of social networks in the American Southwest. However, the example here presents a fuller description of the procedure and draws explicitly from the breadth of research on the behavior of random graphs though the use of graph models generated by randomization simulations (e.g. Monte Carlo) (Barabási and Albert 1999; Erdős and Rényi 1959, 1960; Newman 2005; Watts and Strogatz 1998; Watts 1999a)and (ii. Using a randomization simulation is also in accordance with more general archaeological research that advocates the use of randomized tests to detect whether a structuring principal organizes observed data (Hodder and Orton 1976: 53). It is to these larger, structural patterns that those interested in network analysis seek to investigate and ultimately explain (Wellman 1983).

2.3 Outline of Experiment

In order to start addressing these issues, an experiment was conducted that incorporated the use of bootstrapping methods using null graph models based on similar parameters to a set of real-world archaeological networks. The data for the real-world archaeological network was drawn from a case study centered on the Göksu River valley of south-central Turkey (Bikoulis 2012). The use of this existing dataset was based on a number of ideal factors. First, it was originally created to explicitly assess the prominence of sites in the Göksu Valley and their possible role as a significant corridor connecting sites on the south Anatolian Plateau and those on the Mediterranean coast. Evaluated based on their Centrality scores, sites within the Göksu Valley were determined to not be significant within overall network movement. Second, Bikoulis (2012) used Least Cost pathways as simulated routes to connect actors within theorized networks of human mobility and exchange across the Taurus mountain chain that dominates the region. Least Cost pathways seek to model the impact of 'effort' from one place to another, taking into account hindrances and impediments to an individual's movement across landscapes (Bell *et al.* 2002; Contreras 2011; Doyle *et al.* 2012; Field *et al.* 2007; Golden and Scherer 2013; Llobera *et al.* 2011; Morgan 2008; Robinson 2010; eds White and Surface-Evanseds 2012). While not explicitly stated, the underlying structuring principle of these networks was that logistical constraints on the movement of people and materials, or accessibility effort more generally, are primary considerations in forming social relations at large scales. To this end, he presents three 'snap shot' networks corresponding to three defined time periods, allowing for a long-term comparison across multiple graphs.

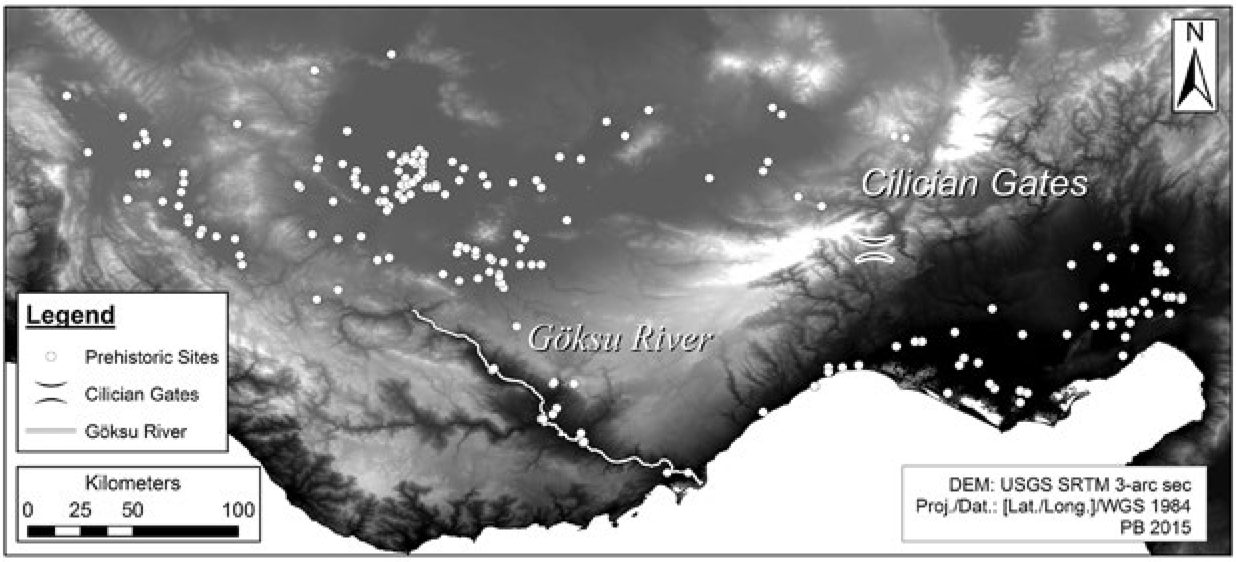

Fig. 1. Map of south-central Anatolia showing prehistoric sites in the Göksu River valley, south-central Turkey (from Bikoulis 2012).

Combined, these features offer an attractive opportunity to outline how to proceed in hypothesis testing and validation of network data in the way proposed here.

A second parallel set of networks is presented here that were created using an alternative structuring principle to construct and test multiple scenarios. The use of spatial proximity serves as a null model counterpart to the use of effort as a structuring principle. Spatial proximity has been positively associated with high levels of social intimacy and increased interaction between network participants within analyses more broadly (Butts *et al.* 2012; Faust *et al.* 2000; Giordano and Cole 2011; Onnela *et al.* 2011; Rushmore *et al.* 2013; Verdery *et al.* 2012; Zhang *et al.* 2012). Networks based on spatial proximity were created to evaluate the suitability of this structuring pattern within landscape or regional-scale archaeology. An additional motivation was to investigate the possibility of equi-finality, with the question addressed by this second set of networks concerning the ways networks with different behavioural principles differed in terms of their structure and network metrics. Lastly, the two network creation strategies are compared to determine which offering a 'best fit' for understanding long-term inter-regional interaction in southern Turkey. These evaluations were made at different levels, including the randomness of the sample set, statistical comparison of network values from the two paralleled versions, and finally the ability of network creation strategies to present realistic models of social interaction within the context of south-central Turkey.

3 Creating the Networks

3.3.1 Archaeological Background and Site Selection

The archaeological context of this research is the Late Chalcolithic to Early Bronze Age III period (c. 4200 - 2000 BC) of south-central Turkey. The region of south-central Anatolia has been subject to sporadic archaeological research since the 1950s. James Mellaart (1954, 1958) conducted the first major field work in the area in the early 1950s, soon followed by M. V. Seton-Williams (1954) and D. French (1965). Mellaart reconnoitered the area from the eastern Cilician Plain to the Lakes District in the west. Seton-Williams investigated sites on the Cilician Plain, while French focused on sites in the Göksu Valley. Combined, these projects documented over 200 unique prehistoric mounds of various dates (Fig. 1). More recent research at the site of Kilise Tepe (Baker *et al.* 1995; Postgate and Thomas 2007) in the central valley and the Göksu Archaeological Project (Elton 2005, 2007; Newhard *et al.* 2013) in the upper part of the valley have deepened understanding of human occupation in the valley.

Sites used in the networks were selected on the basis of important ceramic types reported by the archaeological surveys carried out by Mellaart, Seton-Williams, and French in the region (Bikoulis 2012). Due to the inability to distinguish more finely between chronologically transgressive ceramic types, such as Early Bronze Age Burnished and Metallic wares, three 'snap-shot' periods were created corresponding to the Late Chalcolithic (c. 4200-3200 BC), the EBA I-II period (c. 3200-2300 BC), and the EBA III period (c. 2300-2000 BC). While Mellaart, Seton-Williams, and French report a sizeable number of prehistoric mounds, a small number of these could not be securely categorized using major ceramic types; this situation primarily affected the Early Bronze Age I-II period. In total, 53 sites were used to create the Late Chalcolithic network, 169 sites were used to create the Early Bronze Age I-II network, and 23 sites were used to create the Early Bronze Age III network.

3.3.2 Method used to create Proximity Networks

Handling of spatial data and the determination of the closest neighbours based on distance were carried out in the open source geographical information system (GIS) known as GRASS GIS (GRASS Development Team 2015). Pajek was used to perform the transformation of spatial data to network graphs and obtain network measures (Batagelj and Mrvar 1998; de Nooy *et al.* 2011). In order to ensure minimal network connectivity (i.e.

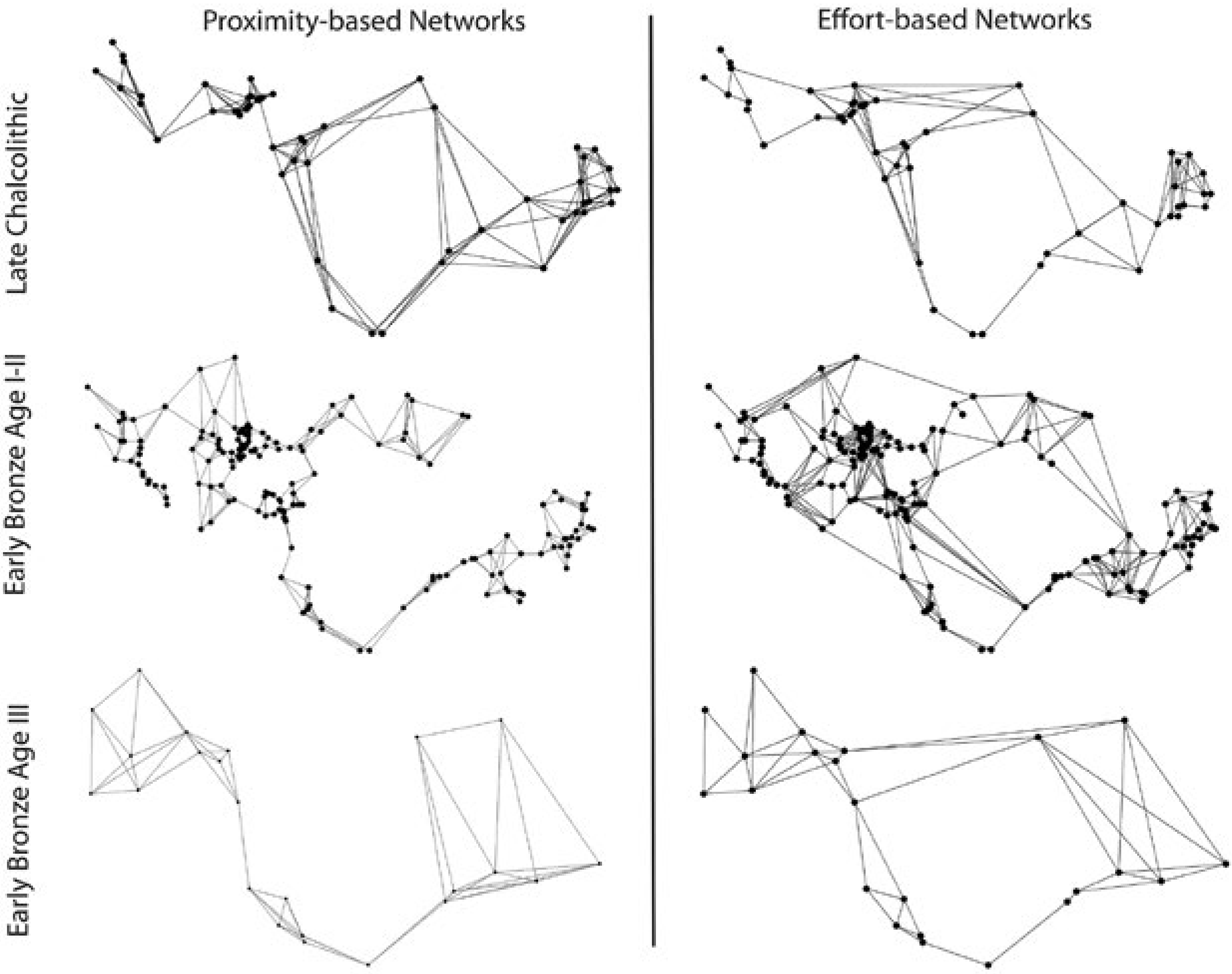

Fig. 2. Graphs for Proximity and Effort-based networks of the Late Chalcolithic, Early Bronze Age I-II and Early Bronze Age III periods.

each vertex had at least one connection) in the proximity graph, linkages were created between Late Chalcolithic sites and their four (4) closest neighbours, and EBA I-II and EBA III sites and their three (3) closest neighbours were used (Fig. 2). Using less than these specified number of linkages resulted in a disconnected graph due to the clustering of sites.

3.3.3 Method used to create Random graphs

Within Graph Theory more generally, the behaviour of random graphs is based on the pioneering graph theoretical work of Erdős and Rényi (1959, 1960). Following the recommendation of Croft and colleagues (Croft *et al.* 2008, 2011; James *et al.* 2009; see also Kolaczyk 2009: 162–165), a Monte Carlo was conducted to generate expected values based on random graph models that could be compared in aggregate to the two different network creation methods. The simulation of 10,000 Degree conditioned Bernoulli/Erdős-Rényi random graphs was carried out in Pajek using the technique proposed by de Nooy *et al.* (2011: 356–360). Bernoulli (or Poisson) model random graphs are the simplest of random graphs, created using a probability (*p*) to assign link placement that is independent of other edges. Their implementation in Pajek of a random () network follows the set of algorithms outlined in Batagelj and Brandes (2005). The mean Degree for each network was used to constrain the creation of the random graph models in order to ensure that each random network was an independent test of each comparator (Fig. 3). This resulted in the conducting of a total of six random graph trials, corresponding to three for the proximity-based networks and three for the effort-based networks.

4 Results

4.1 Metrics used to assess network models

Different ego-based metrics of Centrality were used to compare the networks across three time periods and between two creation strategies. They include different Centrality measures (Betweenness, Closeness, Degree and Eigenvector), as well as the use of Clustering Coefficient (de Nooy *et al.* 2011; Wasserman and Faust 1994) (Table 1). These assess aspects of individual nodes within the network. Clustering Coefficient of Transivity was used to compare proximity-based and effort-based networks at the network-wide level. Various archaeological studies have used Centrality to empirically assess network data, although much fewer have presented the raw data (Bikoulis 2012; Isaksen 2008; Larson *et al.* 2007; Mizoguchi 2009; Munson and Macri 2009).

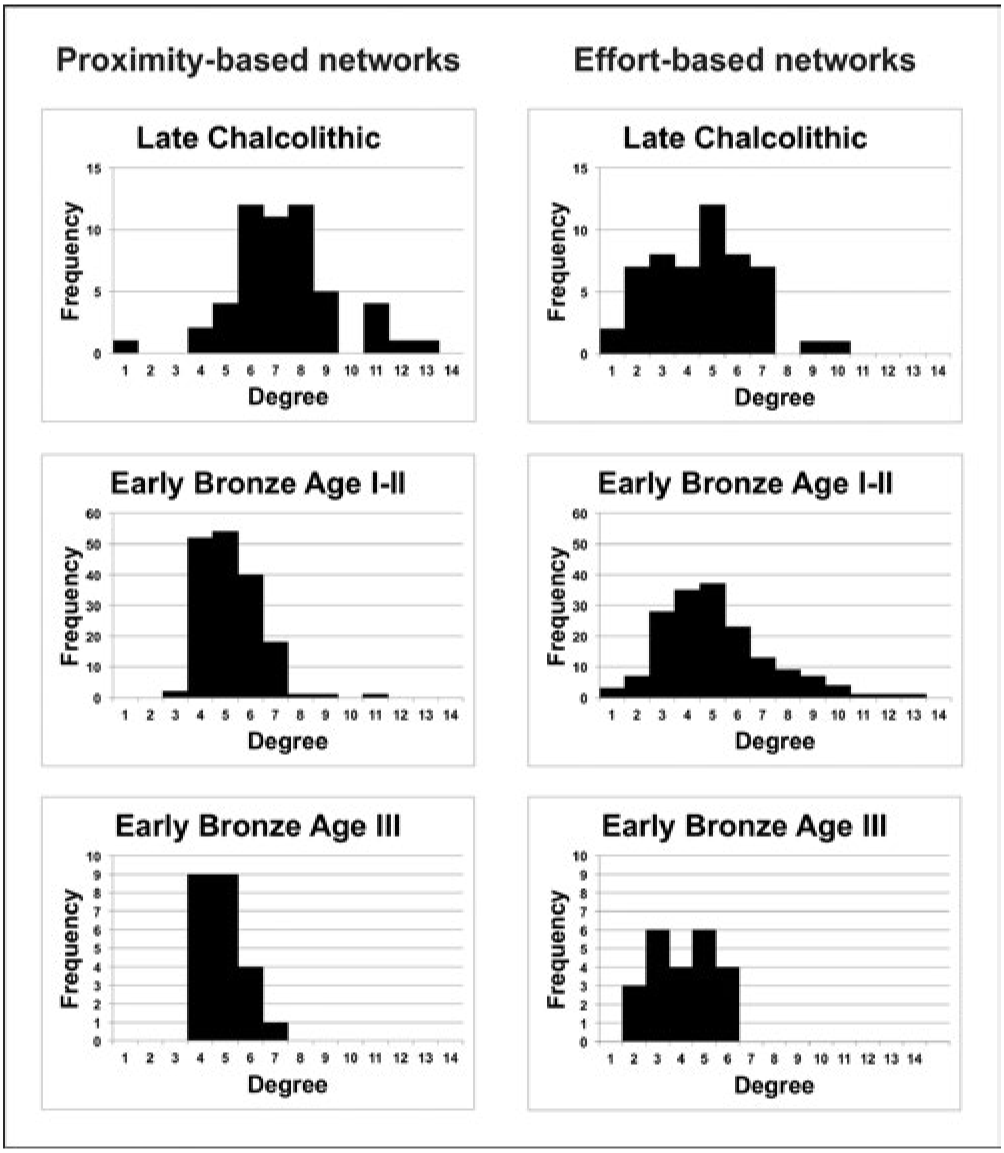

Fig. 3. Histograms of Network Degree distribution.

4.2 Evaluation of random graphs

The Centralization scores, or a global version of the ego-based Centrality scores, are used to assess network wide phenomenon. The Closeness Centralization could not be determined because many, if not most, of the random graphs were not weakly connected. For example, in the Early Bronze Age I-II random graph comparator to the 'effort' based network, approximately 60 percent of random graphs were not weakly connected and produced a null value. When compared to the randomly generated graphs, nearly all of the scores for the proximity networks are significant, except for the Degree Centralization in the Late Chalcolithic and Early Bronze Age III periods. A significant result for the proximity-based Early Bronze Age I-II graph is surprising, since the random graph models were based on the mean degree of the original networks; they should in theory be similar to their random graph comparator.

In the effort-based networks, most of the results are significant, especially those in the Late Chalcolithic and Early Bronze Age I-II periods. The Early Bronze Age III network does not differ significantly from random, with only a small measure of difference in Betweenness Centrality ($p > 0.1$) and in Clustering Coefficient ($p > 0.05$). The widely dispersed nodes in the Early Bronze Age III effort-based graph are uniformly reachable to all others, which reduces the ability of individual nodes to control communication with others (i.e. prestige), resulting in a non-significant Eigenvector Centralization score. The Clustering Coefficient scores for the proximity network are on the whole much higher than those of the effort-based network. Once again, this most likely is the result of how the proximity-based network was created, namely the stipulation that a minimum number of connections be made for each node to ensure minimal connectivity across the entire network. By mandating a minimum of 3-4 connections per node, triads are inevitably formed and the Clustering Coefficient is inflated in an artificial manner.

4.3 Evaluation of network creation strategies

The results indicate that there are significant quantitative differences between the effort-based and proximity-based

Tab. 1. Comparison of network scores for Effort based, Proximity based, and Bernoulli/Erdős–Rényi random graphs for Late Chalcolithic, Early Bronze Age I-II, and Early Bronze Age III. Notes: * = 95% Quantile (p ≤ 0.10), ** = 97.5% Quantile (p ≤ 0.05). Random graph values are the mean of 10,000 iterations. Effort-based Betweenness and Closeness Centralization from Bikoulis (Bikoulis 2012).

Period	Network Measure	Proximity	Random	Effort	Random
LC	Betweenness Centralization	0.4378 **	0.0531	0.3730 **	0.0949
	Closeness Centralization	0.1547	-	0.1858	-
	Degree Centralization	0.1135	0.1213	0.1078	0.1014
	Eigenvector Centralization	0.5097 **	0.2022	0.4402 **	0.2901
	Clustering Coefficient	0.6612 **	0.139	0.4714 **	0.0871
EBA I-II	Betweenness Centralization	0.3678 **	0.0462	0.1981 **	0.0469
	Closeness Centralization	0.0629	-	0.0978	-
	Degree Centralization	0.3497 **	0.0416	0.0474	0.0411
	Eigenvector Centralization	0.5357 **	0.2058	0.3648 **	0.2078
	Clustering Coefficient	0.5570 **	0.0306	0.3633 **	0.0303
EBA III	Betweenness Centralization	0.4089 **	0.1218	0.2890 *	0.1535
	Closeness Centralization	0.174	-	0.2605	-
	Degree Centralization	0.1061	0.1925	0.0952	0.1825
	Eigenvector Centralization	0.5277 **	0.3045	0.318	0.3516
	Clustering Coefficient	0.6637 **	0.214	0.5273 **	0.1776

networks depending on the period that is being compared (Table 2). There are no significant differences between the two methods of creating graphs for the Late Chalcolithic graphs, expect for the Degree centrality – it appears that there are more ties between actors using the proximity based method than the effort based one. This outcome is likely the result of the stipulation of requiring four closest neighbours to connect each node, which resulted in a higher total number of connections for each vertex. Results for Betweenness, Closeness, and Eigenvector Centrality are also similar, that is, no significant differences between the network scores. This is likely owing to the similarity in graph organization between the two network sets.

The primary differences between the two network creation strategies are found in the Early Bronze Age I-II and Early Bronze Age III networks, where the graphs contrast significantly both quantitatively and visually (Fig. 4). The linear structure of the Proximity-based graph has a great impact on the Centrality scores. The highest ranked sites in the Proximity networks for the Early Bronze Age I-II and III periods in terms of Betweenness Centrality are the only connections between the northern and southern halves of the network; these sites will always appears in the geodesics when tracing pathways (see Fig. 2c and 2d). Like the Late Chalcolithic period network, the Effort-based network contains a number of cycles in the Early Bronze Age I-II and III graphs (see Fig. 2d, and 2f). This ring structure decreases the probability that a singular site will act as a highly frequented intermediary by increasing the number of pathways for finding a geodesic between two sites. The degree values between sites in the two networks are not significantly different, indicating that there is similar number of incident edges per vertex even though different methods for connecting sites were used.

5 Discussion

The experiment produced mixed results. Both network creation strategies satisfy the requirement that they exhibit non-random properties. This was demonstrated through comparison to the 95% (p > 0.10) and 97.5% (p > 0.05) Quartile for corresponding Bernoulli graphs that values recorded for the two methods were not obtainable from random placement of network edges; quartile values were obtained in Pajek when running the Monte Carlo. Such a straightforward comparison of the network Centralization scores to those obtained by Monte Carlo of random graphs is sufficient to satisfy the requirement of non-randomness. However, as some have pointed out, ‘we should remind ourselves that detecting nonrandomness in our observed data is usually just the starting point for a more detailed investigation of the observed pattern(s), and not an end in itself’ (Croft *et al.* 2008: 96).

The different network creation strategies produced statistically different network values depending on the periods compared. Based solely on the Late Chalcolithic graphs, the possibility of equi-finality is high when comparing the two methods of making networks. While the two Late Chalcolithic graphs did

Tab. 2. Comparison of mean network measures for Effort based and Proximity based networks. Note: * = significant at p ≤ 0.05, ** = significant at p ≤ 0.01.

Period	**Network Measure**	**Proximity**	**Effort**	**Wilcoxon Signed-Rank Test (2-tailed)**	
				Z-score	W-value
LC	Betweenness Centrality	0.0682	0.0693	-1.1623	539
	Closeness Centrality	0.2307	0.2287	-0.4825	661
	Mean Degree	7.3208	4.6037	-5.477 **	54
	Eigenvector Centrality	0.0744	0.0889	-0.7569	630
EBA I-II	Betweenness Centrality	0.0644	0.0317	-3.8032 **	4634
	Closeness Centrality	0.0895	0.1504	-11.2702 **	3
	Mean Degree	5.1952	5.1242	-0.8706	4649
	Eigenvector Centrality	0.0285	0.0427	-2.401 *	5653
EBA III	Betweenness Centrality	0.1284	0.0982	-0.6387	117
	Closeness Centrality	0.2794	0.3366	-3.0111 **	39
	Mean Degree	4.8696	4.087	2.1731 *	41
	Eigenvector Centrality	0.167	0.1759	0	138

not produce significantly different network graphs or Centrality values, they were organized using two very different structuring principles. In addition to similar quantitative results, they also have very similar graph structures (compare Fig. 2a and 2b). Both contain network cycles, forming ring structures with sites in the Göksu Valley and on either side of the Cilician Gates (modern Gülek Boğazı). However, the second and third network sets display remarkable differences in both quantitative results and their visualization. The cycle at the center of the previous graphs disappears from the proximity-based networks, where sites in the Göksu Valley dominate in the Early Bronze Age I-II and Early Bronze Age III. In contrast, graphs for the effort-based networks in the Early Bronze Age I-II and III periods retain a basic cycle structure.

While the Centrality scores for each network set in the Early Bronze Age I-II and III periods are significantly different from each other, they do not differ in the same direction. The proximity-based networks will not always have higher or lower individual scores than the effort-based ones, or vice-versa, as each measurement varies in the comparison. This points to the need for further consideration of both the method of connecting sites and the network measurements used. Furthermore, numerical differences between the network creation strategies were only evident after a comparison across a number of related networks. As can be seen from this outcome, producing a single network representation for a particular problem or period may not be sufficient to mitigate the possibility of equi-finality or ‘false positive’ scores. The problem of equi-finality arises because it would be very difficult to determine at this point which method of connecting sites was a better model of inter-regional interaction in southern Anatolia.

While the scores for the proximity-based networks are certainly non-random, they are not a realistic representation of prehistoric connectivity in south-central Anatolia, relating primarily to issues of historical geography and how individual measurements are calculated. The major differences between the graphs strongly underscore the unrealistic use of spatial proximity to construct interaction networks at this scale. Both the Early Bronze Age I-II and Early Bronze Age III proximity-based networks do not make connections between sites on either side of the Cilician Gates, which was a well-known mountain pass from the earliest written records concerning the region. Major historical sources relate that the Cilician Gates was a much more travelled route crossing the Taurus Mountains that divide the Southern Anatolian Plateau from the Mediterranean coast. It was the favoured path of Alexander the Great in his conquest of Asia (Diodorus Siculus *Bibliotheca Historica* 14.20.1) and Xenophon and the army of 10,000 Greeks as they marched from Asia Minor into Mesopotamia (Xenophon *Anabasis* 1.2.21). Classical authors are not alone in this assessment. Views stressing the prominence and preference for the Cilician Gates over all other routes through the Taurus Mountains can be found in historical sources ranging from the Late Hittite Empire c. 12th century BC (Symington 2001), the First Crusade led by Frederick I Barbarossa (Otto of Freising and his continuator Rahewin, *The Deeds of Frederick Barbarossa*), to early modern travellers’ accounts (Hogarth 1907; Ramsay 1890). It is reasonable to suggest that networks incorporating this well-known feature of Anatolian geography would present a more convincing model for the movement of goods and people in exchange. The networks based on proximity fail to capture this crucial aspect of the historical geography of the region in the Early Bronze Age I-II and III periods, deviating

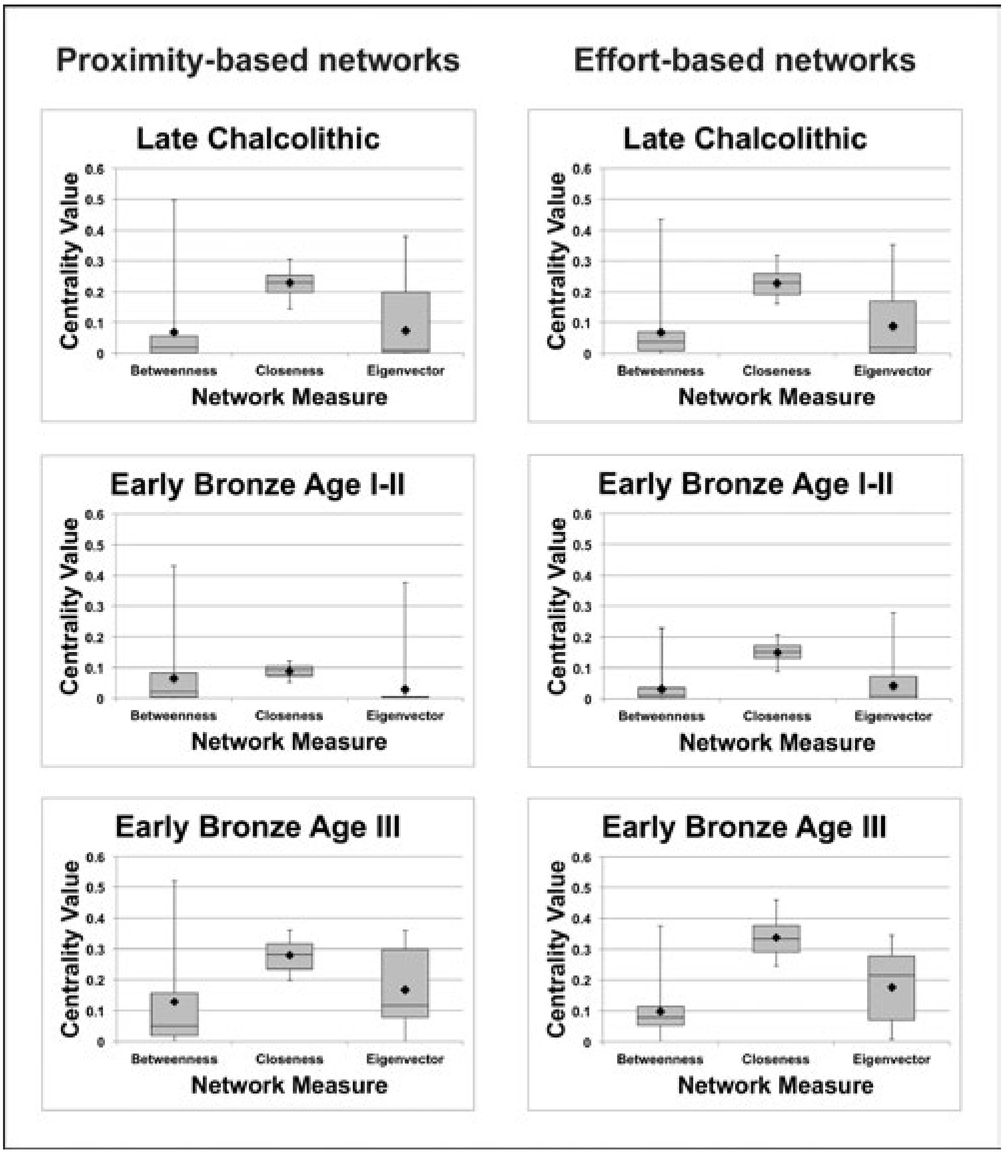

Fig. 4. Box plot of network Centrality values.

sharply from all previous knowledge regarding long-standing patterns of communication and travel in the region. Based on this strong discordance between the proximity-based network graphs and what is known from other contexts like historical documents and the artefacts themselves, the proximity-based graphs should be rejected as viable representations of theorized trade and exchange networks. In contrast, the effort-based graphs all highlight the importance of this key topographic feature, leading to the conclusion that the Cilician Gates were a primary route through the Taurus mountains and the mountain passes in the upper Göksu Valley were secondary or local in nature (Bikoulis 2012; Newhard *et al.* 2008). The emphasis placed on logistical constraints in the formation of trade and exchange networks appears to capture these dynamics better. This underscores the need to recursively check the output of network modelling against what is already known about the original context, as there is no statistical means of directly comparing one network model to another's performance.

Failure to consider physical exertion or perceived effort, and how these would have facilitated or impeded interaction is a serious drawback of using spatial proximity as a means of connecting networks that ostensibly model the movement of people and materials. These results support the observation of Mills *et al.* (2013) that spatial proximity may not be useful within archaeological networks as a means of modelling social interaction between sites at large scales. While it has been demonstrated that interaction within social networks in general decays over increasing geographical distance (Doreian and Conti 2012; Expert *et al.* 2011; Glückler 2007; Illenberger *et al.* 2012)the analysis reveals that the number of contacts an individual possesses is independent from its spatial location and the spatial distribution of opportunities. This means that individuals living in areas with a low accessibility to other persons (rural areas, using 'as the crow flies' (i.e. Euclidean) distance may not be advisable when modelling large-scale prehistoric interaction networks. In fact, it may be highly problematic. Proximity may be a valid proxy for intra-troupe social interaction (Rushmore *et al.* 2013; Zhang *et al.* 2012) or even in burials (Sosna *et al.* 2012), but may not be suitable at regional or greater scales. Instead, accessibility between network actors may be a more valuable concept when constructing networks that seek to model the movement of people and objects (Llobera *et al.* 2011).

Additional applications of the approach presented here is a move towards quantitative perspectives in archaeological applications of social network analysis. Shifting towards a more empirical network approach includes the adoption of similar methods that can be used to help define the structural pattern of networks themselves. One such example would be a move way from a metaphorical use of the popular term 'small world' for describing archaeological phenomena (e.g. Malkin 2013; Sindbæk 2007), to one grounded in explicit and empirical models. The 'small world' phenomenon is based on the pioneering work of Milgram, but has been given a solid empirical base by Watts and others (Barrat and Weigt 2000; Milgram 1967; Watts and Strogatz 1998; Watts 1999a, 1999b, 2003). Comparisons to such well known properties of 'small-world' networks have also been used to explore real-world observations, such as railway systems (Seaton and Hackett 2004; Sen *et al.* 2003). Moving from the metaphorical to analytical use of the term in archaeology could be pursued using the method outlined above, substituting Watts-Strogatz rewiring models instead of Bernoulli/Erdős-Rényi random graphs, perhaps even using the mean degree as outlined here (Newman *et al.* 2001). This procedure would greatly aid in substantiating whether archaeological networks share the established empirical properties of this well-known phenomenon. Additionally, pursuing an analytical approach to 'small world' identification would add a much-needed historical depth to contemporary network science by providing additional examples of this established social dynamic that only archaeology can bring (see Amaral *et al.* 2000).

6 Conclusion

Formal network analysis can be integrated easily within archaeology in a number of ways. First, existing tools in Social Network Analysis can increase the explanatory strength of interpretations about social relations and interaction based on disparate archaeological data and analysis. These formal capacities can be harnessed to assess the connections between selected actors and the social relations between them. As advocated here, Social Network Analysis can be used to conduct more rigorous hypothesis testing targeting specific social relations and the structure and role of particular actors within theorized networks in the past. The next phase of network thinking in archaeology must move beyond visualization and descriptive studies to one where hypotheses of archaeological phenomena are made explicit and quantitatively assessed. One path to this end is a more critical examination of how archaeological networks are constructed. It was found that the 'effort' and 'proximity' based networks produced considerably diverging results, which indicated that the way in which connections between nodes are made might produce unreliable results and lead to faulty conclusions. The use of random graph values obtained from Monte Carlo trials provides a 'benchmark' from which to compare the two network creation strategies. These indicated that the two contrasting ways of creating archaeological networks presented here each provide significantly different network-wide assessments from what one would expect from random network dynamics. Comparison of different networks based on varying network creation strategies suggests that one common way of connecting prehistoric networks may produce unreliable results. While some may argue that this has been a trivial comparison, this approach takes seriously the dynamics of random networks. Because even random graphs produce surprisingly patterned associations, we cannot assume that networks engineered based on what ever we may wish to examine archaeologically are inherently significant and meaningful.

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Bibliography

Alexander, M. C. and J. A. Danowski 1990. Analysis of an Ancient Network: personal communication and the study of social strucutre in a past society. *Social Networks* 12: 313–35.

Amaral, L. A., A. Scala, M. Barthelemy and H. E. Stanley 2000. Classes of small-world networks. *Proceedings of the National Academy of Sciences of the United States of America* 97, 11149–52.

Baker, H. D., D. Collon, J. D. Hawkins, *et al.* 1995. Kilise Tepe 1994. *Anatolian Studies* 45: 139.

Barabási, A. L. 2002. *Linked: The New Science Of Networks Science Of Networks*. Cambridge, MA: Perseus.

Barabási, A.-L. and R. Albert 1999. Emergence of Scaling in Random Networks. *Science* 286: 509–12.

Barrat, A. and M. Weigt 2000. On the properties of small-world network models. *The European Physical Journal B* 13: 547–60.

Barrett, L., S. P. Henzi and D. Lusseau 2012. Taking sociality seriously: the structure of multi-dimensional social networks as a source of information for individuals. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 367: 2108–18.

Batagelj, V. and U. Brandes 2005. Efficient generation of large random networks. *Physical Review E* 71, 036113.

Batagelj, V. and A. Mrvar 1998. Pajek – Program for Large Network Analysis. *Connections* 21: 47–57.

Bell, T. L., A. Wilson and A. Wickham 2002. Tracking the Samnites: Landscape and Communications Routes in the Sangro Valley, Italy. *American Journal of Archaeology* 106: 169–86.

Bernardini, W. 2007. Jeddito yellow ware and Hopi social networks. *Kiva* 72: 295–328.

Bikoulis, P. 2012. Revisiting prehistoric sites in the Göksu valley: a GIS and social network approach. *Anatolian Studies* 62: 35–59.

Bollobás, B. 2001. *Random Graphs*. (Cambridge Studies in Advanced Mathematics). Cambridge, Cambridge University Press.

Borgatti, S. P., Mehra, A., Brass, D. J., Labianca, G. 2009. Network analysis in the social sciences. *Science* 323: 892–5.

Bradley, B. J., D. M. Doran-Sheehy, D. Lukas, C. Boesch and L. Vigilant 2004. Dispersed male networks in western gorillas. *Current Biology* 14: 510–3.

Brandes, U., Robins, G., Mccranie, A., Wasserman, S. 2013. What is network science? *Network Science* 1: 1–15.

Brent, L. J. N., J. Lehmann and G. Ramos-Fernández 2011. Social network analysis in the study of nonhuman primates: A historical perspective. *American Journal of Primatology* 73: 720–30.

Broodbank, C. 2000. *An Island Archaeology of the Early Cyclades*. Cambridge, Cambridge University Press.

Brughmans, T. 2013. Thinking Through Networks: A Review of Formal Network Methods in Archaeology. *Journal of Archaeological Method and Theory* 20: 623–62.

Brughmans, T., S. Keay and G. Earl 2014. Introducing exponential random graph models for visibility networks. *Journal of Archaeological Science* 49: 442–54.

Buchanan, M. 2002. *Nexus: Small Worlds and the Groundbreaking Theory of Networks*. New York, NY, W. W. Norton.

Butts, C. T., R. M. Acton, J. R. Hipp and N. N. Nagle 2012. Geographical variability and network structure. *Social Networks* 34: 82–100.

Christakis, N. A. and J. H. Fowler 2009. *Connected: The Surprising Power of Our Social Networks and how They Shape Our Lives*. New York, NY, Little Brown.

Clark, E. a. 1991. Elite Networks and Heresy Accusations: Towards a social description of Origenist controversy. *Semeia* 56: 79–117.

Contreras, D. A. 2011. How far to Conchucos? A GIS approach to assessing the implications of exotic materials at Chavín de Huántar. *World Archaeology* 43: 380–97.

Croft, D. P., R. James and J. Krause 2008. *Exploring Animal Social Networks*. Princeton, Princeton University Press.

Croft, D. P., J. R. Madden, D. W. Franks and R. James 2011. Hypothesis testing in animal social networks. *Trends in Ecology and Evolution* 26: 502–7.

Cross, P. C., J. O. Lloyd-Smith and W. M. Getz 2005. Disentangling association patterns in fission-fusion societies using African buffalo as an example. *Animal Behaviour* 69: 499–506.

Davis, J. L. 1982. Thoughts on Prehistoric and Archaic Delos. *Temple University Aegean Symposium* 7: 23–33.

Doreian, P. and N. Conti 2012. Social context, spatial structure and social network structure. *Social Networks* 34: 32–46.

Doyle, J., T. Garrison and S. Houston 2012. Watchful realms: integrating GIS analysis and political history in the southern Maya lowlands. *Antiquity* 86: 792–807.

Elton, H. 2005. Göksu Archaeological Project 2002-2004. *Araştırma Sonuçları Toplantısı* 23: 331–42.

Elton, H. 2007. Göksu Archaeological Project 2005-2006. *Araştırma Sonuçları Toplantısı* 25: 237–50.

Erdős, P. and Rényi, A. 1959. On random graphs. *Publicationes Mathematicae* 6: 290–7.

Erdős, P. and Rényi, A. 1960. On the Evolution of Random Graphs. *Magyar Tud. Akad. Mat. Kutató Int. Közl* 5: 17–61.

Evans, T. S., C. Knappett and R. Rivers 2009. Using Statistical Physics to Understand Relational Space: A Case Study from Mediterranean Prehistory, vol. 7. In D. Lane, D. Pumain,S. Van Der Leeuw, G. West (eds.), *Complexity Perspectives in Innovation and Social Change*: 451–80. Springer.

Evans, T. S., Rivers, R. J., Knappett, C. 2012. Interactions in Space for Archaeological Models. *Advances in Complex Systems* 15, 1150009.

Expert, P., Evans, T. S., Blondel, V. D., Lambiotte, R. 2011. Uncovering space-independent communities in spatial networks. *Proceedings of the National Academy of Sciences of the United States of America* 108, 7663–8.

Faust, K., Entwisle, B., Rindfuss, R. R., Walsh, S. J., Sawangdee, Y. 2000. Spatial arrangement of social and economic networks among villages in Nang Rong District, Thailand. *Social Networks* 21: 311–37.

Field, J. S., Petraglia, M. D., Lahr, M. M. 2007. The southern dispersal hypothesis and the South Asian archaeological record: Examination of dispersal routes through GIS analysis. *Journal of Anthropological Archaeology* 26: 88–108.

French, D. H. 1965. Prehistoric Sites in the Göksu Valley. *Anatolian Studies* 15: 177–201.

Giordano, A. and T. Cole 2011. On Place and Space: Calculating Social and Spatial Networks in the Budapest Ghetto. *Transactions in GIS* 15: 143–170.

Glückler, J. 2007. Economic geography and the evolution of networks. *Journal of Economic Geography* 7: 619–34.

Golden, C. and A. K. Scherer 2013. Territory, Trust, Growth, and Collapse in Classic Period Maya Kingdoms. *Current Anthropology* 54: 397–435.

Golitko, M., J. Meierhoff, G. M. Feinman and P. Williams 2012. Complexities of collapse: the evidence of Maya obsidian as revealed by social network graphical analysis. *Antiquity* 86: 507–23.

Gorenflo, L. J. and T. L. Bell 1994. Network Analysis and the study of past regional organization. In *Ancient road networks and settlement hierarchies in the New World* (ed) C. D. Trombold: 80–98. Cambridge, Cambridge University Press.

GRASS Development Team 2015. Geographic Resources Analysis Support System (GRASS).

Guimarães, P., de Menezes, M., Baird, R., Lusseau, D., dos Reis, S. 2007. Vulnerability of a killer whale social network to disease outbreaks. *Physical Review E* 76, 042901.

Hart, J. P., Engelbrecht, W. 2011. Northern Iroquoian Ethnic Evolution: A Social Network Analysis. *Journal of Archaeological Method and Theory* 19: 322–49.

Henzi, S. P., D. Lusseau, T. Weingrill, C. P. Schaik and L. Barrett 2009. Cyclicity in the structure of female baboon social networks. *Behavioral Ecology and Sociobiology* 63: 1015–21.

Herzog, I. 2013. Least-cost Neworks. In G.Earl, T. Sly, A. Chrysanthi *et al.* (eds.), *Archaeology in the Digital Era: Proceedings of the 40th Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 2-29 March 2012*: 237–48. Amsterdam, Amsterdam University Press.

Hirsch, B. T., M. A. Stanton and J. E. Maldonado 2012. Kinship shapes affiliative social networks but not aggression in ring-tailed coatis. *PloS one* 7, e37301.

Hodder, I., Orton, C. R. 1976. *Spatial Analysis in Archaeology*. Cambridge, Cambridge University Press.

Hogarth, D. G. 1907. Problems in Exploration: I. Western Asia. *The Geographical Journal* 32: 549–563.

Illenberger, J., K. Nagel and G. Flötteröd 2012. The Role of Spatial Interaction in Social Networks. *Networks and Spatial Economics* 13: 255–282.

Isaksen, L. 2008. The application of network analysis to ancient transport geography : A case study of Roman Baetica. *Digital Medievalist* 4: 1–22.

Jackson, M. O. 2008. *Social and Economic Networks*. Princeton, Princeton University Press.

James, R., Croft, D. P., Krause, J. 2009. Potential banana skins in animal social network analysis. *Behavioral Ecology and Sociobiology* 63: 989–97.

Jenkins, D. 2001. A Network Analysis of Inka Roads, Administrative Centers, and Storage Facilities. *Ethnohistory* 48: 655–87.

Johansen, K. L., S. T. Laursen and M. K. Holst 2004. Spatial patterns of social organization in the Early Bronze Age of South Scandinavia. *Journal of Anthropological Archaeology* 23: 33–55.

Kadushin, C. 2012. *Understanding Social Networks: Theories, Concepts, and Findings*. Oxford, Oxford University Press.

Kasper, C. and B. Voelkl 2009. A social network analysis of primate groups. *Primates; journal of primatology* 50: 343–56.

Kelley, J. L., L. J. Morrell, C. Inskip, J. Krause and D. P. Croft 2011. Predation risk shapes social networks in fission-fusion populations. *PloS one* 6, e24280.

Knappett, C., Evans, T. S., Rivers, R. 2008. Modelling maritime interaction in the Aegean Bronze Age. *Antiquity* 82: 1009–24.

Knappett, C., Evans, T. S., Rivers, R. 2011. The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network. *Antiquity* 85: 1008–23.

Knoke, D., Yang, S. 2008. *Social Network Analysis*. Thousand Oaks, CA, SAGE.

Kolaczyk, E. D. 2009. *Statistical Analysis of Network Data: Methods and Models*. New York, NY, Springer.

Krause, J., Croft, D. P., James, R. 2007. Social network theory in the behavioural sciences: potential applications. *Behavioral Ecology and Sociobiology* 62: 15–27.

Larson, F., Petch, A., Zeitlyn, D. 2007. Social Networks and the Creation of the Pitt Rivers Museum. *Journal of Material Culture* 12: 211–39.

Larson, K. 2013. A Network Approach to Hellenistic Sculptural Production. *Journal of Mediterranean Archaeology* 26: 235–60.

Llobera, M., P. Fábrega-Álvarez and C. Parcero-Oubiña 2011. Order in movement: a GIS approach to accessibility. *Journal of Archaeological Science* 38: 843–51.

Lusseau, D. 2003. The emergent properties of a dolphin social network. *Proceedings of the Royal Society of London B* 270: 186–8.

Lusseau, D. 2007. Evidence for social role in a dolphin social network. *Evolutionary Ecology* 21: 357–66.

Lusseau, D., B. Wilson, P. S. Hammond, *et al.* 2006. Quantifying the influence of sociality on population structure in bottlenose dolphins. *Journal of Animal Ecology* 75: 14–24.

Malkin, I. 2013. *A Small Greek World: Networks in the Ancient Mediterranean*. Oxford and New York, Oxford University Press.

Mellaart, J. 1954. Preliminary report on a survey of pre-classical remains in southern Turkey. *Anatolian Studies* 4: 175–240.

Mellaart, J. 1958. The End of the Early Bronze Age in Anatolia and the Aegean. *American Journal of Archaeology* 62: 9–33.

Merrill, M. and D. Read 2010. A new method using Graph and Lattice Theory to discover spatially cohesive sets of artifacts and areas of organized activity in archaeological sites. *American Antiquity* 75: 419–51.

Milgram, S. 1967. The Small-World Problem. *Psychology today* 1: 61–7.

Mills, B. J., Clark, J. J., Peeples, M. A. *et al.* 2013. Transformation of social networks in the late pre-Hispanic US Southwest. *Proceedings of the National Academy of Sciences of the United States of America* 110: 5785–90.

Mizoguchi, K. 2009. Nodes and edges: A network approach to hierarchisation and state formation in Japan. *Journal of Anthropological Archaeology* 28: 14–26.

Morgan, C. 2008. Reconstructing prehistoric hunter–gatherer foraging radii: a case study from California's southern Sierra Nevada. *Journal of Archaeological Science* 35: 247–58.

Munson, J. L. and Macri, M. J. 2009. Sociopolitical network interactions: A case study of the Classic Maya. *Journal of Anthropological Archaeology* 28: 424–38.

Newhard, J. M. L., Levine, N., Rutherford, A. 2008. Least-Cost Pathway Analysis and Inter-Regional Interaction in the Göksu Valley, Turkey. *Anatolian Studies* 58: 87–102.

Newhard, J. M. L., Levine, N. S., Phebus, A. D., Craft, S., Littlefield, J. D. 2013. A geoinformatic approach to the collection of archaeological survey data. *Cartography and Geographic Information Science* 40: 3–17.

Newman, M. E. J. 2005. A measure of betweenness centrality based on random walks. *Social Networks* 27: 39–54.

Newman, M. E. J., S. H. Strogatz and D. J. Watts 2001. Random graphs with arbitrary degree distributions and their applications. *Physical Review E* 64, 026118.

De Nooy, W., Mrvar, A., Batagelj, V. 2011. *Exploratory Social Network Analysis with Pajek*. (Revised ed). Cambridge, Cambridge University Press.

Onnela, J.-P., S. Arbesman, M. C. González, A.-L. Barabási and N. a Christakis 2011. Geographic constraints on social network groups. *PloS one* 6, e16939.

Östborn, P. and Gerding, H. 2015. The Diffusion of Fired Bricks in Hellenistic Europe: A Similarity Network Analysis. *Journal of Archaeological Method and Theory* 22: 306–44.

Peregrine, P. 1991. A Graph-Theoretic Approach to the Evolution of Cahokia. *American Antiquity* 56: 66–75.

Postgate, J. N. and D. Thomas 2007. *Excavations at Kilise Tepe, 1994-98: From Bronze Age to Byzantine in Western Cilicia*. *British Institute of Archaeology at Ankara monograph*. Cambridge, McDonald Institute for Archaeological Research.

Ramsay, W. M. 1890. *The Historical Geography of Asia Minor*. (Royal geographical society, London. Supplementary papers, v. 4). London, John Murray.

Robinson, D. 2010. Land Use, Land Ideology: an integrated geographical information systems analysis of rock art within south-central California. *American Antiquity* 75: 792–818.

Rothman, M. 1987. Graph theory and the interpretation of regional survey data. *Paleorient* 13: 73–91.

Ruffini, G. 2008. *Social Networks in Byzantine Egypt*. Cambridge, Cambridge University Press.

Rushmore, J., D. Caillaud, L. Matamba, *et al.* 2013. Social network analysis of wild chimpanzees provides insights for predicting infectious disease risk. *The Journal of Animal Ecology* 82: 976–86.

Schor, A. M. 2007. Theodoret on the 'School of Antioch': A Network Approach. *Journal of Early Christian Studies* 15: 517–62.

Schor, A. M. 2009. Patronage Performance and Social Strategy in the Letters of Theodoret, Bishop of Cyrrhus. *Journal of Late Antiquity* 2: 274–99.

Schor, A. M. 2011. *Theodoret's People: Social Networks and Religious Conflict in Late Roman Syria*. Berkley, CA, University of California Press.

Scott, J. 2012. *Social Network Analysis*. Thousand Oaks, CA, SAGE.

Seaton, K. A. and L. M. Hackett 2004. Stations, trains and small-world networks. *Physica A: Statistical Mechanics and its Applications* 339: 635–44.

Sen, P., Dasgupta, S., Chatterjee, A. *et al.* 2003. Small-world properties of the Indian railway network. *Physical Review E* 67, 036106.

Seton-Williams, M. 1954. Cilician Survey. *Anatolian Studies* 4: 121–74.

Sindbæk, S. M. 2007. The Small World of the Vikings: Networks in Early Medieval Communication and Exchange. *Norwegian Archaeological Review* 40: 59–74.

Sosna, D., Galeta, P., Smejda, L., Sladek, V., Bruzek, J. 2012. Burials and Graphs: Relational Approach to Mortuary Analysis. *Social Science Computer Review* 31: 56–70.

Sueur, C., Deneubourg, J.-L., Petit, O. 2012. From social network (centralized vs. decentralized) to collective decision-making (unshared vs. shared consensus). *PloS one* 7, e32566.

Sueur, C., Jacobs, A., Amblard, F., Petit, O., King, A. J. 2011. How can social network analysis improve the study of primate behavior? *American journal of primatology* 73: 703–19.

Sueur, C., Petit, O., Deneubourg, J. L. 2010. Short-term group fission processes in macaques: a social networking approach. *The Journal of experimental biology* 213: 1338–46.

Sueur, C., Petit, O., De Marco, A. *et al.* 2011. A comparative network analysis of social style in macaques. *Animal Behaviour* 82: 845–52.

Sundaresan, S. R., Fischhoff, I. R., Dushoff, J., Rubenstein, D. I. 2007. Network metrics reveal differences in social organization between two fission-fusion species, Grevy's zebra and onager. *Oecologia* 151: 140–9.

Symington, D. 2001. Hittites at Kilise Tepe. In Jean É., Dinçol A. M. and Durugönül S. (eds.), *La Cilicie: espaces et pouvoirs locaux (2e millénaire avant J-C. - 4e siècle ap. J-C).Actes de la table ronde internationale d'Istanbul, 2-5 Novembre 1999*: 167–84. Istanbul, Ege Yayınları.

Terrell, J. E. 2010a. Social network analysis of the genetic structure of Pacific islanders. *Annals of human genetics* 74: 211–32.

Terrell, J. E. 2010b. Language and Material Culture on the Sepik Coast of Papua New Guinea: Using Social Network Analysis to Simulate, Graph, Identify, and Analyze Social and Cultural Boundaries Between Communities. *The Journal of Island and Coastal Archaeology* 5: 3–32.

Verdery, A. M., Entwisle, B., Faust, K., Rindfuss, R. R. 2012. Social and spatial networks: Kinship distance and dwelling unit proximity in rural Thailand. *Social Networks* 34: 112–27.

Voelkl, B., Kasper, C. 2009. Social structure of primate interaction networks facilitates the emergence of cooperation. *Biology letters* 5: 462–4.

Wasserman, S. and K. Faust 1994. *Social Network Analysis: Methods and Applications*. (Structural Analysis in the Social Sciences). Cambridge: Cambridge University Press.

Watts, D. J. 1999a. *Small Worlds: The Dynamics of Networks Between Order and Randomness*. Princeton studies in complexity. Princeton, Princeton University Press.

Watts, D. J. 1999b. Networks, Dynamics, and the Small-World Phenomenon. *American Journal of Sociology* 105: 493–527.

Watts, D. J. 2003. *Six Degrees: The Science of a Connected Age*. New York, NY, W. W. Norton.

Watts, D. J. 2004. The 'New' Science of Networks. *Annual Review of Sociology* 30: 243–70.

Watts, D. J., Strogatz, S. H. 1998. Collective dynamics of 'small-world' networks. *Nature* 393: 440–2.

Wellman, B. 1983. Network Analysis: some basic principals. *Sociological theory* 1: 155–200.

Wey, T. W., D. T. Blumstein, W. Shen and F. Jordán 2008. Social network analysis of animal behaviour: a promising tool for the study of sociality. *Animal Behaviour* 75: 333–44.

White, D. A., Surface-Evans, S. L. (eds) 2012. *Least Cost Analysis of Social Landscapes: Archaeological Case Studies*. Salt Lake City, University of Utah Press.

Whitehead, H. and D. Lusseau 2012. Animal social networks as substrate for cultural behavioural diversity. *Journal of theoretical biology* 294: 19–28.

Wiszniewski, J., D. Lusseau and L. M. Möller 2010. Female bisexual kinship ties maintain social cohesion in a dolphin network. *Animal Behaviour* 80: 895–904.

Zhang, P., B. Li, X. Qi, A. J. J. MacIntosh and K. Watanabe 2012. A Proximity-Based Social Network of a Group of Sichuan Snub-Nosed Monkeys (Rhinopithecus roxellana). *International Journal of Primatology* 33: 1081–95.

Traveling Across Archaeological Landscapes: the Contribution of Hierarchical Communication Networks

Sylviane Déderix
sylviane.dederix@uclouvain.be
Université catholique de Louvain (INCAL/CEMA/ARC 'A World in Crisis')

Abstract: The present paper is concerned with focal mobility networks, a procedure developed some years ago by Fábrega-Álvarez (2006) in order to explore the location of ancient sites in relation to optimal routes of movement. More specifically, Early Bronze Age south-central Crete is used as a case study to test the potential and limitations of the procedure in examining general mobility patterns across archaeological landscapes. Through a series of analyses and comparisons this paper shows that, in spite of certain limitations, focal mobility network offers new opportunities to 1) describe the landscape in terms of its potential for movement, 2) delineate natural corridors of movement by taking into account the distribution of known sites, and 3) model hierarchical communication networks in which the paths are ranked according to their attractiveness.

Keywords: GIS, Movement, Focal Mobility Network, Landscape, Prepalatial South-central Crete

Introduction

The development of cost surface and least cost path analyses has opened new avenues to investigate patterns of movement and accessibility in past landscapes. Their application has proven of particular interest for the study of human societies which did not produce tangible remains of road systems (Hazell and Brodie 2012; Howey 2007; Wheatley *et al*. 2010; White and Surface-Evans 2012), but it has also raised a series of issues (e.g. Branting 2012; Kantner 2012; Herzog 2013; Wheatley and Gillings 2002: 151-9). Among others, the quantification of the factors that impact on ease and speed of movement, the choice of the algorithms to be used, as well as the assumption that travellers know which one is the optimal route between an origin and a destination and that they are willing and able to take that route are questions which still need consideration. In addition, least cost path analysis tends to presuppose that each pair of sites was connected by means of a direct road, which is far from the case. It is with this latter issue that the present paper is concerned.

Various methodologies have been set up to investigate general patterns of movement instead of calculating least cost paths among all known archaeological sites. The simplest option is to observe the position occupied by the sites along optimal paths connecting pairs of settlements located at opposite edges of the study area (e.g. Vouzaxakis 2015). The most elaborate methodology, developed by Llobera (2000), requires the calculation of the shortest route between each pair of cells of the Digital Elevation Model (DEM). If it allows describing the entire landscape in terms of its potential for movement, it has a major drawback since it is computationally intensive and time-consuming. To get around this limitation, some GIS practitioners have reduced the amount of starting and arrival locations (and hence, the number of least cost paths to be computed) by making use of points regularly spaced across the whole study area (Verhagen 2013) or along its border (Whitley and Burns 2008). Faíren Jimenez (2007: 290-2) and Murrieta Flores (2012) adopted a similar approach, but rather than random points, they used natural entry points to their study area as the origin and destination of multiple least cost paths. Lately, Mlekuž (2013; 2014) calculated potential path fields to describe the accessibility of the landscape within given time budgets. But as stressed by the author himself, potential path fields are 'computationally extremely intensive' (Mlekuž 2014: 11), which limits their applicability.

This paper aims at testing the potentialities and limitations of yet another procedure – the so-called focal mobility network (Fábrega-Álvarez 2006; Llobera *et al*. 2011) – to explore patterns of movement and interaction in past societies. Prepalatial south-central Crete (Greece, ca. 3100-1925/1900 BC) is used as a case study. Focal mobility network is first compared to least cost path, before being implemented to highlight natural corridors of movement in relation to monumental circular tombs recorded in the area. Eventually, it is suggested to expand on focal mobility networks to create a hierarchical communication network, that is to say a network in which optimal communication channels are ranked according to their estimated importance in connecting local communities.

1 Focal mobility network

Focal mobility network was first developed by Fábrega-Álvarez, who specifically aimed at addressing the location of known archaeological sites with respect to optimal routes of movement (Fábrega-Álvarez 2006). Originally defined as a way to describe movement without a destination, the procedure was reconceptualised in a later paper as a means to approach movement towards a destination but without an origin, hence offering an opportunity to explore the accessibility of ancient sites (Llobera *et al*. 2011). Indeed, focal mobility network outlines natural corridors that channel movement towards a given endpoint, and this from the entire landscape (Fig. 1). It highlights the direction that an individual would tend to take to reach the destination when starting anywhere in the study area. In other words, focal mobility network describes the landscape in terms of its potential for movement towards the archaeological site of interest.

The procedure, which is both fast and easy to implement, combines cost distance and hydrological tools (Fábrega-Álvarez 2006; Llobera *et al*. 2011). More specifically, it consists in performing hydrological modelling on an

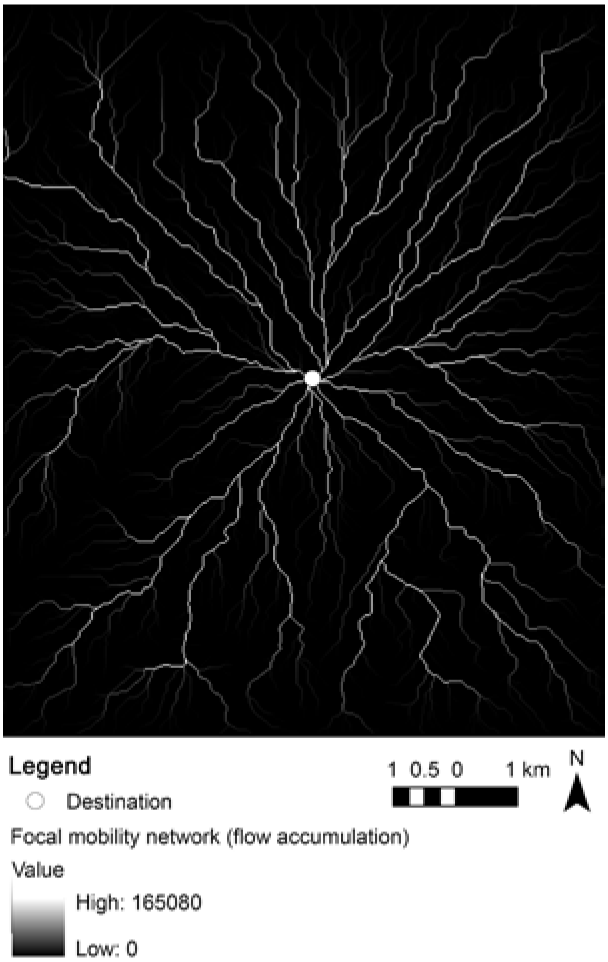

Fig. 1. Focal mobility network computed for the cemetery of Platanos (south-central Crete).

accumulated cost surface. The workflow is straightforward (Fig. 2). The first step is to generate an accumulated cost surface where each cell records the optimal accumulation of cost (in time or energy) from the chosen archaeological site. As a second step, this surface is used as the input raster for the creation of a flow direction model. In hydrology, the latter represents the direction of water flow based on a topographical model: water flows from one cell of the DEM into the adjacent cell that has the lowest elevation value. In the case of focal mobility network, the flow direction analysis proceeds in a similar manner, driving the cells with a high cost towards those with a low cost. In a third and final step, the flow direction map is itself used to calculate a flow accumulation map (Fig. 1). Such a map records the accumulated flow to each cell and emphasizes areas of greater accumulation, which correspond to streams in the case of hydrological modelling and to optimal paths leading to the destination in focal mobility network.

In brief, focal mobility network reconstructs a system of paths based on an accumulated cost surface in the same manner as hydrological modelling reconstructs a system of streams based on topographical data. The result is a road network that irradiates around the destination. And just like the importance of a stream in a hydrological network depends on the number of cells that flow into it, the importance of a path in a focal

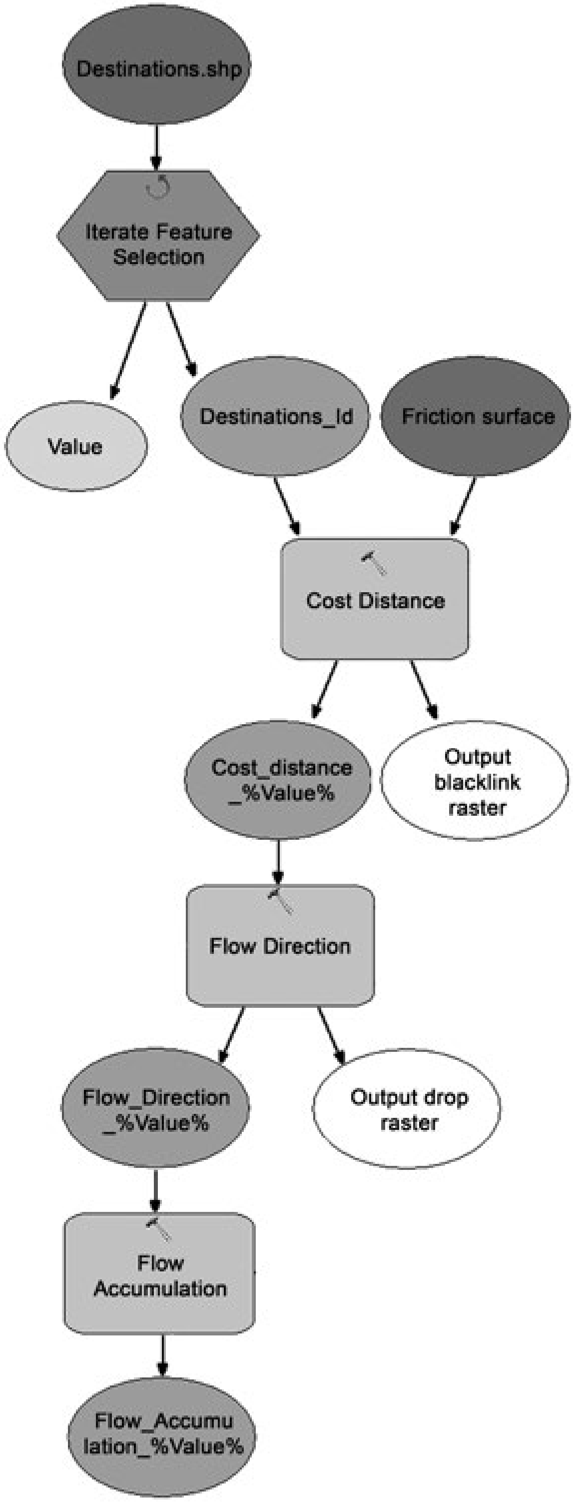

Fig. 2. Workflow developed in ModelBuilder (ArcGIS 10) to iterate the computation of focal mobility networks.

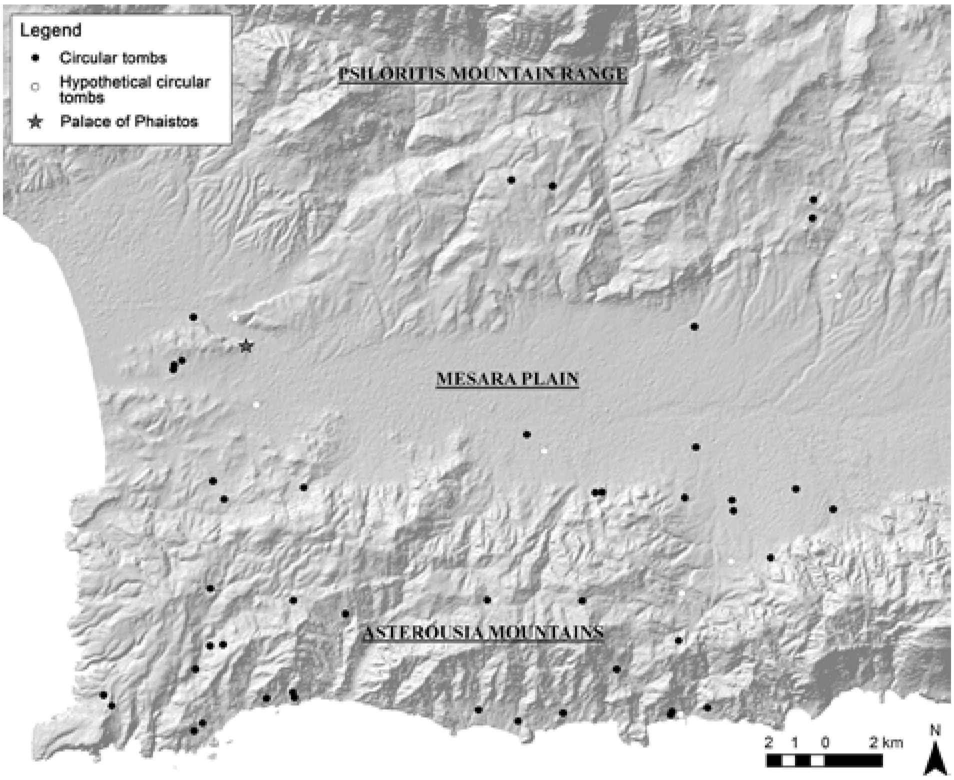

Fig. 3. Distribution of circular tombs and possible circular tombs in south-central Crete.

mobility network depends on its catchment. This further implies that the accumulation rate of the cells increases the closer one gets to the destination (Llobera *et al*. 2011: 844).

Eventually, it is also possible to extract discrete paths based on the flow accumulation surface. This is done by defining a threshold value representing the minimum number of cells that must flow into a cell in order for that cell to be considered as part of the road network. As stressed by Fábrega-Álvarez (2006: 10), there is no rule as to how to define this threshold. Low values produce a dense network, whereas high values result in the extraction of the most important paths only.

2 Case-study: the circular tombs of south-central Crete

A focal mobility network analysis was applied to the study of Prepalatial south-central Crete (Fig. 3). The region chosen ranges between 0 and 1470m above sea level. It is bordered by the Libyan Sea to the south and southwest, and includes the large fertile Mesara plain, the southern slopes of the Psiloritis, and the Asterousia Mountains. As far as the third millennium BC is concerned, the archaeological record of south-central Crete is dominated by monumental circular tombs that were used for collective burials by small-sized communities whose social organization remains uncertain (for a recent summary of the issue, see Legarra Herrero 2014: 35-7). Contemporary settlement data are scarce, with the consequence that these tombs are our main source of information regarding life and death in the region prior to the construction of the first Palace of Phaistos in the 20th century BC.

Although a few circular tombs have been discovered in north-central and eastern Crete (for an updated catalogue of circular tombs, see Goodison and Guarita 2005), their concentration in and around the Mesara has long been taken as a proof of the existence of a distinct cultural group in this region. Doubts have recently been expressed on such an interpretation by researchers who stress the chronological and geographical variations that actually characterize the body of evidence (e.g. Déderix 2014; Legarra Herrero 2014; Relaki 2004). In addition, instead of merely reflecting the existence of a common cultural identity, the adoption of circular tombs and the associated practices now appears to have played an active role in the development of intercommunity relationships in the region (Relaki 2004). In this context, focal mobility network provides an opportunity to take a fresh look at issues of integration and interactions. In the absence of actual traces of ancient paths, it indeed offers the opportunity to assess whether circular tombs were built in close proximity to natural corridors of movement, which would in turn suggest that the communities living in the surroundings were easily accessible from one another and that they were thus potentially well interconnected. Even though spatial proximity is neither a necessary nor a sufficient condition, people are indeed more likely to meet and interact if they can rapidly and easily reach each other.

The analyses presented in this paper were undertaken in ArcGIS 10, using a DEM constructed by SPOT satellite stereoscopic images and characterized by a resolution of 20m (courtesy of the Laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment IMS-FORTH). The research focus was on inland movement, even though Early Bronze Age Cretans undoubtedly made good use of the sea for regional and long-distance journeys. The island lacks navigable rivers and detailed information regarding past environmental conditions (e.g. vegetation cover, seasonal streams) is not available. It was therefore decided to rely on slope only to calculate the cost of walking across the landscape. In addition, since the goal was to model general mobility patterns rather than directional movement, the isotropic equation developed by Bell and Lock (2000: 88-9) was chosen to create the friction surface: C = tan *s*/tan 1. This equation implies that that the relative cost (C) of moving up or down the slope is equal to the tangent of the slope (*s*, in degrees) divided by the tangent of 1°. An extra constraint was however added to cope with the rugged character of the mountains of south-central Crete: the cells characterized by a slope steeper than 30° were conventionally assigned the very high cost of 500, so as to force the software to bypass areas that regular human walkers regard as difficult to climb and too abrupt to walk down (Proffitt *et al*. 1995).

3 Natural corridors of movement in south-central Crete

Fábrega-Álvarez (2006) developed focal mobility network with the aim of assessing whether known archaeological sites are located along optimal paths leading to each other. However, to test its potential, it was decided to first implement the procedure to model natural corridors of movement in south-central Crete, irrespectively of the distribution of known archaeological sites. To do so, Verhagen's (2013) example was followed and movement was simulated for a sample of non-archaeological locations. More specifically, a regular grid of points spaced 2000m apart was generated across the study area, and a focal mobility network was calculated for each of these points. The procedure was thus iterated 201 times. No distance limit was specified so that the paths were left free to run across the whole region. To avoid defining an arbitrary threshold to extract the paths, each individual flow accumulation map was reclassified using the ¼ standard deviation classification method. This had the additional advantage of ranking the paths according to their relative importance in the network. The lowest values were reclassified as NoData, hence being dismissed for subsequent processing, whereas the remaining categories were assigned a new value ranging from 1 (minor paths) to 11 or 12 (major paths) depending on the distribution of the original values. The 201 individual focal mobility networks were then converted to polylines before being added up so as to produce a cumulative focal mobility network. Eventually, the density of paths created by this means was calculated using the line density command of ArcGIS 10 and a 50m search radius. The end product of the whole process is a raster surface that highlights areas that present the least resistance to movement, i.e. areas where multiple focal mobility networks converge (Fig. 4).

For comparative purposes, least cost paths were then calculated between each pair of the 201 points that were previously used as the destination of the focal mobility networks, in order to compute cumulative cost paths. An isotropic method was chosen (cost path command of ArcGIS 10), with the consequence that 20,100 least cost paths had to be generated. An anisotropic method would have doubled the computation requirements, as the least cost path from A to B would not have matched that from B to A. As was done for the focal mobility networks, the least cost paths were then summed and their density was calculated by making use of a 50m search radius (Fig. 5).

The calculation of these 20,100 least cost paths necessitated ca. 12 hours, when only ca. 40 minutes were needed to calculate 201 focal mobility networks. Fábrega-Álvarez's (2006) procedure opens therefore new opportunities for archaeologists to simulate past movement at landscape level, which is of particular relevance when many recent GIS-based innovations are described as time-consuming and computationally intensive. From a time management perspective, the advantage of focal mobility network is obvious. But what about the reliability of the result? Visual examination of Figs 4 and 5 allows concluding that the two methodologies lead to comparable end products. In mountainous regions, movement tends to be constrained by topography and the paths follow therefore similar trajectories, which often correspond to valley bottoms. In contrast, the network is dense and chaotic in the flat Mesara plain, where multiple paths are possible. It also appears that both maps suffer from an edge effect, as the paths fade away near the borders of the study area. Yet, this edge effect is less pronounced in the case of the cumulative focal mobility network. The phenomenon is for instance illustrated by the discreet path that follows the south coast in Fig. 4 but does not show in Fig. 5. The most problematic drawback of cumulative cost paths lies, however, in the strong impact exerted on the final result by the location of the grid points (Fig. 5). Each grid point is associated with 200 least cost paths, many of which follow the same trajectory as they get close to the particular point. As a result, the density map includes numerous stretches that deviate from the main branches of the network only to lead to the grid points. Such stretches are a by-product of the methodology; they do not correspond to natural corridors of movement.

The cumulative focal mobility network (Fig. 4) provides therefore a more accurate model of the landscape in terms of potential for movement, given that only stretches that give access to more than one grid point are outlined. This is not to say that the end product is optimal as such, as the network appears to be extremely dense. A simple additional step is therefore necessary to reclassify the map so as to conceal low value, emphasize the most important branches of the mobility network, and thereby avoid a cluttered system of paths that would lose its analytical potential. In this way, Fig. 6 was produced by reclassifying the values of the density map into deciles and highlighting the three highest categories. The result is pretty similar to the cumulative cost paths, yet with a more limited edge effect and without the impact of the location of the grid points. In the particular case of the Mesara plain, it must nevertheless be stressed that the cumulative cost paths (Fig. 5) better illustrate the possibility to travel in a north-south direction, whereas the cumulative focal mobility network (Fig. 6) seems more constrained by the east-west orientation of the plain. This issue will again be discussed in the next section.

4 A hierarchical communication network in Prepalatial south-central Crete

In his original presentation of the procedure, Fábrega-Álvarez (2006) stressed that focal mobility network allows modelling natural corridors of movement in relation to known archaeological sites. In this way, it offers a middle way between simulations that are strictly constrained by the location of recorded archaeological sites (e.g. least cost paths calculated among known sites) and those that ignore available cultural data during the computation of the paths (e.g. Figs 4-6). Following Fábrega-Álvarez's example, focal mobility networks were produced for 45 cemeteries of circular tombs

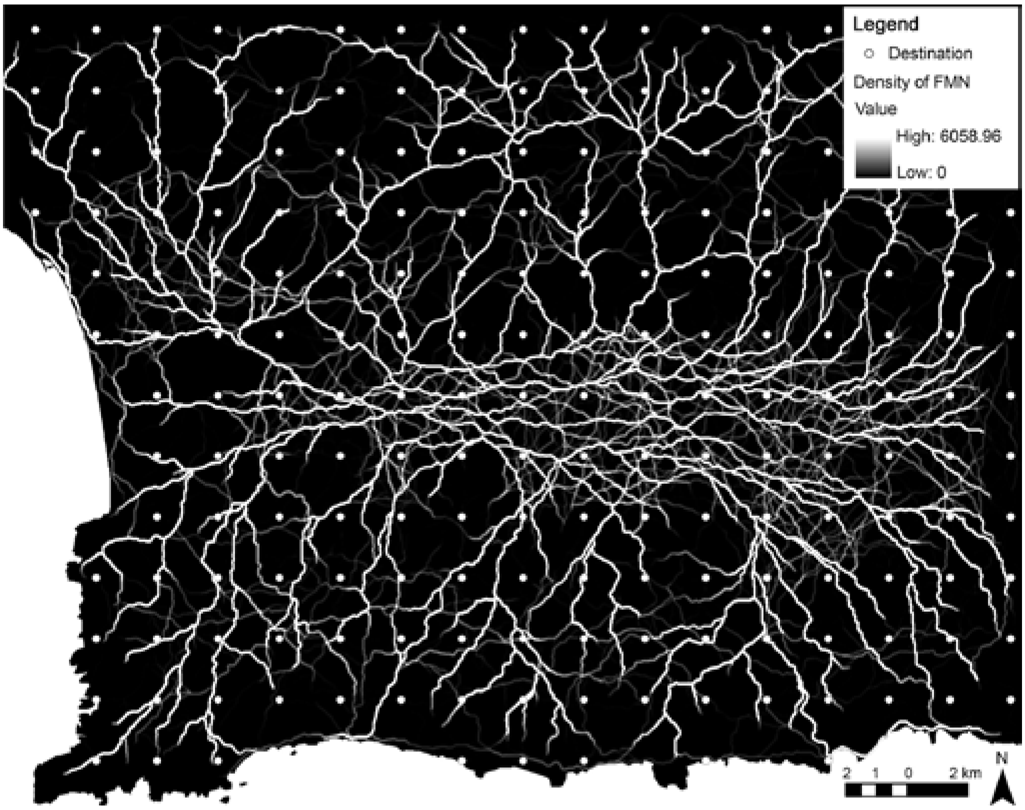

Fig. 4. Cumulative focal mobility network produced for a regular grid of points spaced 2km apart. The density of focal mobility networks was calculated using a 50m searching radius.

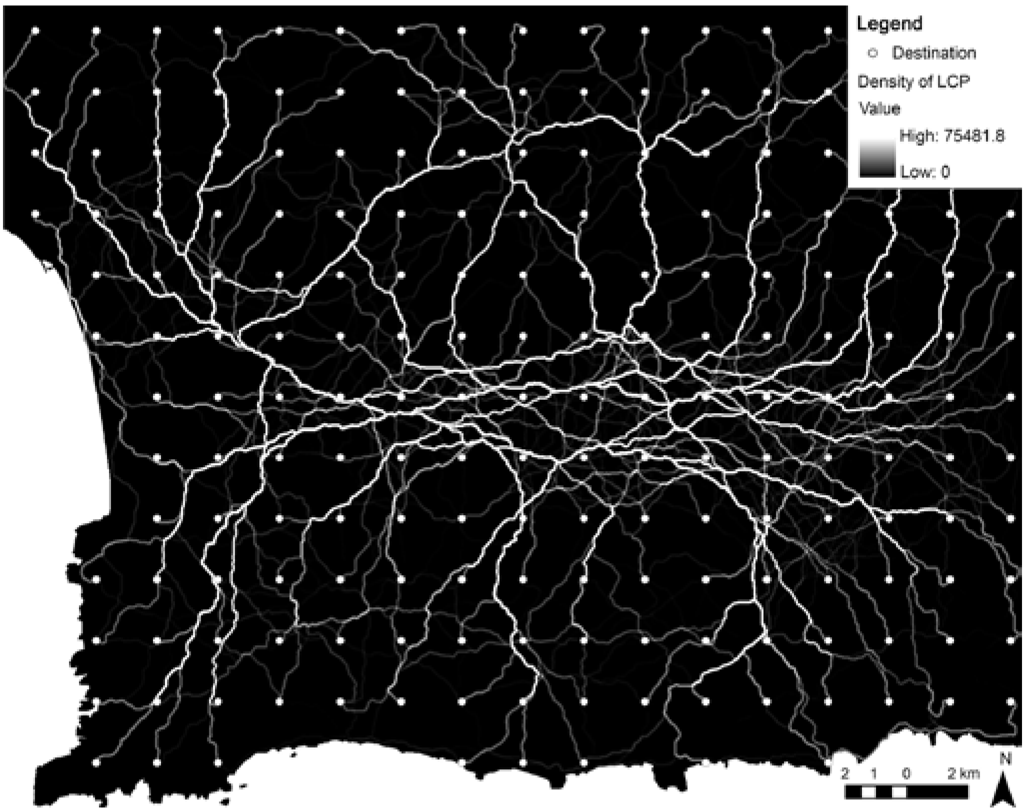

Fig. 5. Cumulative cost paths computed from a regular grid of points spaced 2km apart. The density of least cost paths was calculated using a 50m searching radius.

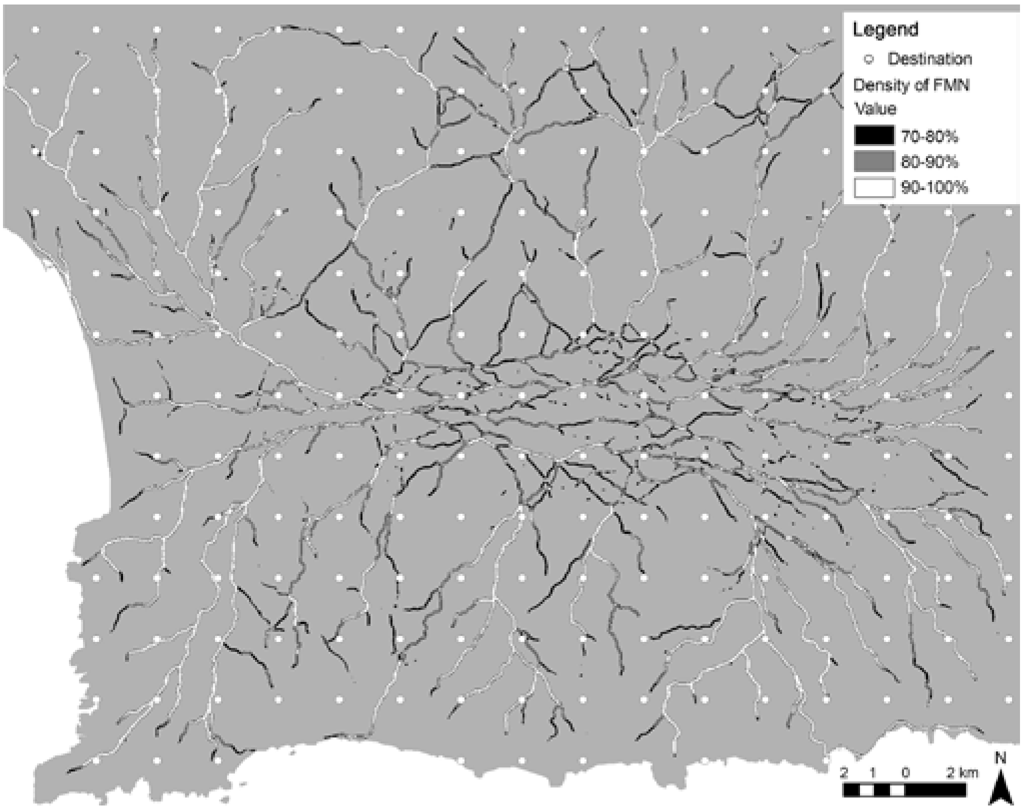

Fig. 6. Reclassification of the cumulative focal mobility network produced for a regular grid of points spaced 2km apart (Fig. 4).

located in south-central Crete. The same procedure was adopted as in the previous section. These 45 networks were reclassified using the ¼ standard deviation classification method, converted to polylines, and appended. Eventually, the density of paths created by these means was calculated with a 500m searching radius (Fig. 7).

If the resulting map is already of interest, the procedure allows going one step further. It is indeed possible to rank the paths according to their importance, so as to produce what could be called a hierarchical communication network (Fig. 8). Once more, there is no rule as to how to proceed to do so. Some experimentation and trial-and-error may be necessary to obtain a satisfactory result – i.e. a network that is neither too sparse nor too dense. In the case of Prepalatial south-central Crete, the density of focal mobility networks was calculated twice, first with a 50m searching radius, then with a 20m searching radius, and the resulting raster files were reclassified using the standard deviation classification method. In this way, major and secondary paths correspond respectively to the high and medium values of the density map produced with a 50m searching radius, whereas minor paths are the extra branches that were generated by means of the 20m searching radius. The end product is an uncluttered road system in which the recurrent and most significant paths are outlined, whereas tracks that occurred in a single focal mobility network are dismissed. In other words, the branches that deviate from natural corridors of movement only to give access to the sites used for the calculation of the networks remain invisible.

A comparison between the hierarchical mobility networks respectively created for regularly spaced points (Fig. 9) and for the burial sites (Fig. 8) proves informative. The chosen classification method has resulted in a very dense network with extra branches in the first case (Fig. 9), but globally, the paths follow similar trajectories in both maps. There are nevertheless some noteworthy differences. The network computed from the grid of points is consistent with the topography as represented by the DEM (Fig. 9). In the Asterousia Mountains and on the foothills of the Psiloritis, the main valleys follow a north-south orientation, and so do the optimal corridors of movement, whereas the paths are predominantly oriented east-west in the Mesara plain. This pattern is somewhat altered in the second case (Fig. 8), which is a consequence of the concentration of cemeteries in the southern part of the study area. The result is the creation of a few more obvious paths that cross the Mesara from north to south and, even more important, two long routes that run in an east-west direction in the Asterousia Mountains. These two routes must have played a crucial role in connecting local communities during the Early Bronze Age, but they are overlooked when the distribution of known archaeological sites is not taken into account.

All in all, hierarchical communication network appears to model optimal corridors of movement in a manner that is somewhat balanced by the distribution of archaeological sites. As such, the network follows the natural topography without falling into the traps of environmental determinism. Another benefit of the procedure is that it accounts for a certain degree of uncertainty and incompleteness, as the addition of a few extra sites would not drastically change the result – even though additional paths

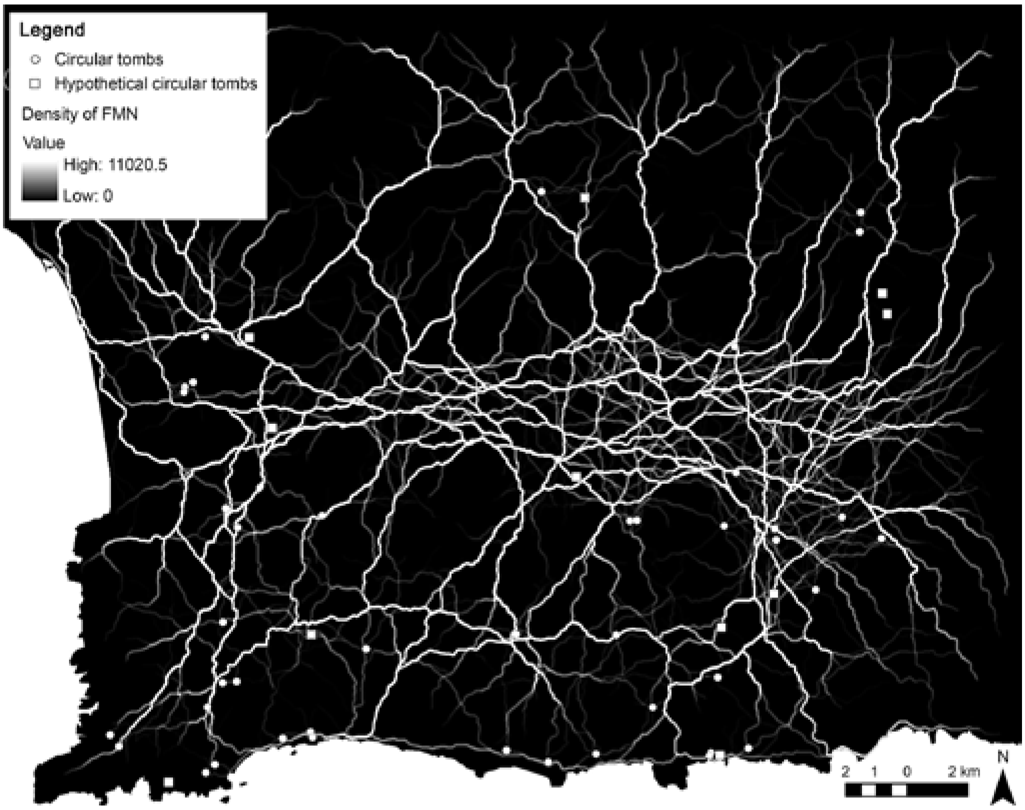

Fig. 7. Cumulative focal mobility network computed for the Prepalatial circular tombs identified with certainty in south-central Crete. The density of focal mobility networks was calculated using a 50m searching radius.

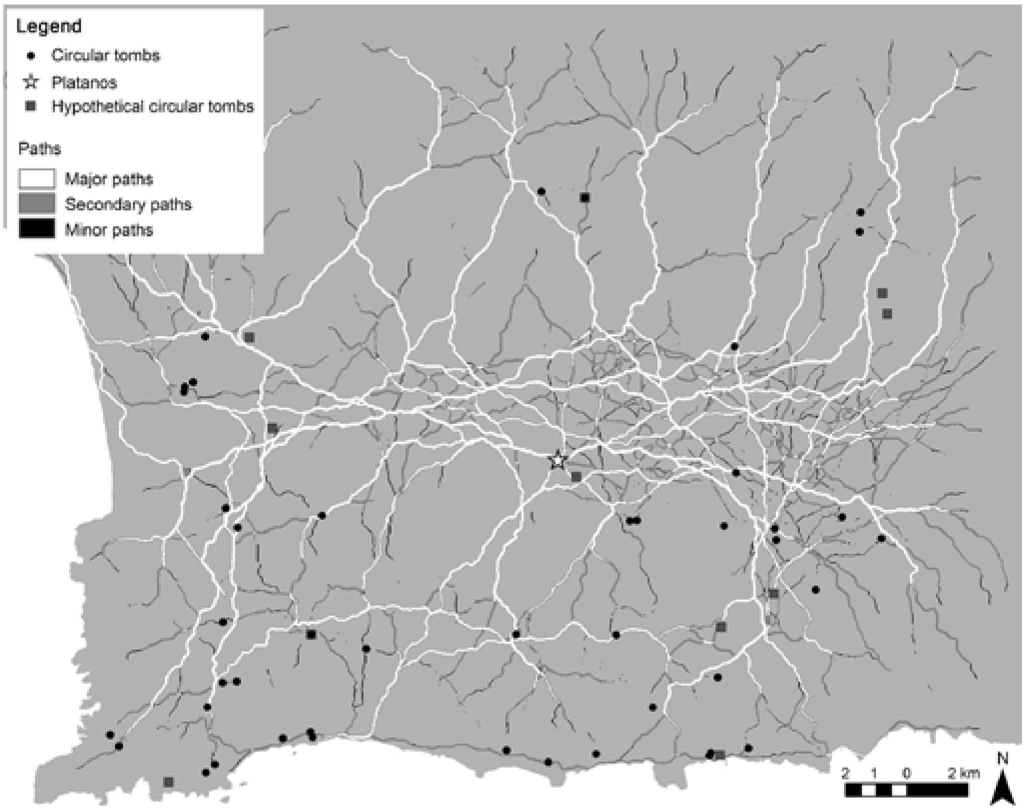

Fig. 8. Hierarchical communication network of Prepalatial south-central Crete. Only the circular tombs identified with certainty were used for the computation of the focal mobility networks.

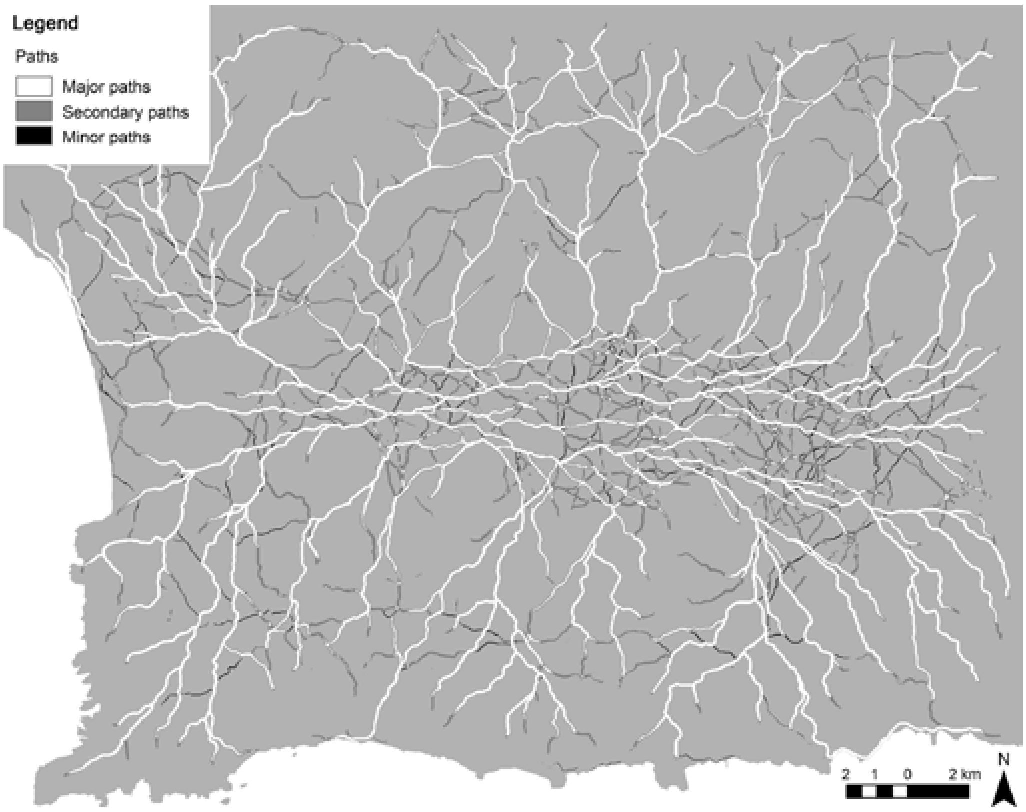

Fig. 9. Hierarchical communication network calculated from a regular grid of points spaced 2km apart.

may be created and/or existing paths could increase or decrease in importance.

The hierarchical communication network of Prepalatial south-central Crete (Fig. 8) deserves further discussion. It illustrates that circular tombs were predominantly constructed in close proximity to natural corridors of movement. If one admits that the living resided close to their dead (e.g. Branigan 1998; Vasilakis and Branigan 2010), such a spatial pattern would imply that the associated communities were indeed easily accessible from one another. There also appears to be a chronological pattern. The first circular tombs were constructed during the Early Bronze Age I period (ca. 3100/3000-2650 BC), essentially in the southwest Asterousia and along the south coast. The mountain range seriously impedes movement, with the result that the area is not easily accessible from the rest of south-central Crete. Yet, interactions among local communities were undoubtedly a central concern, as further suggested by the location of the circular tombs along secondary and minor paths. In contrast, from the Early Bronze Age II period (ca. 2650-2200 BC) onwards, the tombs were preferably constructed near major paths running across south-central Crete and connecting the region with the north coast. The most obvious case is Platanos, which is located at a major crossroad. It is remarkable that it is also from the Early Bronze Age II period onwards that interregional exchange systems gained in importance, first in the Aegean, then in the wider Eastern Mediterranean (Broodbank 2000: 276-87; Colburn 2008; Papadatos 2007; Phillips 2008). The phenomenon is well illustrated by the content of several of the circular tombs excavated in south-central Crete, and most especially in the Mesara plain. Finally, during Early Bronze Age III (ca. 2200-2100/2050 BC) and Middle Bronze Age I (ca. 2100/2050-1875/1850 BC), a series of sites were established along major paths in the central Asterousia, bridging in this way the gap between the Mesara and the south coast. There appears therefore to be some kind of correlation between the location of the tombs along the hierarchical communication network, the development of systems of exchange, and the grave goods discovered in the burial structures.

This said, one can wonder whether the hierarchical communication network is suitable to model the evolution of networks of interaction over time. In theory, it is easy to calculate the density of focal mobility networks computed for sites that were in use during the same chronological phase. But in practice, the results are not conclusive, at least in the present case study and with the decisions that were made – i.e. leaving the paths to run across the whole south-central Crete and extracting a very high number of paths by making use of the ¼ standard deviation classification method. As clearly visible in Figs 10 and 11, the networks produced for the Early Bronze Age I and II phases do not differ much, in spite of the construction of several circular tombs in the Mesara and on the southern foothills of the Psiloritis during the Early Bronze Age II. The reason lies in what was emphasized previously: the procedure models general patterns of movement in a manner that is balanced to some extent by the spatial distribution of the destination points. In the present case study, the concentration of burial sites along the south coast caused two paths running east-west to be created, along the coast and in the centre of the Asterousia Mountains respectively. But since these tombs

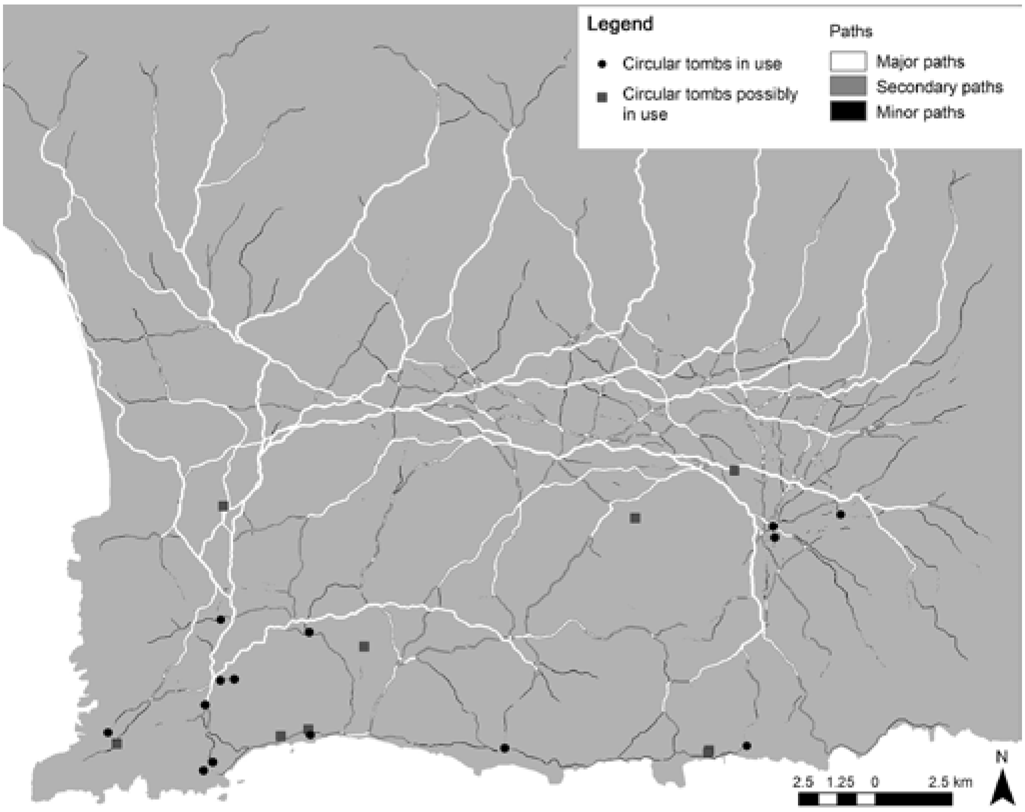

Fig. 10. Early Bronze Age I hierarchical communication network. Only the tombs used with certainty during the Early Bronze Age I were taken into account in the computation of the focal mobility networks.

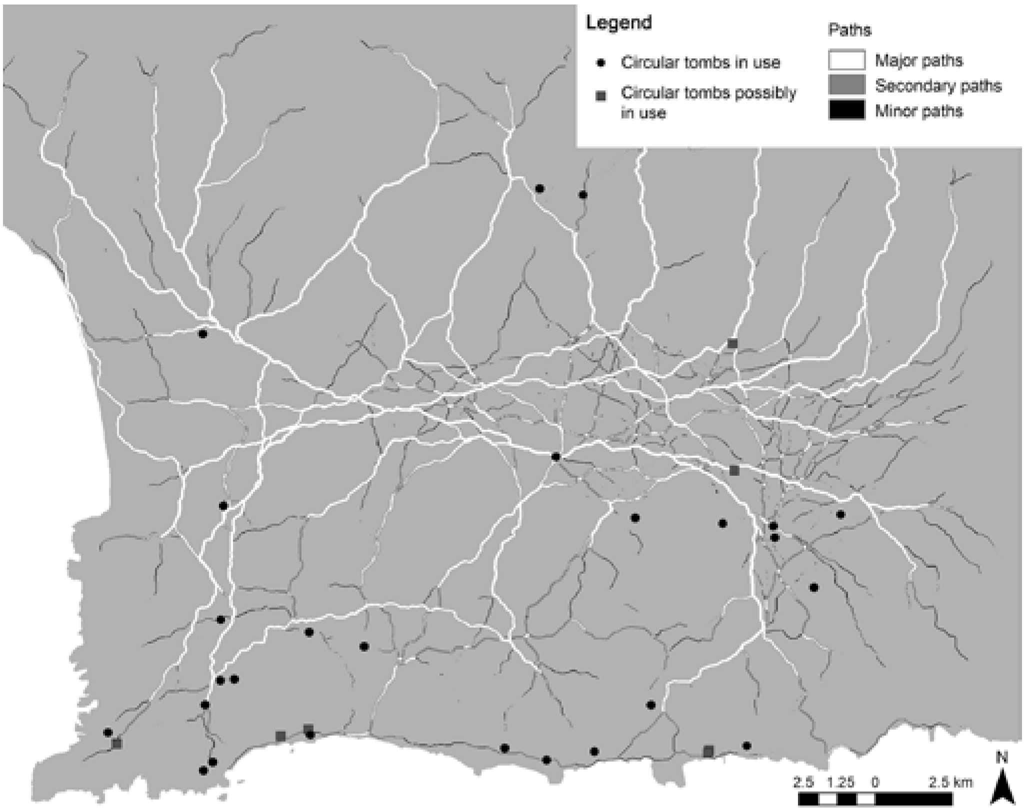

Fig. 11. Early Bronze Age II hierarchical communication network. Only the tombs used with certainty during the Early Bronze Age II were taken into account in the computation of the focal mobility networks.

were in use in both the Early Bronze Age I and II phases, the communication network remained globally the same. The potential of the procedure to explore the evolution of potential networks of interaction necessitates further investigation. One solution could perhaps be to limit the calculation of paths to a defined walking radius around the destination.

5 Conclusion

Focal mobility network provides new opportunities to simulate movement across archaeological landscapes in a simple, fast and efficient manner. As such, it allows exploring the accessibility of ancient sites (focal mobility network per se), modelling general patterns of movement (cumulative focal mobility network), and ranking the pathways according to their attractiveness (hierarchical communication network). Cumulative focal mobility network and hierarchical communication network have a further benefit: they make it possible to take into account the location of known archaeological sites when calculating optimal corridors of movement – and hence to approach past mobility in a (slightly) less environmentally deterministic way. The result of the process is a map that highlights natural areas of transit, but depending on the distribution of the sites of interest, some branches may be given greater weight than it would be expected based on topography only. In other words, the natural attractiveness of some paths may be somewhat balanced to reflect more accurately the past occupation of the region. It must be stressed, however, that the impact of the distribution of the sites remains insufficient to model the evolution of communication networks in accordance with the evolution of settlement patterns. Another issue faced when calculating focal mobility networks, cumulative mobility networks and hierarchical mobility networks is the lack of clear rules to extract the paths, calculate their density and reclassify the values, which necessitates a certain degree of experimentation, trial-and-error, and subjectivity. Focal mobility network and its derivative represent nevertheless a valuable addition to the archaeologist's digital toolbox. Without replacing existing methodologies, they broaden the spectrum of computer-based approaches to past movement and interactions.

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Bibliography

Bell, T. and Lock, G. 2000. Topographic and Cultural Influences on walking the Ridgeway in Later Prehistoric Times. In Lock, G. (ed.) *Beyond the Map. Archaeology and Spatial Technologies*: 85-100. Amsterdam, IOS Press.

Branigan, K. 1998. The Nearness of You: Proximity and Distance in Early Minoan Funerary Landscapes. In Branigan, K. (ed.), *Cemetery and Society in the Aegean Bronze Age*. Sheffield Studies in Aegean Archaeology 1: 13-26. Sheffield, Sheffield Academic Press.

Branting, S. 2012. Seven Solutions for Seven Problems with Least Cost Pathways. In White, D.A. and Surface-Evans, L. (eds.), *Least Cost Analysis of Social Landscapes. Archaeological Case Studies*: 209-24. Salt Lake City, The University of Utah Press.

Broodbank, C. 2000. *An Island Archaeology of the Early Cyclades*. Cambridge, Cambridge University Press.

Colburn, C. S. 2008. Exotica and the Early Minoan elite: eastern imports in Prepalatial Crete. *American Journal of Archaeology* 112: 203-24.

Déderix, S. 2014. *The Minoan Funerary Landscape. A Study of Spatial Relationships between the World of the Dead and the Living in Bronze Age Crete (ca. 3100-1450 BC)*. Unpublished PhD thesis, Université Catholique de Louvain.

Fábrega-Álvarez, P. 2006. Moving without destination. A theoretical, GIS-based determination of routes (optimal accumulation model of movement from a given origin). *Archaeological Computing Newsletter* 64: 7-11.

Faíren-Jimenez, S. 2007. British Neolithic rock art in its landscape. *Journal of Field Archaeology* 32: 283-95.

Goodison, L. and Guarita, C. 2005. A new catalogue of the Mesara-type tombs. *Study Micenei ed Egeo-Anatolici* 47: 171-212.

Hazell, L. C. and Brodie, G. 2012. Applying GIS tools to define prehistoric megalith transport route corridors: Olmec megalith transport routes: a case study. *Journal of Archaeological Science* 39: 3475-9.

Herzog, I. 2013. The Potential and Limits of Optimal Path Analysis. In Bevan, A. and Lake, M. (eds.) *Computational Approaches to Archaeological Spaces*. UCL Institute of Archaeology Publications 60: 179-211. Walnut Creek, Left Coast Press.

Howey, M. C. L. 2007. Using multi-criteria cost surface analysis to explore past regional landscapes: a case study of ritual activity and social interaction in Michigan, AD 1200-1600. *Journal of Archaeological Science* 34: 1830-46.

Kantner, J. 2012. Realism, Reality, and Routes. Evaluating Cost-Surface and Cost-Path Algorithms. In White, D. A. and Surface-Evans, L. (eds.) 2012. *Least Cost Analysis of Social Landscapes. Archaeological Case Studies*: 225-38. Salt Lake City, The University of Utah Press.

Legarra Herrero, B. 2014. Mortuary Behavior and Social Trajectories in Pre- and Protopalatial Crete. *Prehistory Monographs* 44. Philadelphia, INSTAP Academic Press.

Llobera, M. 2000).Understanding Movement: a Pilot Model towards the Sociology of Movement. In Lock, G. (ed.), *Beyond the Map. Archaeology and Spatial Technologies*: 65-84. Amsterdam, IOS Press.

Llobera, M., Fábrega-Álvarez, P. and Parcero-Oubiña, C. 2011. Order in movement: a GIS approach to accessibility. *Journal of Archaeological Science* 38: 843-51.

Mlekuž, D. 2013. Time Geography, GIS and Archaeology. In F. Contreras, M. Farjas, F. J. Melero (eds.), *Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. British Archaeological Reports International Series 2494: 259-365. Oxford, Archaeopress.

Mlekuž, D. 2014. Exploring the Topography of Movement. In Polla, S. and Verhagen, P. (eds.), *Computational Approaches to the Study of Movement in Archaeology.*

Theory, Practice and Interpretation of Factors and Effects of Long Term Landscape Formation and Transformation. Topoi. Berlin Studies of the Ancient World 23: 5-21. Berlin, Boston, Walter de Gruyter GmbH.

Murrieta-Flores, P. 2012. Understanding human movement through spatial technologies. The role of natural areas of transit in the Late Prehistory of south-western Iberia. *Trabajos de Prehistoria* 69: 103-22.

Papadatos, Y. 2007. Beyond Cultures and Ethnicity: A New Look at Material Culture Distribution and Inter-regional Interaction in the Early Bronze Age Southern Aegean. In S. Antoniadou and A. Pace (eds.), *Mediterranean Crossroads*: 419-51. Oxford, Pierides Foundation.

Phillips, J. 2008. Aegyptiaca on the Island of Crete in their Chronological Context: A Critical Review. In *Denkschriften der Gesamtakademie* 49. *Contributions to the Chronology of the Eastern Mediterranean 18*. Vienna, Verlag der Österreichischen Akademie der Wissenschaften.

Proffitt, D. R., Bhalla, M., Gossweiler, R. and Midgett, J. 1995. Perceiving geographical slant. *Psychonomic Bulletin & Review* 2: 409-28.

Relaki, M. 2004. Constructing a Region: The Contested Landscapes of Prepalatial Mesara. In Barrett, J.C. and Halstead, P. (eds.), *The Emergence of Civilisation Revisited*. Sheffield Studies in Aegean Archaeology 6: 170-88. Oxford, Oxbow.

Vasilakis, A. and Branigan, K. (eds.) 2010. Moni Odigitria. A Prepalatial Cemetery and its Environs in the Asterousia, Southern Crete. *Prehistory Monographs* 30. Philadelphia, INSTAP Academic Press.

Verhagen, P. 2013. On the Road to Nowhere? Least Cost Paths, Accessibility and the Predictive Modelling Perspective. In F. Contreras, M. Farjas, F. J. Melero (eds.), *Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. British Archaeological Reports International Series 2494: 383-90. Oxford, Archaeopress.

Vouzaxakis, K. 2015. Αναζήτηση οδικών δικτύων επικοινωνίας κατά τη Νεολιθική περίοδο στη ΝΑ Θεσσαλία μέσω χωρικής ανάλυσης με GIS. In Papadopoulos, C., Paliou, E., Chrysanthi, A., Kotoula, E. and Sarris, A. (eds.), *Archaeological Research in the Digital Age. Proceedings of the 1st Conference on Computer Applications and Quantitative Methods in Archaeology Greek Chapter (CAA-GR), Rethymno, Crete, 6-8 March 2014*. Rethymno, Institute for Mediterranean Studies-Foundation of Research and Technology: 18-27.

Wheatley, D. and Gillings, M. 2002. *Spatial Technology and Archaeology. The Archaeological Applications of GIS*. London, Taylor & Francis.

Wheatley, D. W., García Sanjuán, L., Murrieta Flores, P. A. and Márquez Pérez, J. 2010. Approaching the landscape dimension of the megalithic phenomenon in southern Spain. *Oxford Journal of Archaeology* 29: 387-405.

White, D. A. and Surface-Evans, L. (eds.) 2012. *Least Cost Analysis of Social Landscapes. Archaeological Case Studies*. Salt Lake City, The University of Utah Press.

Whitley, T. G. and Burns, G. 2008. Conditional GIS Surfaces and their Potential for Archaeological Predictive Modelling. In A. Posluschny, K. Lambers, I. Herzog (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin (Germany), April 2-6, 2007*. Kolloquien zur Vor- und Frühgeschichte 10: 292-8. Bonn, Dr. Rudolf Habelt GmbH.

Dispersal Versus Optimal Path Calculation

Irmela Herzog
i.Herzog@lvr.de
The Rhineland Commission for Archaeological Monuments and Sites, Bonn, Germany

Abstract: People who walk into unknown territory see only part of the landscape ahead whereas optimal path calculation relies on the assumption that the walker has total knowledge of the landscape ahead. For this reason optimal path calculations are not appropriate for modelling dispersal processes. But the cost function derived from optimal path calculations can also be applied for modelling dispersal: The walker will prefer paths consisting of locally optimal steps in the direction chosen initially. Based on this assumption, a new agent-based algorithm is proposed for modelling the dispersal into unknown terrain starting from a given location. The corridors of movement generated this way are compared to globally optimal radial paths for a hilly study area located east of Cologne in Germany.

Keywords: Least-cost paths, Agent-based modelling Dispersal processes, Radial networks

Introduction

The agent-based approach for modelling dispersal presented in this paper creates locally optimal paths taking the costs of movement into account. This approach differs from least-cost path (LCP) calculation because LCPs are globally optimal paths if implemented properly. Whereas LCPs are based on the assumption that people in the past had complete knowledge of the landscape, locally optimal paths consist of locally optimal steps in the direction chosen initially. Moreover, traditional LCPs connect two predefined locations whereas only the starting point is known when modelling dispersal.

Many dispersal studies do not model the costs of movement at all but focus on attractors and barriers or NoGo areas instead (e.g. Scherjon 2013). Studies taking the cost of movement into account (e.g. Anderson and Gillam 2000) use a cost function that is not validated for the study area and humans of that time, i.e. the authors present no evidence that this cost function is appropriate for the human movement in the landscape and period considered. In general, it is very difficult to adequately reconstruct the costs of movement for a group of humans living thousands of years ago dispersing into a large study area like a continent and taking into account that the topography changed considerably since that time.

A fairly small study area (Fig. 1) and a fairly recent period (Middle Ages) is chosen in this paper allowing validation of the results. For the study area in a hilly region east of Cologne an adequate cost function for movement in Medieval times was identified by comparing LCPs to known Medieval trade routes (Herzog 2013a,b). The LCPs were generated on the basis of different cost functions. The best fit to the trade routes was achieved with LCPs avoiding wet soils and with a critical slope of 13%. This cost function reconstructs many segments of the Medieval trade routes quite well.

The region of the study area was only sparsely populated before Medieval times (Landschaftsverband Westfalen Lippe and Landschaftsverband Rheinland 2007, on CD: 282). Gummersbach, about 45km east of Cologne was first mentioned in a historical source in 1109 AD and no other settlement close to the centre of the study area considered was mentioned earlier. Gummersbach was already an important place when it was first mentioned because the source refers to its church (Pampus, 1998: 134). Therefore Gummersbach was chosen as a presumed origin of a spreading process. One of the Medieval trade routes (Bergische Eisenstraße) passes Gummersbach. Fig. 1 shows two alternative variants of this route recorded by Nicke (2001: 106-109) as well as all other old trade routes described by Nicke for this area. Moreover, the main and minor roads depicted on 'probably the oldest map of the political unit known as Reichsherrschaft Gimborn' (Nehls 1996, reverse side of front cover) are shown.

1 Previous approaches based on movement costs for modelling dispersal processes

Anderson and Gillam (2000) calculate 'least-cost pathways between presumed points of initial human entry into North and South America and 45 early archaeological sites'. As mentioned above, LCP calculations assume a 'God's eye' view i.e. total knowledge of the landscape. This assumption is not realistic for people moving into unknown terrain.

For this reason, this LCP approach is modified by Field, Petraglia and Lahr (2007) for modelling the coastal-based expansion of *homo sapiens* into South Asia. The result of their model is a path consisting of segments covering 60km. After selecting a starting point, each segment is a LCP and proceeds 'in any direction towards the boundary of the [60km] search radius'. Obviously, the starting point of the next segment is the endpoint of the previous segment. New segments are added until the path reaches a high cost barrier or meets another path generated this way. An isotropic cost grid is used to calculate the path segments and the 60km circles for consecutive segment starting points overlap. Therefore the optimal path starting at a segment endpoint may return to the starting point of this segment. The authors do not mention any measures to prevent movement back towards the origin but the paths presented in the paper do not seem to suffer from this unwanted effect. An advantage of this approach is that the destinations are selected by the algorithm. A perception range of 60km with total knowledge of the landscape seems to be quite huge but the method still works with a lower radius.

Another algorithm for modelling least-cost routes starting from a given origin without specific destination points was

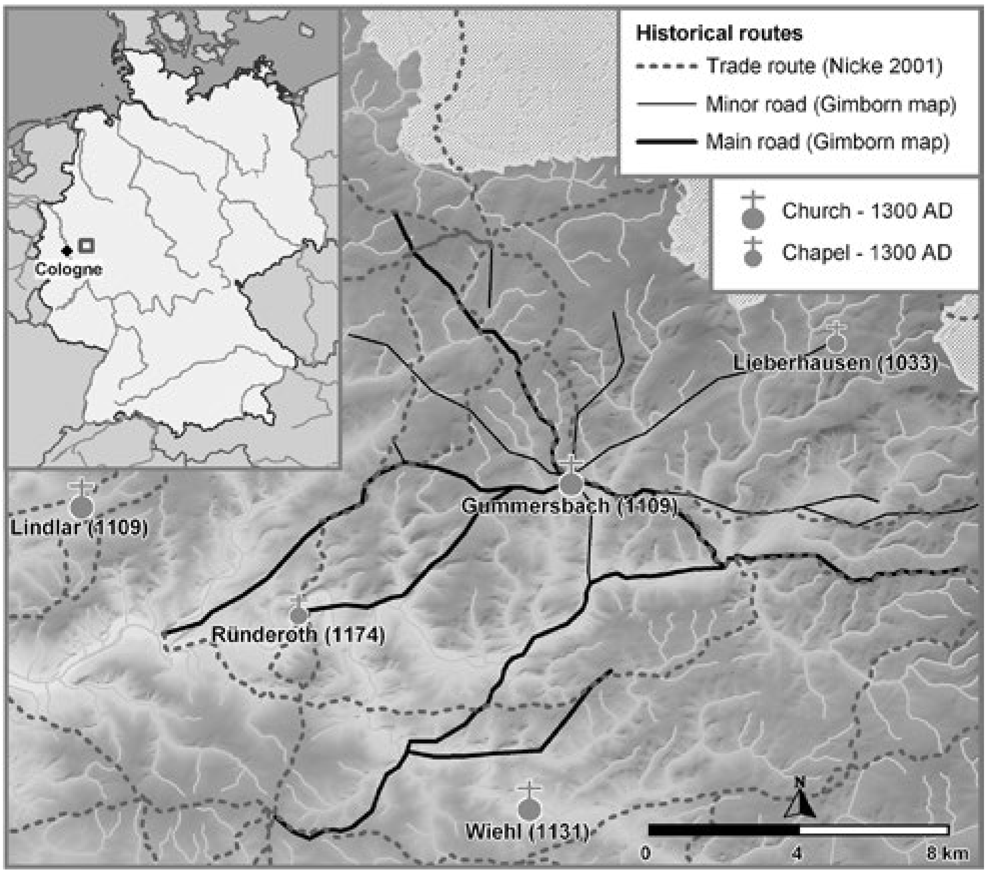

Fig. 1. Location of the study area. The map shows the churches and chapels mentioned in the complete list of churches and chapels (known as *Liber valoris*) for this region set up in the beginning of the 14th century (Oediger 1967). The place names as well as the year when this place was first mentioned in historical sources are given. Moreover, the old trade routes described by Nicke (2001) and the roads recorded on an early map (Nehls 1996) of part of the study area are shown.

proposed by Fábrega Álvarez and Parcero Oubiña (2007). They determine probable paths from an origin outward on the basis of the cost-surface: Destination points of these paths are the locations with maximum distance versus cost ratio, i.e. where large distances can be covered at low costs. Herzog (2013b) presents an algorithm based on these ideas. Each of the paths generated connects the origin to a location on the border of a site catchment with a predefined cost limit. The first path covers the maximum straight-line distance, subsequently selected paths keep a minimum straight-line distance to previously selected paths, and the destinations chosen represent local optima with respect to the neighbouring cells on the border. The result of this method is a radial network consisting of LCPs. This network depends on the cost function, the pre-defined cost-limit of the site catchment and the minimum straight-line distance of the destination locations. For the town of Gummersbach, several radial networks were generated applying the cost function calibrated by Medieval trade routes (Fig. 2). Different cost-limits and straight-line distances of destination locations were chosen.

Figure 2 shows some disadvantages of the approach: The paths of the different radial networks sometimes do not coincide. Especially the final parts often run in different directions, for instance the two paths labelled 1 in the 7.5km / 2km network and in the 10km / 3km network. Initially, I assumed that the paths with low numbers, i.e. covering large straight line distances from the origin, are more reliable than those with large numbers, and therefore my expectation was that these low number paths would coincide in all radial networks (at least in the first part of these paths). But path 3 in the 7.5km / 2km network and path 5 in the 10km / 3km network refute my expectation: No path in one of the 15km networks runs in this direction.

The radial networks created in this way are globally optimal and will be compared to the results of locally optimal approaches.

According to a popular misconception, LCP algorithms in GIS software do not reconstruct the globally optimal path (e.g. Conolly and Lake 2006: 254; Kantner 2012). With the exception of IDRISI, the LCP algorithms implemented in GIS software are based on Dijkstra's approach (Herzog 2013b) that consists of three steps: In the first step the raster data used for deriving the costs of movement is converted to a graph linking each raster cell to its neighbours. The weight of each link corresponds to the costs of movement between the two cells connected by the link. In the second step, the accumulated cost surface is generated on the basis of these links, assigning to each raster cell the costs of moving from the origin to this

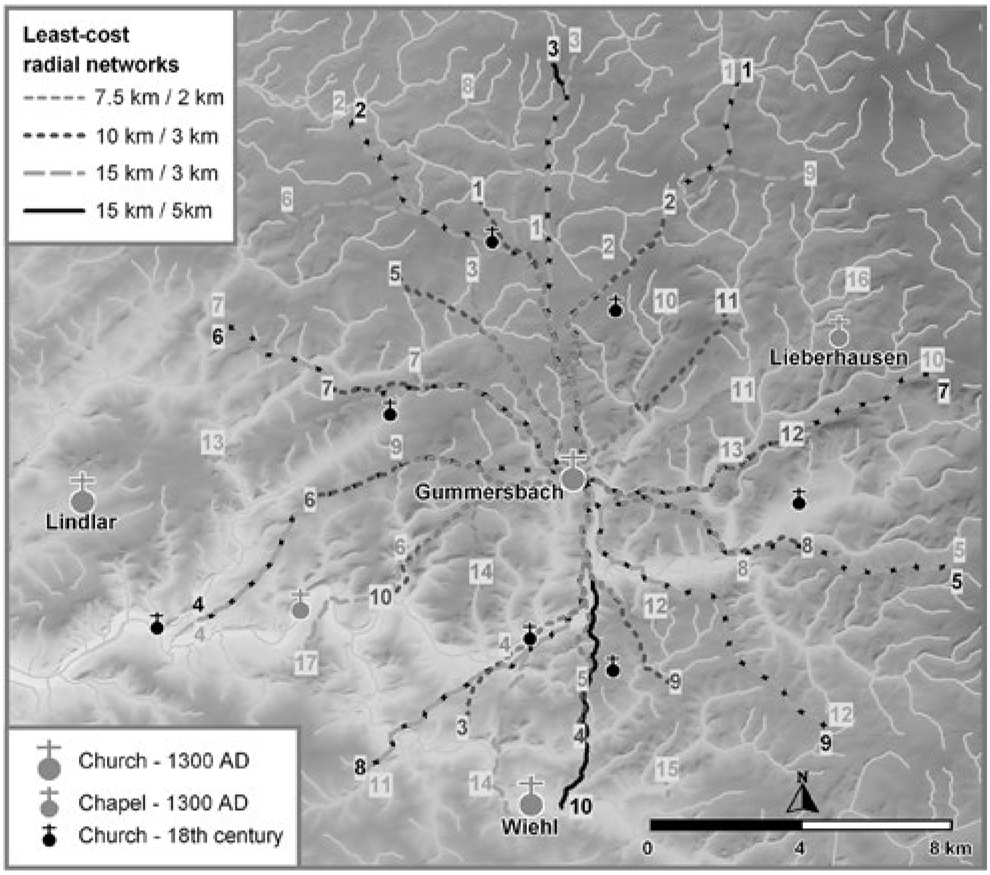

Fig. 2. Least-cost radial networks with different parameters generated for the town Gummersbach. All routes shown are based on a quadratic cost function with a critical slope of 13% and a multiplier of 5 for wet areas, reduced to 2 for ford locations. For each radial network, the upper legend first shows the pre-defined cost-limit followed by the minimum straight-line distance of the destination locations separated by a slash. Costs are measured in terms of costs required for covering 1km on level dry ground. The path numbers in each radial network are ordered according to the straight-line distance from the origin, with path number 1 covering the largest distance.

cell. The third step generates the LCP by backtracking from the target cell back to the origin. The correct way of performing the third step is by tracing back the LCP from the target cell based on a backlink raster created during the second step; this backlink raster records for each cell its predecessor on the LCP route (or the link taken to reach the cell). An alternative but incorrect replacement of the third step is to use a drainage algorithm that identifies the route of steepest cost reduction, which does not necessarily coincide with the optimal path (Smith *et al.* 2007:146). However, a drainage algorithm may be applied for creating locally optimal paths: Based on the cost surface the path is constructed by successively choosing the next least costly step. This has some similarity to the approach of Field, Petraglia and Lahr (2007) but these authors take larger steps (60km). As mentioned above, paths generated this way may return to the origin and lack sense of direction: The path will change direction if this introduces minimal cost savings compared to continuing in the same direction. But it seems a realistic assumption that people in the past had some sense of direction. Other agent-based studies like that of Reynolds *et al.* (2010) modelling pre-hominid hunter gatherer behaviour or Scherjon's (2013) approach for modelling modern humans moving into Europe also include some sense of direction. Moreover, all approaches discussed so far are deterministic, but in reality, some random influences play a role as well.

2 Modelling dispersal processes taking costs of movement into account

2.1 General features of the approach

The agent-based approach presented in this paper has some similarity to the multi-agent algorithm proposed by Reynolds *et al.* (2010): According to this algorithm for foragers, each individual chooses a specific foraging direction and movement is stopped after the predefined maximum distance has been covered (or if the maximum amount of food has been foraged).

To model the dispersal process for Gummersbach an agent-based simulation was chosen where the agent's next move depends on three variables: (i) the environment, i.e. the costs to be paid for the next step, (ii) the strength of the pull towards the preferred (initial) direction and (iii) the number of agents that already visited the possible target cells. The latter condition ensures that corridors rather than single cell paths are identified when tracking the dispersal of a large number of agents. Each agent moves until a predefined cost limit has expired.

According to Gilbert (2008), there are four important features of agents:

- Proactivity: Each agent has a goal. The goal in this approach is: Get away from the origin in a predefined direction, cover as much distance as possible

- Reactivity: The program of each agent reacts on stimuli of the environment. In this approach, the agent takes the movement costs of the next step into account and stops moving after reaching a predefined cost limit.

- Social ability: An agent can interact with other agents. In the implementation presented here, the agents avoid cells that have been visited by many other agents. But the agents do not interact directly so no parallel processing is required. For modelling social ability, a raster v counting the number of visitors in each cell is needed.

- Autonomy: Each agent has its own program, not controlled by a master.

2.2 The outline of the agent-based program

The results presented in this paper were generated by a Delphi program. The outcome of this agent-based program for modelling spreading processes taking movement costs into account is controlled by the following parameters:

- the number n of agents (= paths) to be generated,

- the function estimating the costs of movement on the basis of two grids: a digital elevation model (DEM) and an optional isotropic cost grid,

- the cost limit, given in terms of the costs required to cover a user-supplied distance on flat terrain with not additional difficulties (isotropic multiplier is 1),

- the maximum penalty (multiplier) w>1 for moves in wrong directions,

- the overcrowd factor f>1, ensuring that agents avoid cells with a visitor count exceeding f times the expected number of visitors in uniform terrain.

- Both a deterministic and a non-deterministic variant of the algorithm are provided (see below).

- The output also depends on the random number generator and its seeds. The random number generator proposed by L'Ecuyer (1988) was implemented.

All agents start at the same position, i.e. the assumed starting point of the dispersal process.

The agent‘s program:

Step 1: Choose an initial direction (integer) in the range 0 to 359° (proactivity).

Step 2: $Cost_{expended} = 0$

Step 3: Repeat Steps 4 to 6 until $Cost_{expended} > Cost_{limit}$

Step 4: Choose the direction of the agent‘s next move, depending on

- the environment, i.e. the costs to be paid for the next step (reactivity)

- the strength of the pull towards the preferred (initial) direction

- the number of agents that already visited the possible target cells (social ability).

$Cost_{move}$ is the cost of the move chosen in this step.

Step 5: $Cost_{expended} = Cost_{expended} + Cost_{move}$

Step 6: For each cell visited by the move, increment the corresponding counter in raster v.

The function estimating the costs of the next move to a neighbouring cell were derived from the LCP calculations trying to reconstruct Medieval trade routes (see above). The agents move in a raster grid, and the movement costs are calculated on the basis of two raster grids: The DEM (25m cell size, supplied by GeoBasis NRW) and an isotropic cost grid storing the multipliers for isotropic costs i.e. traversing wet areas.

The details of (i) modelling the pull towards the preferred direction and (ii) avoiding cells that have been visited by many other agents will be given in the next sections.

2.3 Modelling the pull towards the preferred (initial) direction

As mentioned above, LCP algorithms mostly rely on Dijkstra's algorithm, and the first step of this algorithm is to create links between the raster cells. This applies to the algorithm of this paper as well. The accuracy of the LCP result depends on the number of links (directions of moves) considered for each cell (Herzog 2013b). Whereas many GIS implementations of LCP software support only 8 or optionally 16 directions, the software used for my research allows movement in 32 directions. But it does not seem appropriate to move in a direction with an angle deviating more than 90° from the preferred direction. Therefore the number of directions is limited to 17. Figure 3 illustrates how the strength of the pull towards the preferred (initial) direction is modelled.

The user selects a penalty factor w>1 for moving in a direction perpendicular to the preferred angle. The penalty factor w_i for a possible move i depends on the deviation of this move from the preferred angle and w. The value w_i is in the range 1 to w and close to 1 if the angle is close to the preferred angle. This is the formula for calculating the penalty factor w_i:

$$w_i = 1 + (\alpha/90) * (w-1)$$

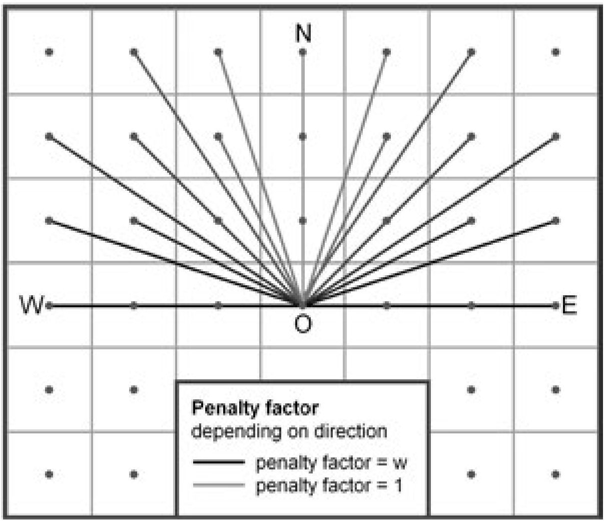

Fig. 3. Penalty factors for cell O with preferred direction N. Movements in 17 directions are supported. The lowest penalty factor 1 is assigned to the preferred direction N, the highest penalty (w) has to be paid when moving in a direction perpendicular to the preferred direction. A 6 by 7 cell grid is shown, grid cell centres are marked by dots.

with α = positive angle between the preferred direction and the direction of the move. Angles are measured in degrees. The model accounts for the fact that moves are of different length:

p_i = (move_cost * w_i) / move_length

For the deterministic variant of the approach, the move i with the lowest p_i value is selected in Step 4 of the agent's program. With the non-deterministic approach, the sum $S = \Sigma 1/p_i$ is calculated; a random number s in the range of 0 to S is generated; the move j is selected that is in the range between S_{j-1} and S_j with S_j the sum of $1/p_i$ taking moves 1 to j into account. So the non-deterministic approach assigns the highest probability to the move with the lowest p_i value.

2.4 Avoiding cells visited previously by many other agents

The user enters the overcrowd factor f>1, and the algorithm ensures that agents avoid cells with a visitor count exceeding f times the expected number of visitors in uniform terrain. The expected number of visitors depends on the distance of a cell to the origin. Therefore the program considers concentric ring buffers with the inner radius r and outer radius r+c where c is the cell size of the raster grid. The number of cells within each concentric ring buffer increases with distance r. For this reason, the number of visitors expected in each cell depends on distance r and can be estimated from the area covered by the concentric ring buffer (Fig. 4).

When the number of cells in each ring buffer is estimated from the area of the ring buffer, $2\pi r+1$ cell centres are expected in each ring with inner radius r (with c=1). So the probability that a given cell is visited by a random path moving outward, passing each ring only once depends on the inner radius r of the concentric ring of the cell: $1/(2\pi r+1)$

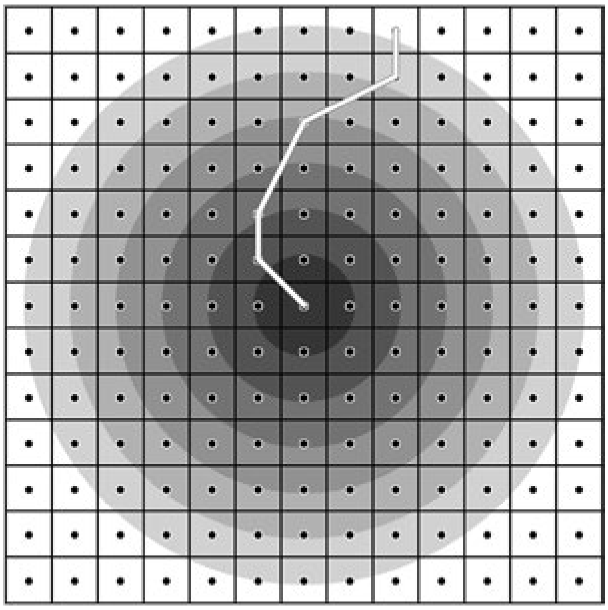

Fig. 4. The expected number of visitors on uniform terrain is estimated based on the size of the concentric ring buffer area for the cell considered. The image shows the raster grid, the cell centres, a possible path and concentric ring buffers centred on the origin. The difference between the inner and the outer radius is equal to the cell size c. The number of cell centres within each ring buffer is estimated by calculating the area of the ring buffer. The number of expected visitors on uniform terrain is proportional to this number.

In the program presented in this paper, a cell is avoided by a path, if the number of visitors of this cell exceeds $\max(n*f / (2\pi r+1), 1)$. Adjustment for $c \neq 1$: $\max(n*f / (2\pi*(r/c)+1), 1)$.

With a low initial cost limit for the paths to be generated, the border of the study area cannot be reached by the paths; in this case, the above formula will overestimate the expected number of visitors in the cells with a distance from the origin beyond cost limit range.

A high overcrowd value f should be chosen if single cell tracks are wanted rather than corridors.

2.5 Checking the approach

On uniform terrain, this approach should create nearly radial paths. This is checked by a visualisation method that is later used for presenting the outcome of the algorithm for Gummersbach.

After creating n paths a grid g_{ik} is shown with each cell visualising the number of visitors after concentric ring normalization:

$g_{ik} = v_{ik} / v_r$ with $v_r = n / (2\pi r+1)$

i.e. v_r is the expected number of visitors in the concentric ring containing the cell v_{ik} (with c=1).

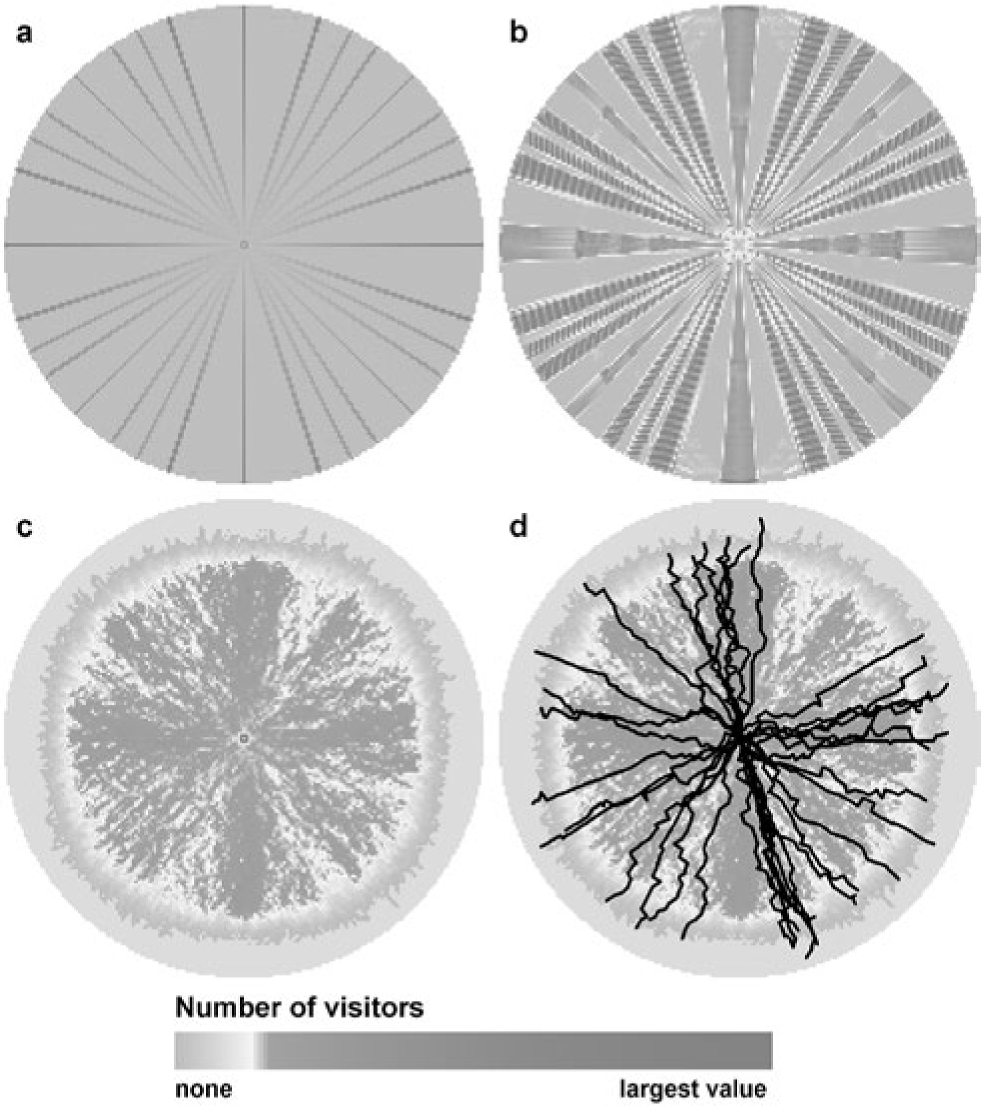

Fig. 5. Results of the agent-based dispersal program on a uniform terrain with n =10000: a – deterministic, w=2, f=100, b – deterministic, w=2, f=2, c – non-deterministic, w=2, f=100, d – same as c, additionally 36 individual paths are shown in black.

Figure 5 shows results of the program using the visualisation method outlined above. On a uniform terrain, 10,000 paths were generated. In this ideal case, the number of visitors in each cell should be close to the number of expected visitors. But according to Figure 5a, with the deterministic variant, the paths move only in 32 directions, if a large overcrowd factor (f=100) is selected. With a smaller overcrowd factor (f=2), the preference of the 32 directions is still visible (Fig. 5b). This is due to the fact that each cell is linked to 32 neighbours only, and an agent can only select a move from the set of links to the neighbouring cells (Fig. 3). With the deterministic approach and uniform terrain, the agent will always select the move in the direction closest to the agent's initial direction.

The result of the non-deterministic approach (Fig. 5c) also shows preferred directions of movement though not quite as clear as with the deterministic variant. So for both the deterministic and the non-deterministic variant, the raster to graph conversion, limiting the number of possible directions of movement, results in visible drawbacks.

Figure 5d explains the fact that the number of visitors after concentric ring normalization decrease towards the border of the circular area considered: All of the 36 agents expend their cost limit before they reach the border of the area, so cells near the border are not visited at all by these agents.

3 Results

3.1 Comparing deterministic paths and a radial network

Figure 6 shows the results of path calculations for Gummersbach generated with a cost limit corresponding to movement of 15km on level and dry terrain. Each path of the radial network consisting of LCPs (see also Fig. 2) covers a larger distance

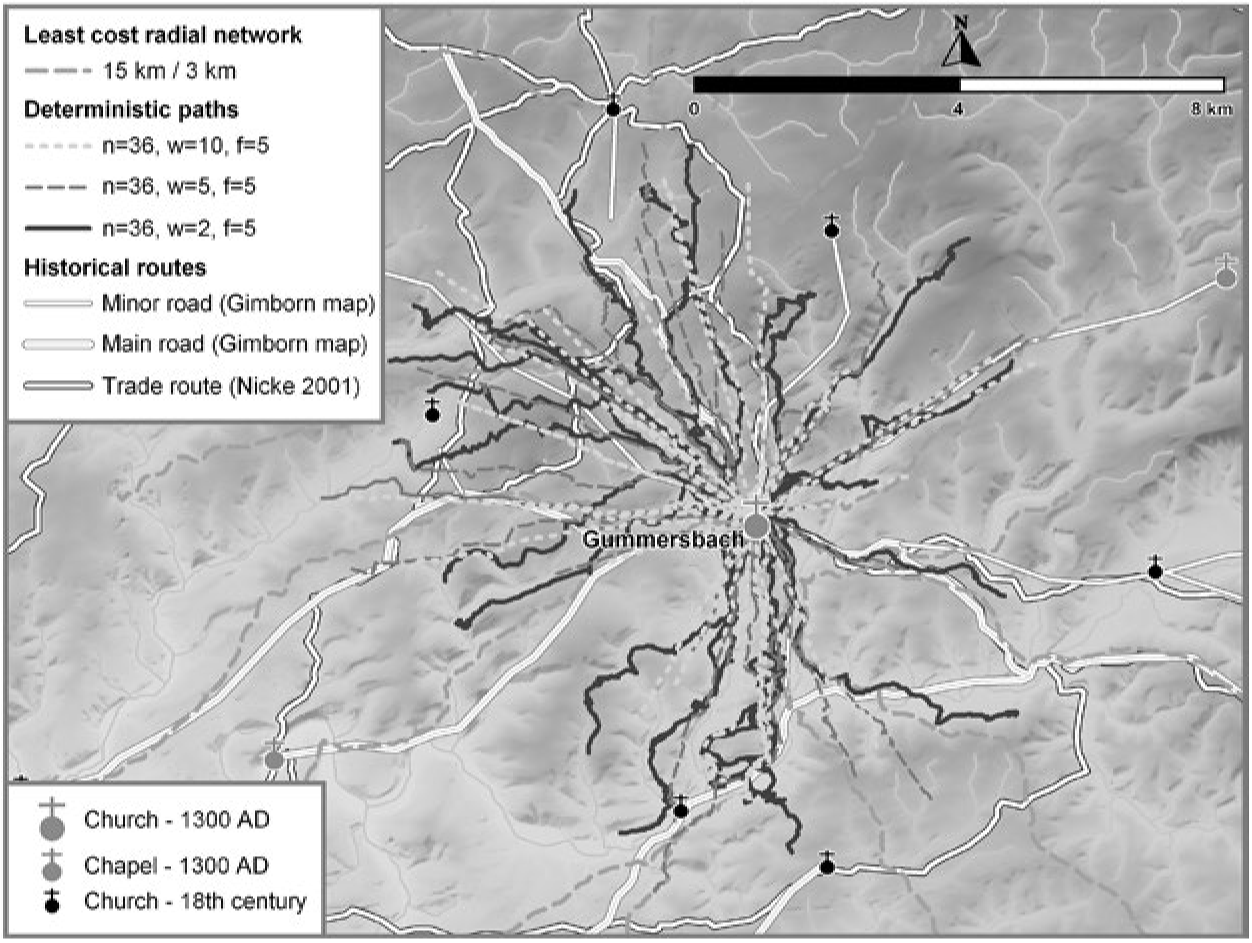

Fig. 6. Results of the agent-based dispersal program spreading from Gummersbach compared to the radial network consisting of LCPs. With a large pull towards the preferred initial direction (w=10), the paths hardly take the terrain into account but move straight in this direction. With a small w value (w=2), the paths take a lot of turns.

from the origin than the agent-based deterministic paths. With a large penalty w for deviating from the preferred direction, the path is very direct, the impact of the terrain costs on the local path direction is low, and the agent expends a lot of costs for obstacles on the way. With a small w value, the deterministic approach wastes costs by taking unnecessary turns.

For the comparison of the radial network consisting of LCPs to deterministic paths the latter paths should cover about the same distance. Therefore a cost limit of 15km is chosen for the radial network and the cost limit is set to 25km for deterministic paths.

3.2 Gummersbach: deterministic and non-deterministic paths

Figure 7 shows the results of agent-based path calculations for Gummersbach generated with a cost limit corresponding to movement of 25km on level and dry terrain. In both runs of the program the overcrowd factor f was set to 3 and the penalty factor w is 3, too.

The non-deterministic approach (Fig. 7 left) generates even shorter paths than the deterministic approach (Fig. 7 right). According to my impression, the non-deterministic corridors are not substantially different from those generated with the deterministic approach. In my view, the corridors resulting from the deterministic approach can be identified more easily and therefore the deterministic variant is preferred for comparison of the agent-based approach with the radial optimal path network.

3.3 Gummersbach, deterministic variant: choosing the parameters f and w

Figure 8 shows the results of deterministic agent-based path calculations for Gummersbach generated with a cost limit corresponding to movement of 25km on level and dry terrain.

Different parameters f and w were chosen. As expected, increasing parameter w reduces the impact of the landscape on the result, i.e. the paths generated with large parameter w are more direct (see also Fig. 6). On the basis of visual inspection of these and additional images, setting w to 3 seemed appropriate.

With f set to 5, the resulting corridors seemed to be rather thin, therefore f=3 is preferred.

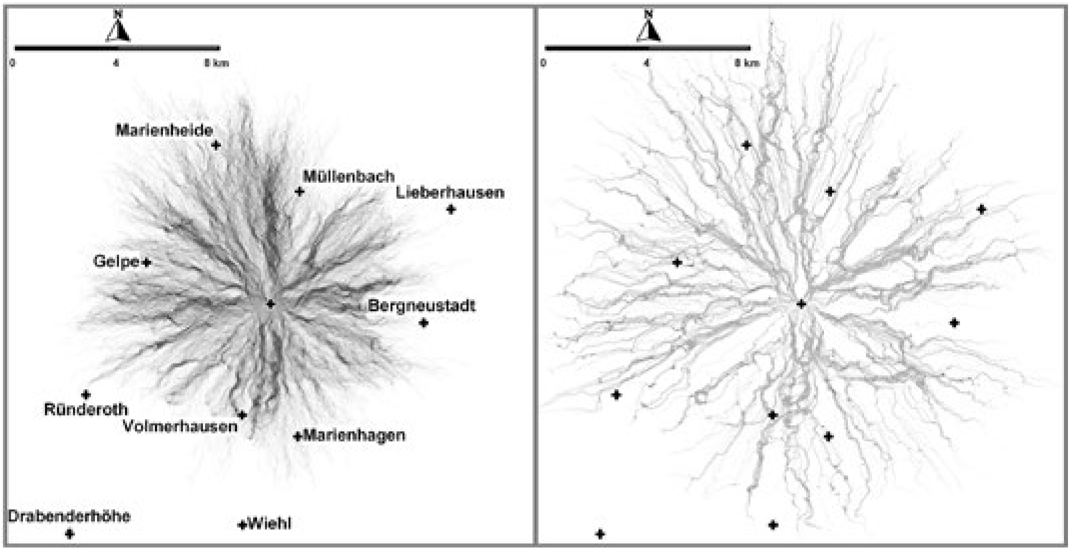

Fig. 7. Comparison of non-deterministic (left) and deterministic (right) results for Gummersbach. Historical church locations also shown in Figure 2 are indicated by cross symbols.

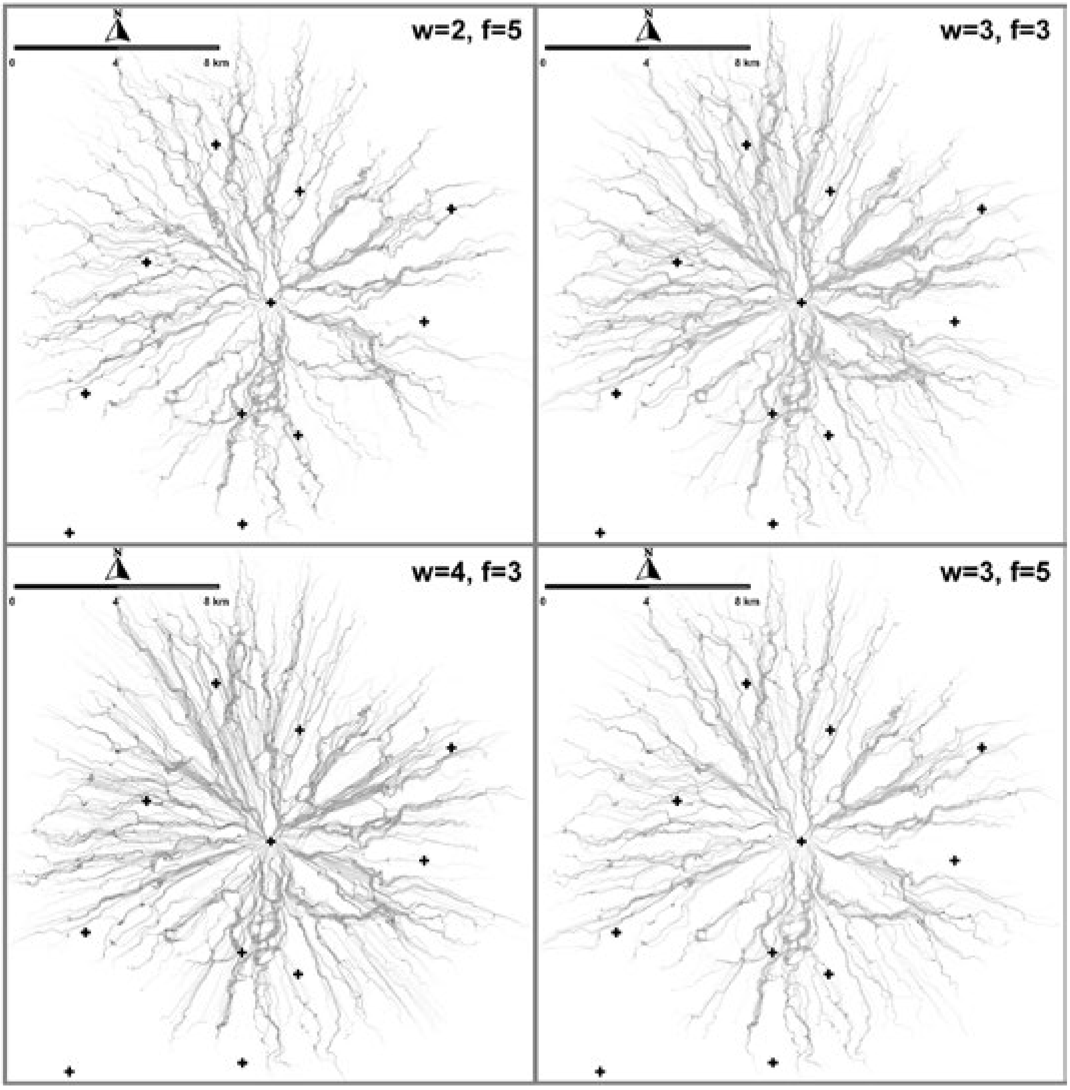

Fig. 8. Comparison of the outcomes of the deterministic variant of the algorithm with different parameters w and f. Cross symbols indicate the historical church locations.

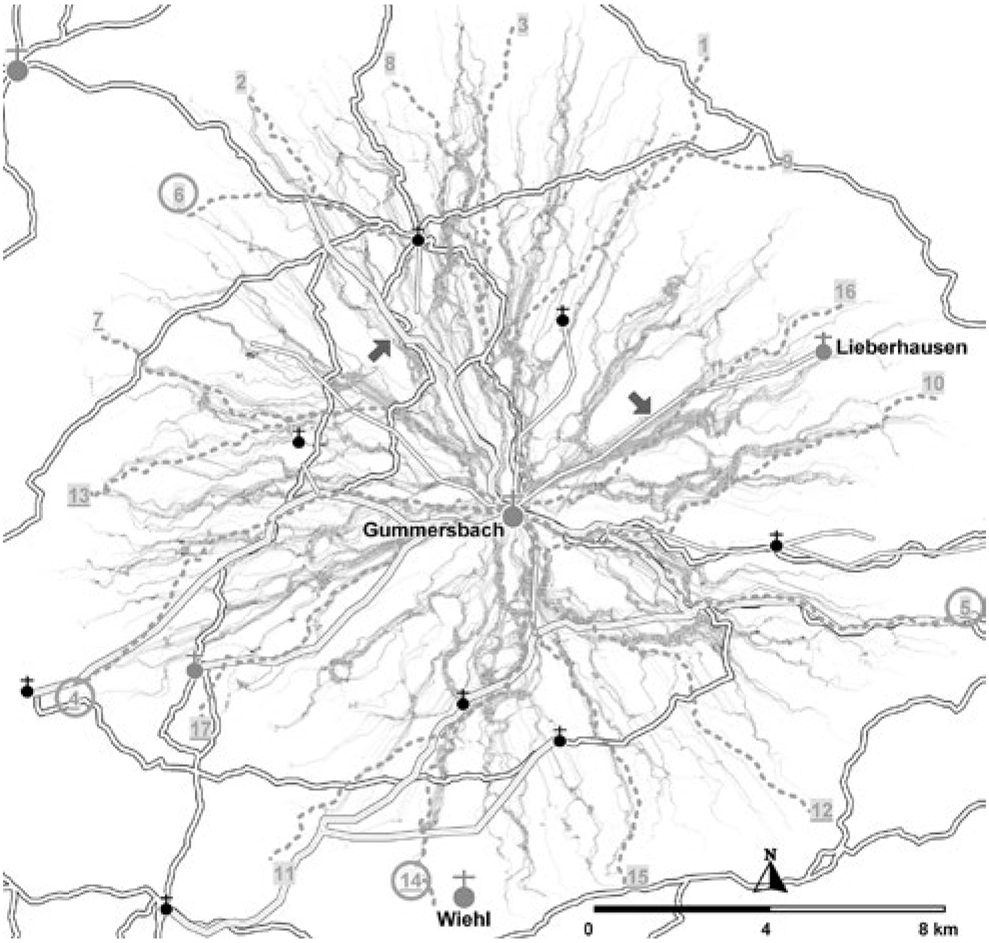

Fig. 9. Comparison of historical routes with least-cost radial network and agent-based spreading (w=3, f=3). The least-cost radial network with parameters 15km / 3km is shown as in Figure 2. Historical routes are shown as in Figure 6. The map also depicts churches and chapels as in Figure 2.

3.4 Gummersbach: comparison of route calculation results to historical routes

Figure 9 shows historical routes, a least-cost radial network and agent-based corridors, with dispersal starting at Gummersbach for the calculated results. Figure 9 allows three comparisons:

1. least-cost radial networks versus corridors calculated using the deterministic agent-based approach
   When a least-cost radial path and a deterministic agent-based corridor coincide for a substantial part of the path, path numbers are underlined. The best fit is with paths 4, 7 and 14 (path number background is yellow). For paths 5, 12, 13, and 17 the fit is not quite as good.

2. least-cost radial networks versus historical routes
   When a least-cost radial path and a historical route coincide for a substantial part of the path, path numbers are marked by a circle. This applies to four paths of the radial network: 4, 5, 6, and 14.

3. corridors calculated using the deterministic agent-based approach versus historical routes
   According to the first and second comparison, three agent-based corridors corresponding to paths 4, 5, and 14 in the radial network coincide for a substantial part with the historical routes. Two additional fairly broad corridors with a good fit to historical routes are marked by grey arrows.

The comparisons are based on visual inspection and are therefore subjective. It is difficult to count the agent-based corridors. For this reason, it does not seem to be fair to compare the number of fits to the historical routes for radial network paths on the one hand and agent-based corridors on the other hand.

The historical route Bergische Eisenstraße from Gummersbach in eastern direction coincides both with a historical route on the Gimborn map, the radial network path 5 and an agent-based corridor. Figure 9 creates the impression that there is hardly any alternative route for cost-saving movement in eastern direction. More cost-effective choices are available for movements towards the northern direction.

4 Conclusion, discussion and future work

4.1 Conclusion

This study proposes an agent-based model for spreading from a user-supplied origin taking the costs of movement into account. The results presented for the study area east of Cologne rely on the assumptions that the Medieval roads preserve patterns of movement of that time and that these patterns can be reconstructed by calculating LCPs; the cost model resulting in LCPs close to the Medieval roads is used to estimate movement costs.

Two variants of the agent-based approach creating local optimal paths were presented – deterministic and non-deterministic. The outcome of these simulations is compared to least-cost radial networks consisting of globally optimal paths.

With a given cost limit, the distances between origin and end location of the calculated paths differ substantially depending on the approach selected: Paths of the radial optimal network cover a larger distance to the end locations than the agent-based paths, and the non-deterministic paths are shorter than the deterministic paths. For the test case of Gummersbach, the radial optimal paths and the agent-based corridors coincide in several cases. Both approaches generate routes close to several segments of historical roads but it is difficult to decide which of the methods produces the best reconstruction.

4.2 Discussion and future work

Allowing movements in 32 directions only results in paths that prefer these directions and this is a substantial drawback (Fig. 5). This issue might be overcome by modifying the set of possible moves for each intermediate location on the path: Instead of selecting one out of 17 predefined angles, at each intermediate location, m possible angles α_i (i=1..m) in the range between –90° and 90° could be chosen at random. Candidate locations for the next step on the path are at a one cell map distance from the current location in direction $\beta+\alpha_i$, with β the preferred direction of the path. The altitude of each candidate location and the isotropic costs could be derived from the respective raster grids by interpolation allowing the estimation of the costs of moving from the current to each candidate location. With this modification, a random component is introduced to the deterministic variant.

The agent-based approach presented in this contribution has also been criticized because the agent's decision on the next move is only based on the neighbouring cells in the grid, so the length of the possible moves vary between c and about 3.6*c, with c the cell size (Fig. 3). With c=25 m in the Gummersbach test case, the agent's perceptive range is very short and not realistic. The perceptive range may be adjusted by deriving the movement costs from an accessibility map based on kernels with a limited range (Herzog 2013d).

Comparing the radial optimal and the historical routes on the one hand with the agent-based corridors on the other hand, it seems necessary to introduce a change in the main direction of a path. This could be a gradual change or a turn. Depending on scale a turn could also be considered as a gradual change, and small scale turns are created in the agent-based approach presented here anyway. So the issue of turns is quite complex. Changes in path direction of animals searching for food are often modelled by Lévy-walks or alternatively by composite correlated random walks (Plank, Auger-Méthé and Codling 2013; Reynolds 2013). These paths consist of straight line segments in random directions, and there are many short and a few long segments. Such paths could model the search for an adequate place for building a farm house: First an empty patch has to be found suitable for agriculture. So the agent has to cover some distance to get away from her home location to reach an adequate patch. Once a location is found that seems suitable, the agent starts searching the surroundings and checks if the patch really fulfils the expectations; if so, the agent selects a place for building the farm house. If the patch does not meet the first impression, the agent moves on covering again a large distance in some direction until another patch candidate is reached. Such an agent based model could be generated with the building blocks outlined above but is hard to validate.

Bibliography

Anderson, D. G. and Gillam, J. C. 2000. Paleoindian Colonization of the Americas. Implications from an Examination of Physiography, Demography, and Artifact Distribution. *American Antiquity*. 65: 43-66.

Conolly, J. and Lake, M. 2006. *Geographical Information Systems in Archaeology*. Cambridge, Cambridge University Press.

L'Ecuyer 1988. Efficient and portable combined random number generators. *ACM communications*. 31: 742-9.

Fábrega Álvarez, P. and Parcero Oubiña, C. 2007. Proposals for an archaeological analysis of pathways and movement. *Archeologia e Calcolatori* 18: 121-40.

Field, J. S., Petraglia, M. D. and Lahr, M. M. 2007. The southern dispersal hypothesis and the South Asian archaeological record: Examination of dispersal routes through GIS analysis. *Journal of Anthropological Archaeology* 26: 88-108.

Gilbert, N. 2008. *Agent-based models*. *Quantitative Applications in the Social Sciences*. Los Angeles, Sage.

Herzog, I. 2013a. Theory and Practice of Cost Functions. In F. J. Melero, P. Cano, J. Revelles (eds.), *Fusion of Cultures. Proceeding of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. British Archaeological Reports International Series 2494: 375-82.

Herzog, I. 2013b. The Potential and Limits of Optimal Path Analysis. In A. Bevan, M. Lake (eds.), *Computational Approaches to Archaeological Spaces*: 179-211. Walnut Creek, Left Coast Press.

Herzog, I. 2013c. Least-cost networks. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 240-51. Amsterdam, Amsterdam University Press.

Herzog, I. 2013d. Calculating accessibility. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*, [Online] Volume II. Amsterdam, Amsterdam University

Press: 720-34. Available from: http://dare.uva.nl/cgi/arno/show.cgi?fid=545855 [Accessed: 29 June 2015].

Kantner, J. 2012. Realism, Reality, and Routes. In D. A. White, S. Surface-Evans (eds.), *Least Cost Analysis of Social Landscapes. Archaeological Case Studies*: 225-38. Salt Lake City, The University of Utah Press.

Landschaftsverband Westfalen Lippe and Landschaftsverband Rheinland 2007. *Erhaltende Kulturlandschaftsentwicklung in Nordrhein-Westfalen*. Münster, Köln (detailed version on CD).

Nehls, A. 1996. *Als in den Tälern die Hämmer dröhnten*. Wiehl, Gronenberg.

Nicke, H. 2001. *Vergessene Wege. Das historische Fernwegenetz zwischen Rhein, Weser, Hellweg und Westerwald, seine Schutzanlagen und Knotenpunkte*. Nümbrecht, Martina Galunder-Verlag.

Oediger, F. W. 1967. *Der Liber Valoris*. *Die Erzdiözese Köln um 1300. Erstes Heft. Publikationen der Gesellschaft für Rheinische Geschichtskunde*. Bonn, Peter Hanstein.

Plank, M. J., Auger-Méthé, M. and Codling, E. A. 2013. Lévy or Not? Analysing Positional Data From Animal Movement Paths. In Lewis, M.A., Maini, K., and Petrovskii, S. V. (eds.), *Dispersal, Individual Movement and Spatial Ecology. A Mathematical Perspective.* Lecture Notes in Mathematics 2071: 33-52. Berlin, Heidelberg, Springer.

Pampus, K. 1998. *Urkundliche Erstnennungen oberbergischer Orte*. *Beiträge zur Oberbergischen Geschichte. Sonderband*. Gummersbach, Bergischer Geschichtsverein.

Reynolds, A. 2013. Beyond Optimal Searching: Recent Developments in the Modelling of Animal Patterns as Lévy Walks. In Lewis, M.A., Maini, K., and Petrovskii, S. V. (eds.), *Dispersal, Individual Movement and Spatial Ecology. A Mathematical Perspective.* Lecture Notes in Mathematics 2071: 53-76. Berlin, Heidelberg, Springer.

Reynolds, R. G., Whallon, R., Ali, M. Z. and Zadegan, B. M. 2010. Agent-Based Modeling of Early Cultural Evolution. In: A. Costopoulos and M. Lake (eds.), *Simulating change. Archaeology into the twenty-first century*: 38-52. Salt Lake City, The University of Utah Press.

Scherjon, F. 2013. SteppingIn – Modern Humans Moving into Europe – Implementation. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 105-17. Amsterdam, Amsterdam University Press.

Visibility Analysis and the Definition of the Ilergetian Territory: the Case of Montderes

Núria Otero Herraiz
notero@icac.cat
Catalan Institute of Classical Archaeology

Abstract: This paper revolves around the application of GIS-based viewshed, intervisibility and spatial analysis methods to the Ibero-Roman site of Montderes (Aragón, Spain) located on the northern border of the Ilergetian political space. This work has as its aim a better comprehension of the site's role with respect to the Ilergetian settlement networks and the main communication axes of the area during the Late Iberian Period and the early Roman occupation.

Keywords: Visibility, Iberian Peninsula, Iron Age, GIS, Ilergetian Culture

Introduction

The Ibero-Roman site of Montderes (Castillonroy, Aragón, Spain) is located in the Pyrenees foothills on the northern limit of the Ebro depression (Fig. 1 and 2). The archaeological remains stand at the top of an elevation that is 630 masl at the exit of the St. Anna Gorge; at its feet runs the Noguera Ribagorçana, a tributary of the Ebro River. The gorge is blocked by a dam built during the late 1950s and the early 1960s (Figs. 3 and 4). Downstream the Noguera Ribagorçana joins the Segre, one of the main Ebro River tributaries, at 100 masl.

The flatlands that spread out between the northern shore of the Ebro River and the Pyrenees mountain range were, during the Iron Age, the political space of the Ilergetians, one of the most powerful peoples of the north-eastern Iberian Peninsula. The Ilergetians appeared in the written chronicles during the 2nd Punic War (218-201 BC) where they played an active role. Firstly allied with the Carthaginians, they were later defeated by the Romans after the Ilergetian riot of 205 BC, becoming after that episode one of Rome's most loyal allies.

The Ilergetian cultural influence reaches over more than 9500km^2 over the plains of western Catalonia and the eastern Aragón, although the area is divided by a river terrace which separates the Cinca and the Segre rivers watersheds. Montderes has a privileged location in the northern border of this area. During the late Iberian Period (205-50 BC) a demographic explosion in the area is observed. In this respect, Sanmartí (2010: 91–108) proposes a demographic density close to 14.3 h/km^2, which is similar to the demographic data given by the 16th century written sources. In this sense, in the whole Ilergetian territory more than 150 Iberian settlements can be identified, and there are 28 settlements of this period within the 30km radius around Montderes that we have set as our analysis area (Fig. 5). We should note that the Ilergetians showed at the time an hierarchical society with developed state structures, headed by a dual monarchy and an expansionist policy towards the west (*ab urb cond* 28, 25).

Montderes is one day away from *Iltirta*, the *caput* Ilergetian city; however, its existence is known only through coins and written sources. It is accepted that it was re-founded during the 2nd century BC becoming *Ilerda.* In this sense *Iltirta / Ilerda* and the Ilergetians are mentioned by roman chroniclers such as Livy (*Ab urb cond* 21, 61 and 28, 31, 51), Pliny the Elder (*Naturalis Historia III*, 4: 18-24), Polibius (*Hist* 10, 35, 6) and Julius Caesar (*De bello civile* I: 37-87). Its environs (Fig. 6) had been inhabited since prehistoric times, as proved by the presence of prehistoric rock paintings and Bronze Age dated cave occupations first studied by Maya (1991) and more recently by Montes and Utrilla (2006). In addition, the finding of a bronze deposit (Gallart 1991) shows the relevance of the Noguera Ribagorçana valley as a corridor connecting with the Garonne and the Atlantic façade, and this area with the Iberian Peninsula interior during the late Bronze Age through the fluvial network.

The strategic placement of the Montderes foothills makes it an optimal candidate for the application of visibility analysis in order to exploit the potential of the GIS in understanding visual relationships in the Ilergetian ethnic space between the 3rd and the 1st centuries BC. This site has not been the subject of archaeological excavations, but archaeological surveys had detected demolished walls and rock carved structures, as well as burial structures.

The pottery recovered includes Iberian, Campanian black-varnished productions, common Roman ware and *terra sigillata*. There is also evidence of metallic findings such as an iron knife, Iberian coins of the Ilergetian cities of *Iltirta* and *Bolskan,* Roman Republican and Imperial era coins. However, the site has suffered from intense illegal activity and most of these materials are in private collections or missing. The site on the hilltop was traditionally considered an Iberian settlement (González 1986); however, recent archaeological research at similar locations suggests the possibility of Montderes being a Roman fort, at least during the last phases.

1 Methodology

We will use viewshed and intervisibility tools provided by ArcGis 10.1 in order to achieve a better comprehension of the role of Montderes and its relationship with the other sites of the Iberian settlement network during the Late Iberian period and the early Roman occupation (3rd to 1st centuries BC). The lack of archaeological excavations at Ilergetian sites means that in general GIS environments are crucial to understand not only the role of a single site but the organisation of the region as a whole.

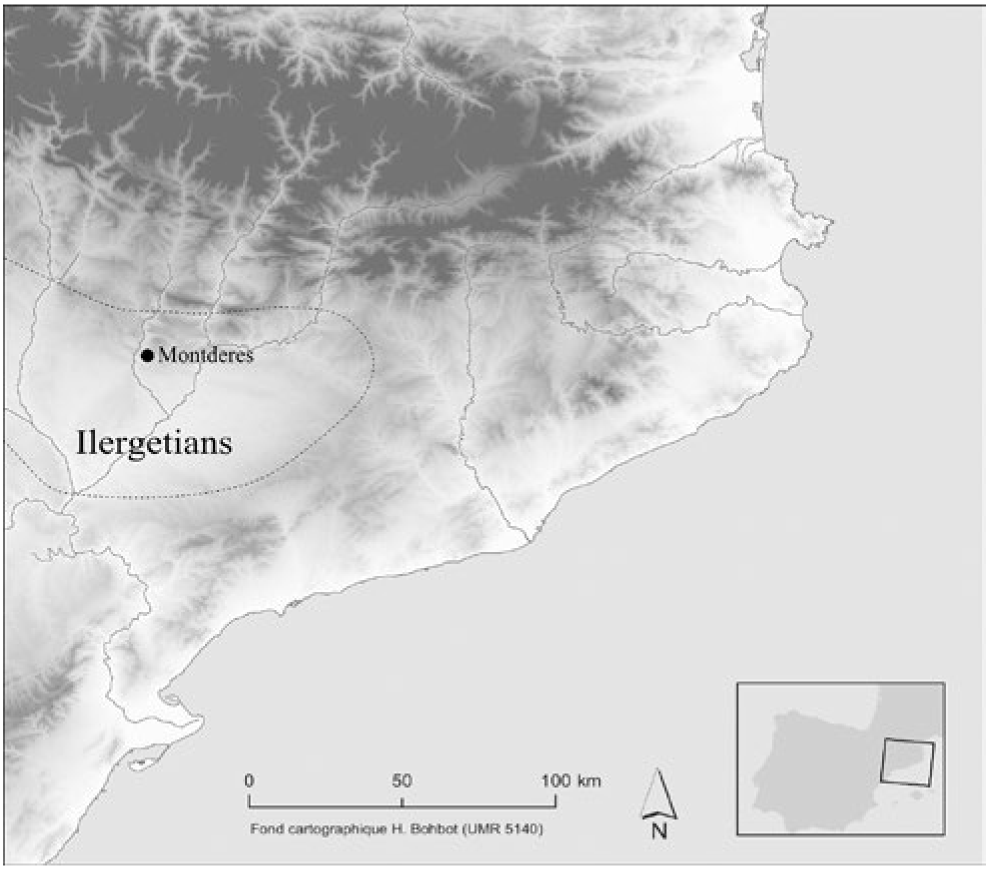

Fig. 1. Location of Montderes in the northeast of the Iberian Peninsula. Source: Fond Cartographique H. Bobot (UMR 5140).

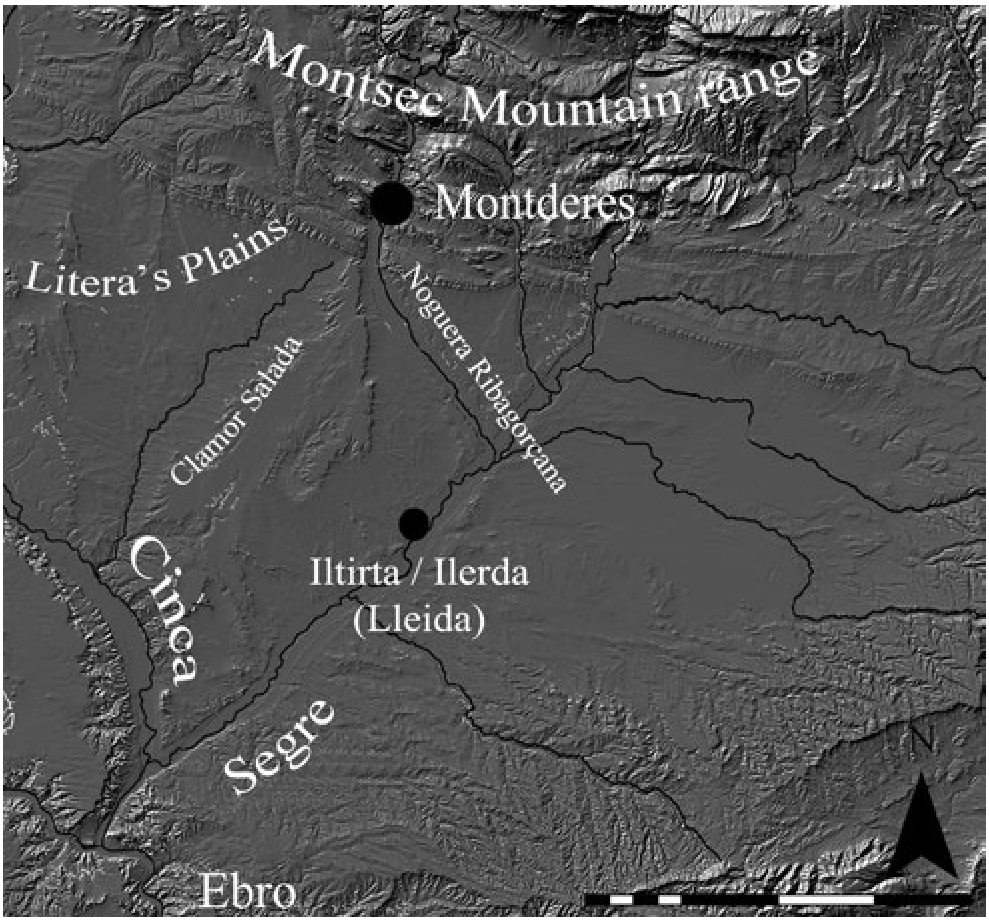

Fig. 2. Montderes in the geographical context of the Ebro Depression.

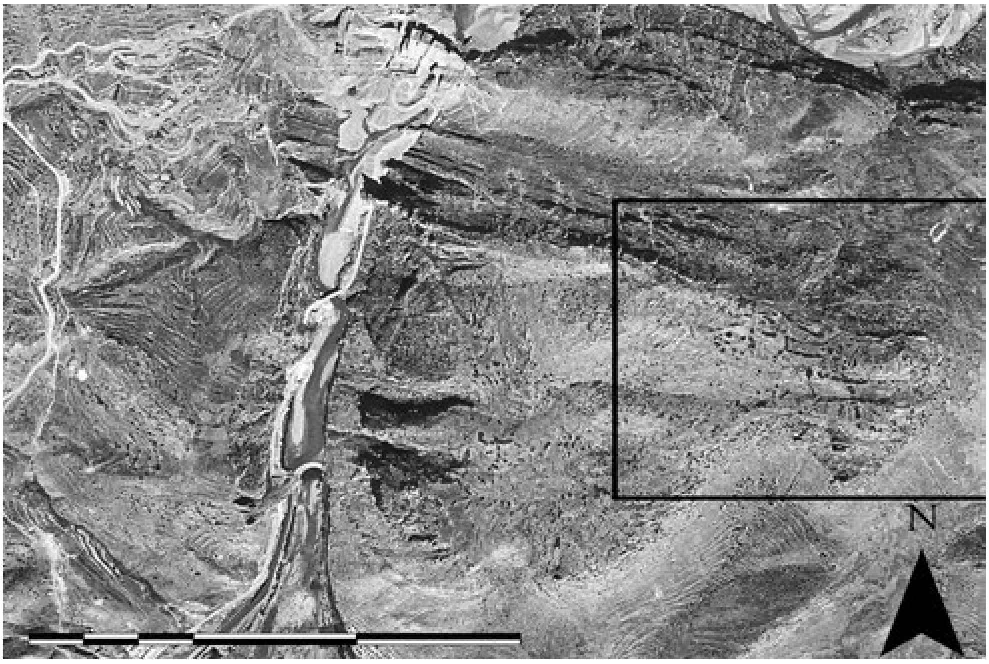

Fig. 3. View of Montderes from the 1956-1957 USS Army aerial photograph.

Fig. 4. View of Montderes from the north.

We my focus on the concept of archaeological visibility, which, in the words of Weathley and Gillings, is defined as 'the past cognitive/perceptual act that serves not only to inform structure and organise the location and form of cultural features, but also to choreograph practice around them. In this sense the visual relations are determined by pre-existing or contemporary cultural elements or natural features, astronomic phenomena or both' (Weathley and Gillings 2000: 3). They also propose the 'will of visibility' concept with the aim of highlighting the concern of antique cultures such as the Ilergetian or the Roman ones for the visual control of their influential areas.

To explore this subject we have obtained the viewshed of Montderes setting a 30km *radius* as a limit of our study area, a distance that will take a Republican army at least one day to cross (Zamora 2006: 49), and 3m above the ground as OFFSET value, simulating the height of an Ibero-Roman watchtower. Performing the cumulative viewshed calculation on our DEM

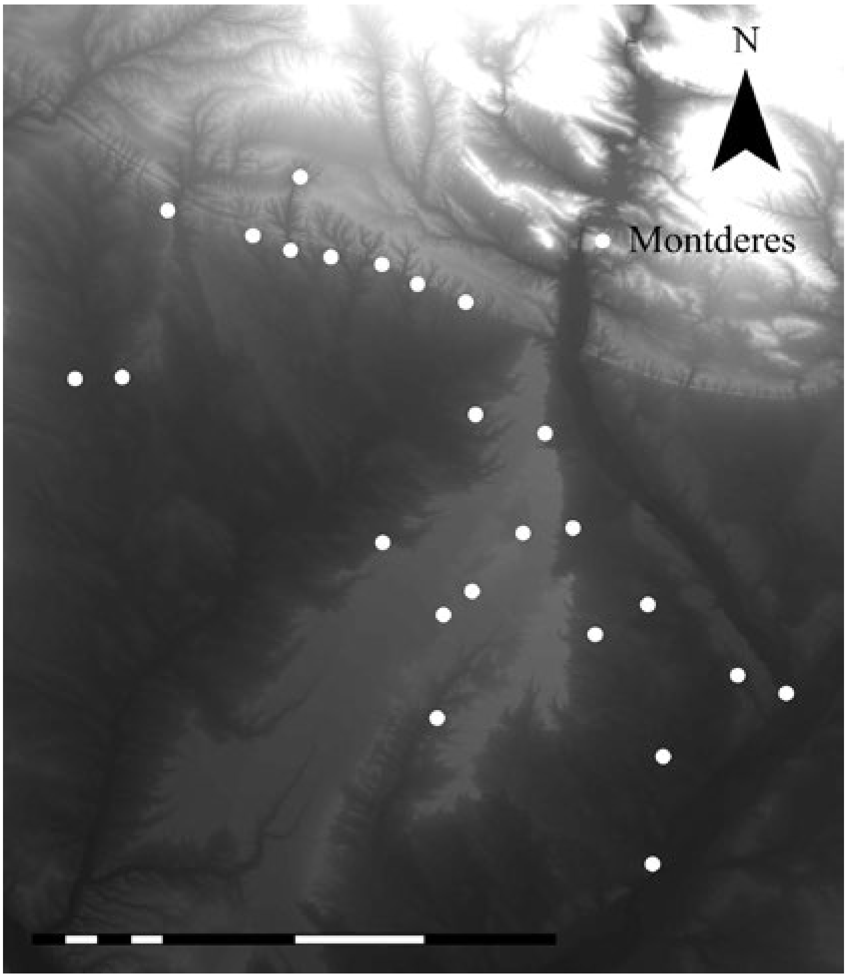

Fig. 5. Late Iberian settlements within a 30km *radius* of Montderes.

Fig. 6. The Santa Ana Strait gap, also known as 'el Pas de la Sabineta', where rock paintings and Bronze Age cave occupations have been documented.

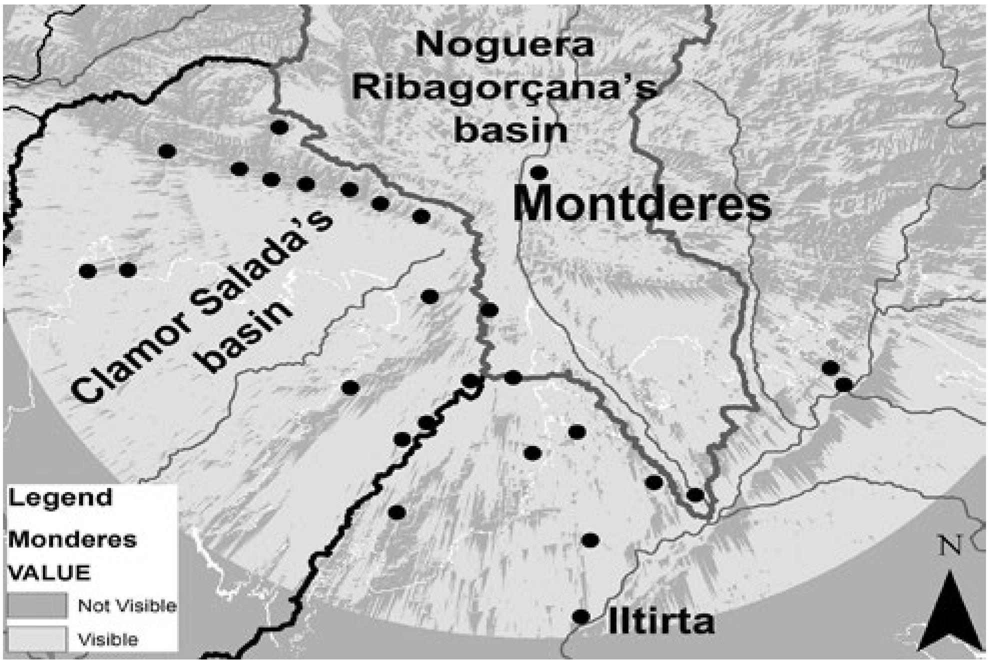

Fig. 7. Montderes viewshed over the Clamor Salada basin and the Noguera Ribagorçana-Segre system, simulating an Ibero-Roman watchower.

is necessary to identify the areas that receive a higher visual impact (García and Weathley 2009). Regarding 'intervisibility', the 'observer points' function tells us how many times each settlement can be seen by its surrounding sites.

In order to acquire a better comprehension of the visual phenomena in the area we have also used the 'line of sight' application which performs the calculation of the intervisibility between the two vertexes of a straight line. This function also shows the areas where the vision is obstructed and will allow us to detect positive or negative visual interactions among specific sites. We have performed the LOS analysis over a TIN because of its more exact accuracy for representing the morphology of geographic features (Weathley and Gillings 2000: 9-10). The earth curvature correction provided by this software has been used.

Visibility analysis was carried out in combination with the relative height analysis. The calculation was made using the Parcero and Fabrega formula (2006: 77-78):

RH= SH – Av H

Std. Dev

The relative height (RH) is equal to the site height (SH) minus the average height (AvH) of the area divided among the standard deviation. This measures the trend of the settlement height, and the prominence of a specific feature with respect to its surroundings. If the resulting value is 0, the site is average; if it is negative, the site is below average; finally, if it is positive, it shows that the spot has a significant prominence. Other data, i.e. 'Nearest Neighbour Analysis' (NNA), 'Euclidean Distances' measurement, watershed and 'Density Kernel Analysis' (DKA) will help us in our goal to achieve a better knowledge of the role of Montderes in terms of the territorial organisation of this area during the transition between the end of the Iberian era and the Roman Republic. The cartography sources are the following: Instituto Geográfico Nacional MDT25 raster, Plan Nacional de Ortofotografía Aérea, US Army Photographic flight 1956-1957 B Series.

2 Analysis

The Ilergetian settlement pattern goes back to the late Bronze Age (1200-750 BC), and is characterized by small-sized agricultural settlements set on hilltops, adapting its configuration to the terrain morphology, often with community structures such as water tanks or walls, and built of durable materials. The location of the sites is determined by the proximity to water supplies and the visual control of the best agricultural areas. This model, composed of very basic features, evolved during the Iron Age and the Iberian Period, reaching high levels of architectural complexity. The fortress of Els Vilars (Arbeca, Catalonia, Spain) is the paradigm of the Ilergetian ethnogenethic process, with roots in the aforementioned previous phase (Junyent and Poch 2012).

The Montderes viewshed was obtained by setting an observer 3m above the ground, simulating an Ibero-Roman watch tower (Fig. 7). The result shows that this site has visual control of the most of the area; however, the Montpedró Mountain partially obstructs the visibility of Montderes towards the west and only 43% of the sites are set on areas viewed from our observation point. We can also notice that most of its viewshed covers the plains and the river causeways, which are the most important communication corridors.

The proximity to water supplies determines to a large degree the Ilergetian settlement pattern. In our study radius we have two watersheds to analyse: on the eastern side, the Noguera Ribagorçana-Segre system, and the Clamor Salada basin on the

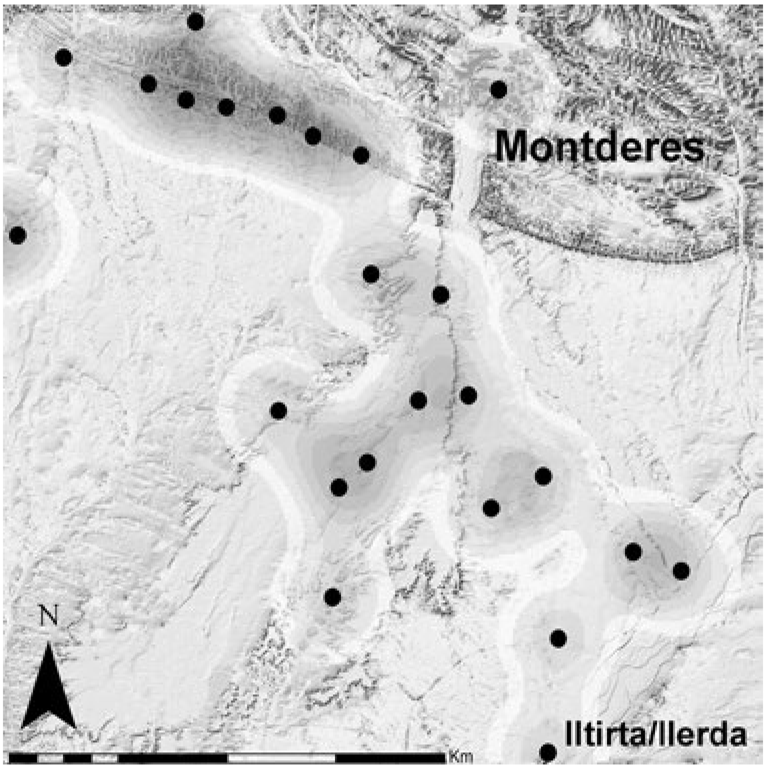

Fig. 8. The Density Kernel Analysis allows two population clusters related to each watershed to be distinguished, while Montderes appears to be disconnected from them.

western side. On the Segre watershed the average distance to the main water course is around 4.62km and the distance to the watershed limit is around 8.24km. On the Clamor Salada basin the mean distance to the main water course is around 9.7km. This indicates that most of the sites are not linked to it but obtained their water supplies from minor springs flowing from the anticline. In this case human occupation avoided the endorreic areas near the lower section of the Clamor Salada where swamps occasionally formed, thus in this sector the settlements appear to be located mostly near to the watershed limit, developing an alignment with visual control of the agricultural plains and avoiding the areas of standing water.

While Montderes' nearest neighbours are 7 and 9km away respectively, the NNA reveals a dispersed settlement pattern for the rest of the sites in the area, with an average distance of 2.6km between sites and a 1.2 *ratio*. The 28 Iberian settlements are divided into two population clusters; their distribution is highly related to the watershed limits and the distance to water courses. However, we can distinguish two groups: one focused around the control of the Segre River and the Noguera Ribagorçana causeways, the other cluster – as pointed out earlier – is formed by an alignment of settlements which follows the slopes of the Barbastro-Balaguer anticline. The Density Kernel Analysis also suggests the idea of these two population clusters while Montderes seems to have remained disconnected from the whole network (Fig. 8).

The location of Montderes does not fit the usual Ilergetian settlement pattern. While most of the sites in the area are found on low hills, the prominence of Montderes is proven by the fact that its height (630 masl) doubles the average height of the area which is 334 masl (Fig. 9). The viewshed analysis shows that Montderes has the widest visual range controlling the northern countryside of *Iltirta* and partially the flatlands of La Litera. The application of the 'observer points' function reveals the most visible areas, which coincide with the ones identified in the Montderes viewshed. Regarding the visual relations, and despite Montderes being the most prominent site with the widest visual range, it is only seen by two observers (Fig. 10).

The application of the 'line of sight' tool revealed Montderes to have six positive visual interactions with other sites: most of them located over the river terrace separating Segre and Cinca basins and on its eastern edge. However this test reveals that there is no direct visual connection with *Iltirta* / *Ilerda* (Fig.11). The altimetry profile of the LOS shows a 400m drop in the 30km between the two locations (Fig. 12). We must point out that *Iltirta/Ilerda'*s highest spot is 235 masl and we simulated a 4m watchtower over this, which is far below the average of the DEM set on 334 masl.

The observer points analysis returns important values of reciprocity among the sites of the anticline, and those of the Noguera Ribagorçana and Segre river system respectively – they seem to work as separate entities as far as the visual aspect is concerned. The cumulative viewshed shows that the areas of our DEM with the highest visual impact are those corresponding to the Noguera Ribagorçana-Segre system and the course of the *via de Italia in Hispania* of the Antonine Itinerary (Fig. 13 and 14).

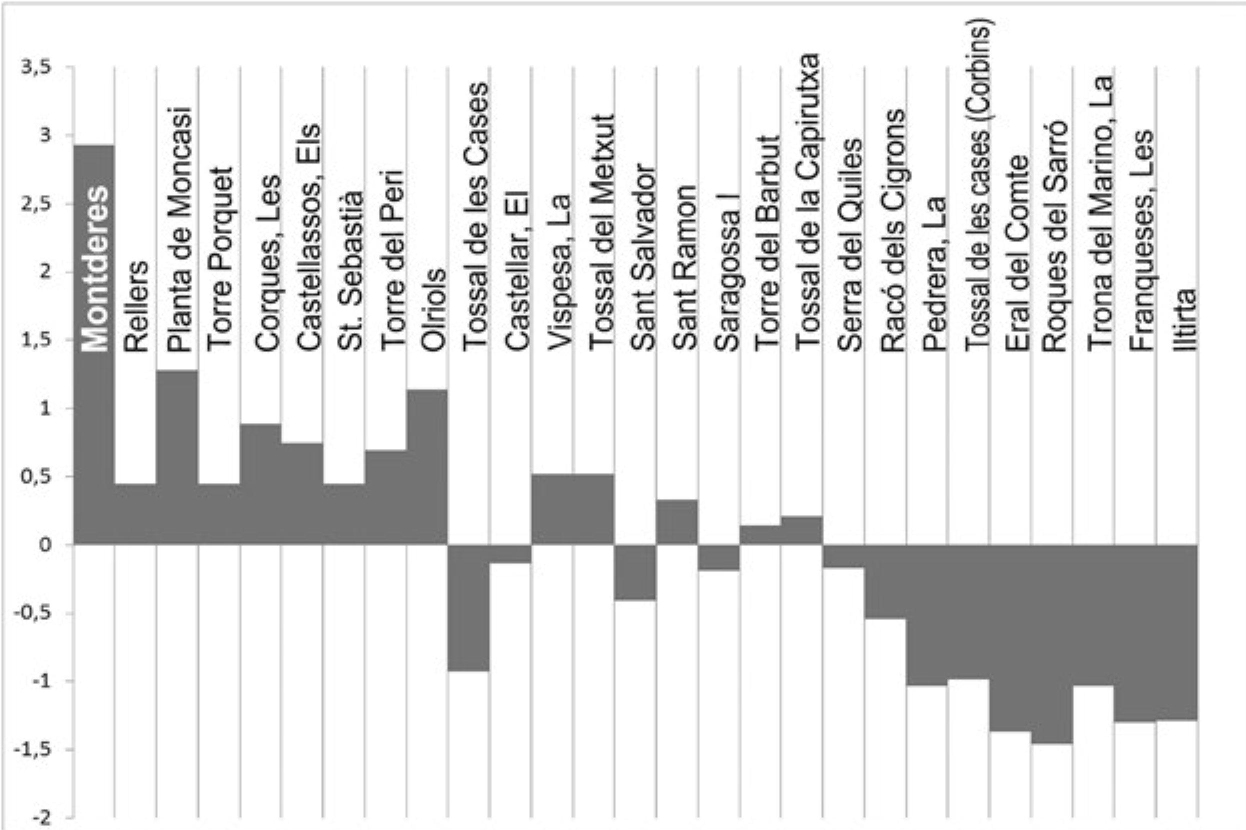

FIG. 9. RESULTS OF THE RELATIVE HEIGHT ANALYSIS.

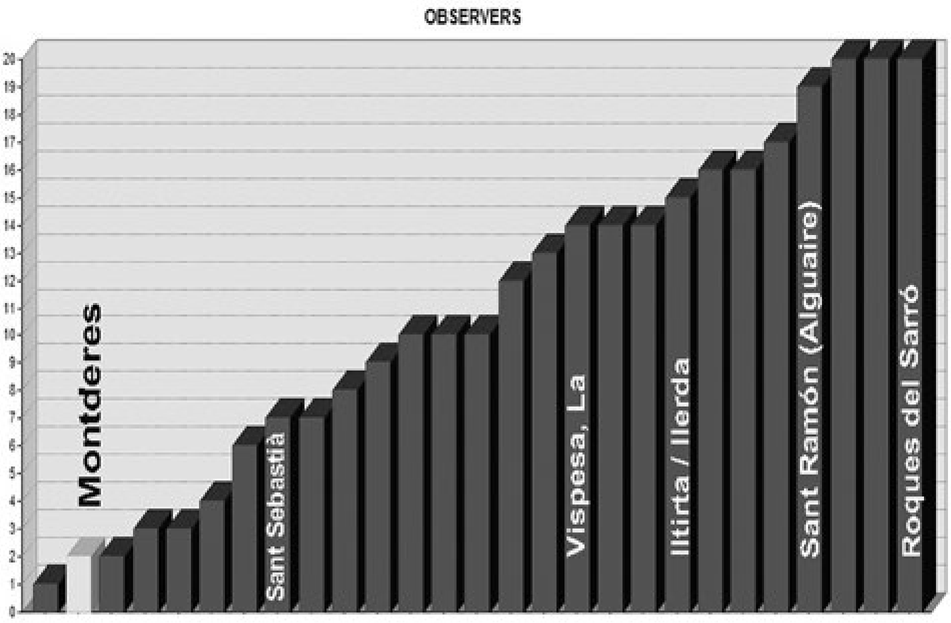

FIG. 10. CHART SHOWING THE NUMBER OF OBSERVERS PER SITE.

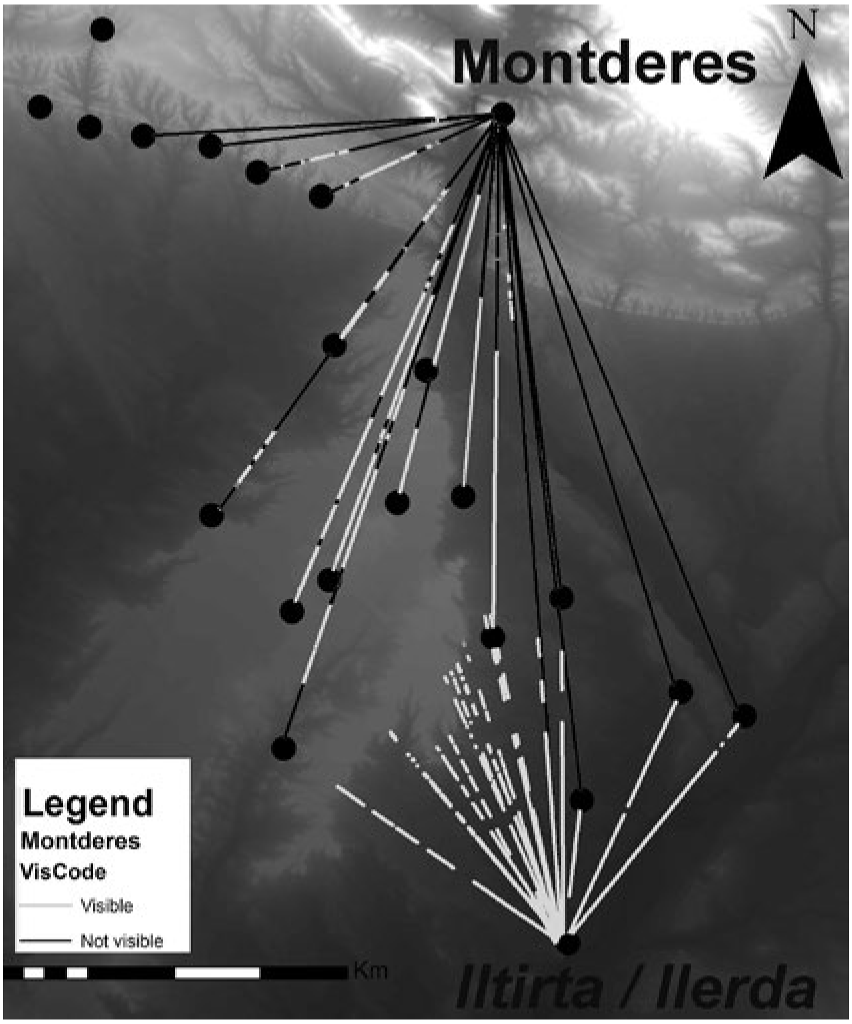

Fig. 11. Graphic displaying the line of sight application to show the visual interaction between Montderes and *Iltirta/Ilerda.*

Fig. 12. Althimetric profile of the Montderes – *Iltirta /Ilerda* line of sight, provided by the Cartographic and Catalan Geological Institute.

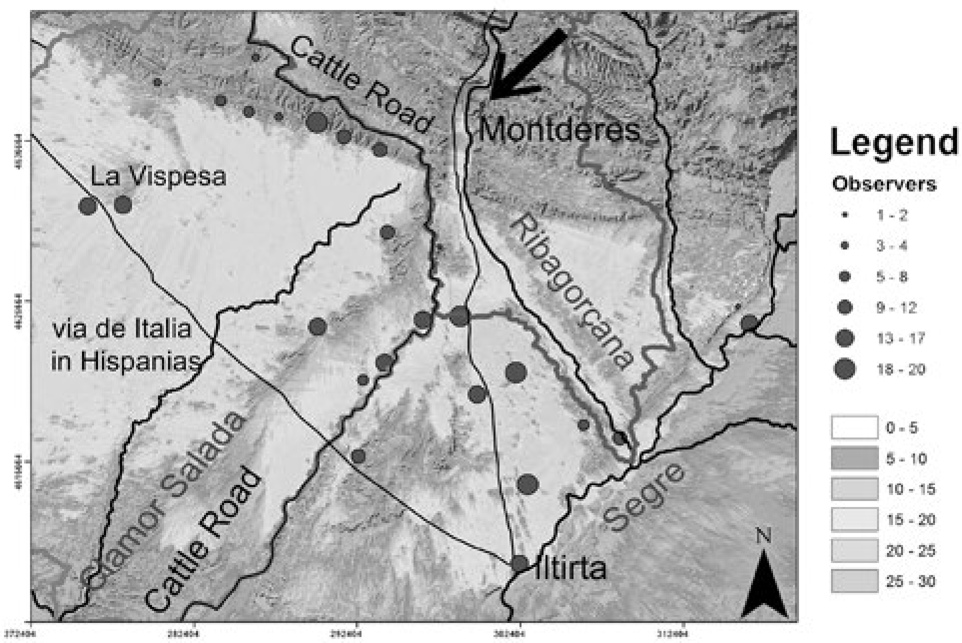

Fig. 13. Graphic displaying the number of observers per site and the areas with a higher visual impact related to the main communication axes.

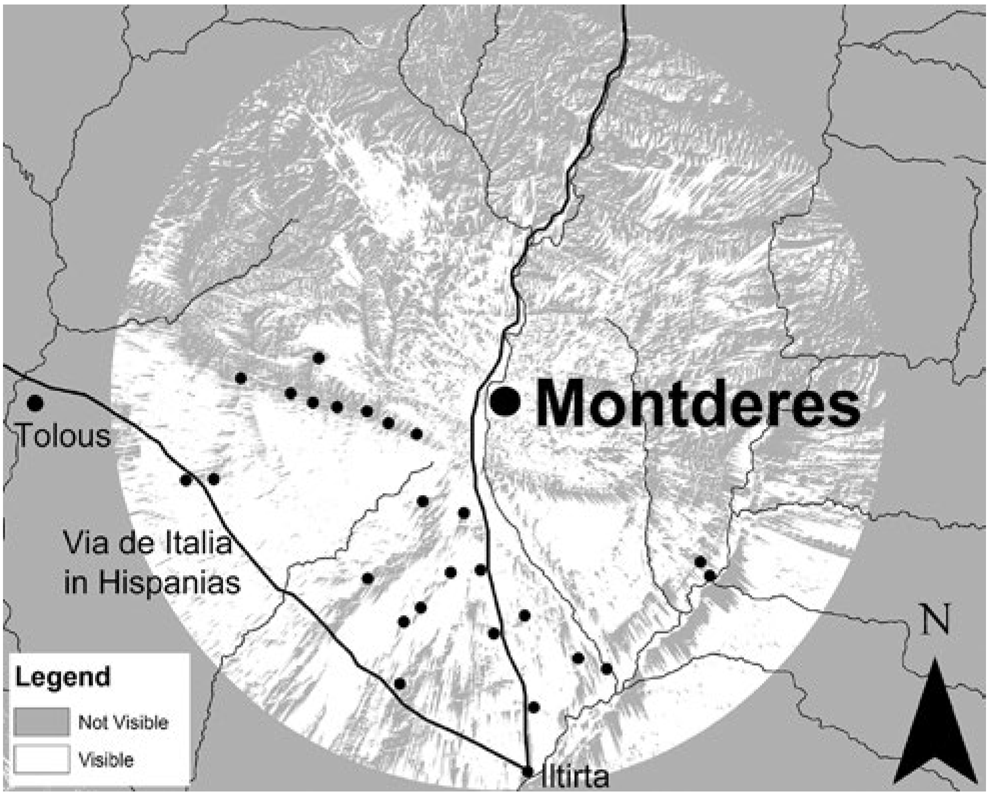

Fig. 14. Montderes' direct control of the most important communication axes: the *via de Italia in Hispanias* from the *Antonine itinerary*, and the N-S route connecting the Pyrenees to the Ebro Valley.

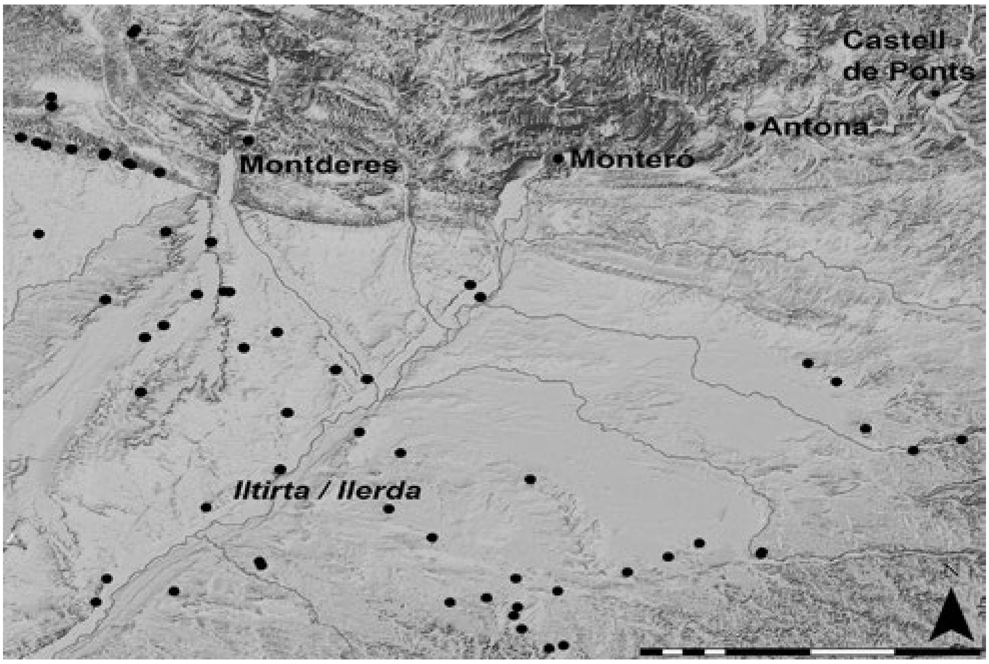

Fig. 15. Montderes on the northern border of the Ilergetian territory, as proposed by Gonzàlez (1986).

We should signal the relevance of Montderes on two levels: at the local scale, Montderes controls the northern countryside of *Iltirta* and part of the plains in the Litera region. It has visual dominance over two watersheds and of the cattle road which runs, following the limit between them, towards the Pyrenees, the gentle slope of this route avoiding the straits and the periodic flooding of the Noguera Ribagorçana and favouring the movement of people and goods. At the regional scale, Montderes is located on the intersection of the main communication axes in the area: the Noguera Ribagorçana valley route towards the Pyrenees, the N-S route towards *Iltirta*, which connects with the Ebro valley, and last but not least the main route of the Antonine Itinerary: *Via de Italia in Hispanias* which connected the Ilergetian cities of *Iltirta* and *Bolskan* with the Mediterranean coast (Fig.14).

Montderes shares a topographic resemblance with a group of sites such as Monteró, a Roman Republic Era *castellum* (Camañes and Moncunill 2010), Antona (Ros and Solanes 2002) and Castell de Ponts. These sites are also spotted on the northern border of the Ebro depression and they take advantage of the prominence of this natural barrier. Gonzàlez (1986) proposed this alignment to be a northern Ilergetian border (Fig. 15). This territorial occupation strategy coincides with both the chain, based on a series of fortified watchtowers, and the frontier type proposed by Ruiz and Molinos (2008). Grau, however, suggests that the aforementioned can also have a symbolic dimension, warning the community about the appropriation of territory (Grau 2012), in this case by the Roman military.

The valuable strategic positioning of these enclaves motivated in some cases their reoccupation and prolonging their life in some cases until the Middle Ages, when the Montsec acted again as the frontier of the upper border of Al-Andalus (*at-tagr-al-'alà*). The subsequent Christian repopulation of the area materialised on the village of Piñana and its castle (both 500m west of the Montderes), as well as a series of mediaeval watchtowers, which guarded the entrance of the strait. However this route and the whole valley entered into decline with the construction of the dam in the 1960s. The submersion of this area caused the loss of a number of important archaeological sites in the valley and changed the routes of ancient paths that were in use since prehistoric times.

3 Conclusions

The location of Montderes is determined by its height, defensive potential, and control of the local and regional communication axes and the extent of its visual scope. These factors suggest the idea of a location being chosen for its surveillance possibilities; in this regard, it is an optimal spot for establishing a watchtower.

The Iberian settlement network displays mainly a rural-agricultural based model characterized by settlements from 0.5 to 1 ha on prominent hilltops in control of water supplies and the best agricultural spaces. We can conclude, for the aforementioned, that the location of Montderes does not fit the agricultural criteria, but, as we have suggested, to military and strategic criteria.

In this sense, we may think of Montderes as an advanced outpost located in a prominent position in order to control the maximum territorial advantage and the main communication axes, more than to have reciprocal visual communication with the rest of the sites. At this point we must remember that Montderes stands at the crossroads of the land routes towards the northwest, the Ebro valley and the Iberian Peninsula interior.

In view of the foregoing we consider Montderes as a crucial location to control the territory of one of the most powerful Iberian populations. Its sight is mainly focused on the Noguera Ribagorçana valley and the northern countryside of *Iltirta*, one of the main cities of the Ilergetian people, which is a day away from this spot for a Republican army. It is important to highlight Montderes' direct view of the cattle road which runs towards the north, following the watershed's limit. In this sense Montderes, located on the northern border of the ancient Ilergetian territory, acts as an intermediate link between the eastern and western side of this political region.

In this matter Montderes may be viewed as part of a frontier defined by a series of Roman-Republican enclaves located on the Ilergetian borders, acting as a reminder of their presence in the territory. They took advantage of the sudden drop which the Montsec range offers over the plains, so we may understand stand that the 'will of visibility' was a basic concern at first for the Ilergetians, and then for the Republican armies during the Roman conquest.

To summarize, the relevance of Montderes in respect of its surroundings makes it an optimal surveillance spot on the crossroads of the corridor towards the Atlantic façade and the major route of the *Antonine Itinerary* to the interior of the Iberian Peninsula, the *via de Italia in Hispanias*, playing an outstanding role in assuring the control of this area of the Ilergetian territories during the early Roman occupation and beyond. The strategic nature of the relationship with the Montsec mountain range as a natural frontier lasted for centuries, with its remains fixed in the later cultural landscapes.

Bibliography

Camañes, P., Moncunill, N., Padrós, C., Principal, J. and Velaza, J. 2010. Un nuevo plomo ibérico escrito de Monteró. *Paleohispánica* 10: 237-47.

ESRI 2013. ArcGis Resource Center. ArcGis 10.1 documentation [Online] http://resources.arcgis.com/en/help/main/10.1/. [Accessed: 20 March 2015].

Fiz, I., Gorostidi, D., López, J. 2013. In conspectu prope totius urbis: an application of different visual methods at the ager Tarraconensis landscape. In F., Contreras, M. Farjas, F. J. Melero, (eds.), *Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010,* British Archaeological Reports International Series 2494: 131-154. Oxford, Archaeopress.

Gallart, J. 1991. *El dipòsit de Bronzes de Llavorsí, Pallars Sobirà*. Barcelona, Departament de Cultura.

García, L., Weathley, D., Murrieta, P., Márquez, J. 2009. Los SIG y el análisis espacial en arqueología. Aplicaciones en la prehistoria reciente del sur de España. In X. Nieto and M. A. Cau (eds.), *Arqueologia Nàutica Mediterrània.* Monografies del CASC: 163-80. Barcelona, CASC-Museu d'Arqueologia de Catalunya

Gonzàlez, J. R. 1986. El poblament ibèric al nord de la ciutat de Lleida. In J. Padró (ed.), *Protohistòria Catalana: 6è Col·loqui internacional d'arqueologia de Puigcerdà, Puigcerdà, 7-9 de desembre de 1984*: 275-80. Puigcerdà, Institut d'Estudis Ceretans.

Grau, I. 2012. Límite, confín, margen, frontera conceptos y nociones en la Antigua Iberia. In F. Prados, I. García, G. Bernard (eds.), *Confines el extremo del mundo durante la antigüedad*: 23-47. Alicante, Publicaciones de la Universidad de Alicante.

Junyent, E., Poch, R. M. 2012. Water and defense systems in Els Vilars fortress (Arbeca, Catalonia, Spain): A multiproxy approach. *Cypsela* 19: 49-70.

Zamora, M. 2006. Visibilidad y SIG en arqueología, mucho más que ceros y unos. In I. Grau (ed.), *La aplicación de los SIG en la arqueología del paisaje*: 41-54. Alicante, Publicaciones de la Universidad de Alicante.

Maya, J. L. 1991. El pantano de Santa Ana (Huesca) y sus materiales en la Edad del Bronce. *Bolskan: Revista de Arqueología del Instituto de Estudios Altoaragoneses* 8: 199-214.

Montes, L., Utrilla, P., Cava, A. and Calvo, M. J. 2006. Yacimientos prehistóricos en el Noguera Ribagorzana. La Cueva de los Huesos de Castillonroy y otros enclaves del entorno. *Salduvie: estudios de prehistoria y arqueología* 6: 95-115.

Parcero, C., Fábrega, P. 2006. Diseño metodológico para el análisis locacional de asentamientos a través de un SIG de base 'raster'. In I. Grau (ed.), *La aplicación de los SIG en la arqueología del paisaje*: 69-90. Alicante, Publicaciones de la Universidad de Alicante.

Ros, J., Solanes, E. 2002. La recerca arqueològica a Antona (Artesa de Segre). Estat de la qüestió. *Revista d'Arqueologia de Ponent* (11-12): 277-89.

Ruiz, A., Molinos, M. 2008. Las fuentes del Guadalquivir. Límites y fronteras para el norte de la Bastetania. In A. Adroher, J. Blánquez (eds.), *Actas del Primer Congreso Internacional de Arqueología Ibérica Bastetana*: 51-72. Madrid, Universidad Autónoma de Madrid.

Sanmartí, J. 2010. Demografía y cambio socio-cultural: el caso de la Iberia septentrional. In Burillo, F. (ed.), *Arqueología de la población: comunicaciones presentadas al IV Coloquio Internacional de Arqueología Espacial, Teruel, 13-14 de diciembre de 2010*, Teruel, Seminario de Arqueología y etnología turolense: 91-108.

Wheatley, D., Gillings, M. 2000. Visual perception and GIS: developing enriched approaches to the study of archaeological visibility. In G. Lock (ed.), *Beyond the map: Archaeology and Spatial Technologies.* NATO Science Series: Life Sciences, 321: 29. Amsterdam, IOS Press.

CHAPTER 8
Spatial Analysis: Predictivity and Postdictivity in Archaeology

Predictivity – Postdictivity: a Theoretical Framework

Antonia Arnoldus-Huyzendveld(1), Carlo Citter(2), Giovanna Pizziolo(2)

[1] Digiter s.r.l.
[2] University of Siena – Department of History and Cultural Heritage

Abstract: Predictivity has a long lasting tradition in archaeology and the debate on deductive and inductive approaches is still going on. With this paper we focus on different questions: which kind of data need to be collected to develop efficient predictive models? How can we face bias problems that affect landscape analyses and predicting procedures? Can we use inductive and deductive approaches in the same procedure?

How can we enrol predictivity into a wider theoretical, helpful context? We think we should put it into the daily toolbox of the archaeologist. In our experience predictivity, field work, and postdictivity are three stops along the same route.

Prediction answers to the question "who?, where? What", postdiction answers to the question "why?" They do not neutralize each other. On the contrary, they can be conceived as two different, but complementary, parts of the same procedure. They both need a severe scrutiny of the archaeological dataset derived from intensive fieldwork. Thus, the theoretical framework we are going to introduce is all but a dogmatic point of view.

Keywords: Predictivity, Postdictivity, GIS, Fieldwork, Archaeological theory

Introduction

Although the concept of predictivity in archaeology has an abundant literature, the theoretical framework is, surprisingly, still quite unexplored. In addition, it seems that prediction is often enclosed within a self-referential fence. Recently, some scholars have admitted the need to overcome the constraints of geostatistical tools settings (Kamermans 2013). Our proposal stands between enthusiastic, though sometimes uncritical use of geostatistical tools, and an outright rejection of them. They are helpful but they are just tools. We think that the historical question is the first, indisputable stage, and the historical interpretation is the end of the process. Here we describe in detail the theoretical framework of this procedure and some case studies to illustrate it.

1 Entangled antinomies

We can summarize the theoretical framework as a list of antinomies. Literally speaking, an antinomy is a contradiction between two or more general rules. We use this word to stress the idea that they are more apparent than real.

The first one seems to us an unnecessary debate. Do we really need to choose between a top-down (deductive) and a bottom-up (inductive) process? They both have positive aspects and disadvantages. The former focuses on general behaviours and therefore local variants are barely considered. The latter focuses on available dataset and therefore the bias is not on the former. The question is: why should we choose? Can we work out a process that incorporates a deductive stage followed by an inductive one?

This leads to a further antinomy. In our experience, which is focused on a field research approach, the prediction is more effective if it is followed by a field survey. The circular procedure we propose has some advantages we wish to emphasize. Firstly, it does not stop at a dead end. Research itself is a never-ending process of harvesting new data and elaborating, producing, and testing models. Secondly, it is helpful to incorporate both a deductive and an inductive stage into the same process, as well as a test in the field. This calibrates the prediction and activates the missing part of classical predictivity — the postdictive phase. It is a relevant stage that answers the question 'why?' We shall describe it in detail below. Thus, one of the most significant antinomies (deductive/inductive) appears to vanish.

A similar fate seems to have affected the human/environment antinomy. There is an entanglement between the natural environment and human activity. Again, this is not a dead end; on the contrary it is a cyclic process of action/reaction, which gives place to landscape.

Resilience is a key word, both for the natural setting and for human communities. This concept has gained wide interest among scientists, although in archaeology is still underestimated. In the last decade increasing concerns on the capability of reacting to environmental changes have encouraged researchers to investigate how past communities adapted to and survived long-term changes and sudden catastrophes (Redman 2005; Fischer *et al.* eds. 2009) The core historical question is to investigate the rhythm of this relationship (Fig. 1). The natural transformation of the coastline is accelerated by human activity inland combined with climate change, but the former triggers resilient behaviour in order to gain from a changed environment. Predictivity has great potential on this subject, if it turns from a deterministic approach to become a more flexible tool.

We can go beyond the traditional subjects (landscape archaeology, environmental archaeology, predictive modelling) if we enrol Earth Sciences as a partner. Archaeological prediction and postdiction require the reconstruction of landscape development over time. The time line is often discontinuous (punctuated), for example, the post-glacial rise in sea level, or the short periods of activity of a volcano separated by long periods of stasis allowing human settlement. In reconstructing the past landscape environment, one should

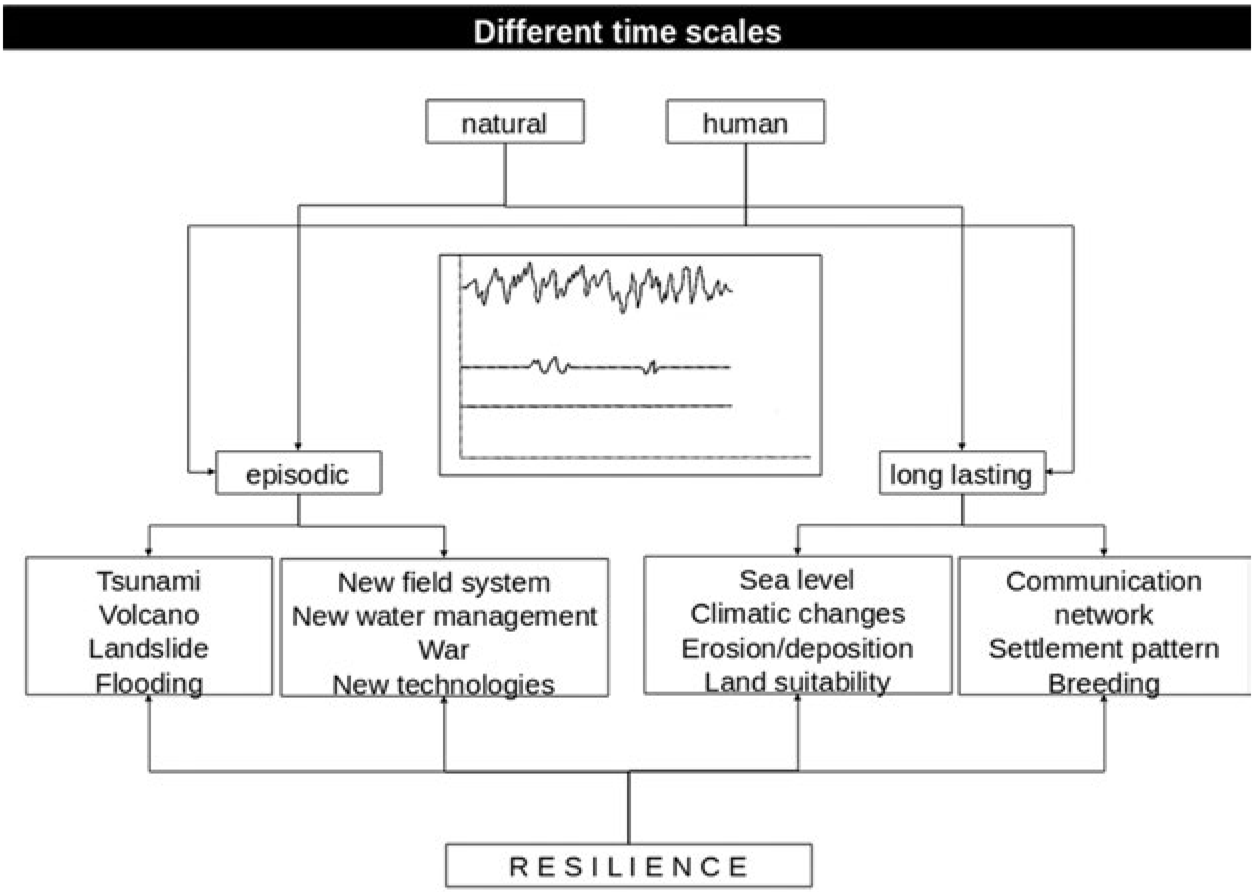

Fig. 1. Schema of different time scales playing a role in entangled antinomies.

strive to distinguish between those parts of the landscape which, within a determined archaeological time span, have remained static in their morphology and environmental conditions, and the parts that were dynamic, that is, that underwent changes, and concentrate on the latter. The challenge in tracing the historical environmental record is to establish how, how much, and when these factors changed.

Time scale is relevant too. Resilience can be a fast process to survive a catastrophe (volcano, tsunami, earthquake, plague, etc.), but it can also be a long process of adaptation to fit in with slow pace changes. We should not consider the settlement pattern dynamics, route network, and field systems from a chrono-typological perspective only. They do not start at a given time and in a space as planned actions, and slowly dissolve until a new plan overtakes the former traces. The reality is much more complex and relationships between the factors involved are on different levels. A new water management can be the result of both human and natural actions, spread over a long time span, without the need to place a chieftain or lord at the head of it, or it could be planned in a given period and the local communities could have maintained it for centuries (Civantos 2012).

2 The prehistoric peculiarities

In this contribution we would like to discuss the potential peculiarities faced when dealing with prehistoric evidence and landscape, as has already emerged during previous (Van Leusen, Pizziolo, Sarti 2011) and more recent meetings (Pizziolo, Sarti 2015) dedicated to prehistoric landscape archaeology. We start from the consistency of prehistoric datasets. It is worth noting that if the prehistoric landscape is often a 'hidden landscape', it is clear that this may affect our information, which may be strongly biased and/or underestimated with regard to pre- and protohistoric evidence. It is important to be aware of this. Other matters concern the possibility of distinguishing particularly useful variables and analytical criteria that could help to predict the location of a prehistoric context. Aside from this general question, some methodological issues need to be solved regarding the relationship between prediction and detection. Thus, it is necessary to find out how to test predictive models in the field and how to obtain representative information in order to develop the model. As stated above, we believe that field activities are a fundamental part of the predictive-postdictive process. For the analysis of prehistoric settings, a basic stage is the assessment of data, which can be developed through a careful study of the formation processes of the archaeological record and of the landscape unit that contains it. We must remember that in general during field surveys, prehistoric evidence is less visible than classical and post-classical evidence (cf. Bintliff *et al*. 2000; Pizziolo, Volante 2015). It is therefore important to assess the archaeological record collected in the field and try to weigh the evidence we can see on the field surfaces.

Moreover, we must take into consideration that to cope with biases due to geomorphological process of erosion and sedimentation, we need to set up a detailed reconstruction of prehistoric landscape settings. This implies that we should divide the landscape into units, which may help in distinguishing homogeneous portions of territory related to a given formation process. Landscape Units can then provide a useful support to assess terrain affected by sedimentary or erosive processes and could be used to evaluate the preservation of prehistoric artefacts. Unfortunately, detailed thematic maps often do not cover all the area under study, and therefore we often have to deal with inconveniences of spatial accuracy. Other problems may be related to prehistoric artefacts that sometimes, especially in case of lithics, cannot be characterized in detail from a chronological or cultural point of view. Even though this may introduce problems of data accuracy, however, these artefacts are important as they testify to prehistoric presence in a given study area. In this case, a specific assessment of post-depositional effects on artefacts should be performed, which nevertheless, introduces further uncertainty regarding the results obtained by the prediction model. Other remarks on predicting prehistory may be relevant for the analysis of social variables. Prehistoric settlement strategies are not classified through specific hierarchical rules and we clearly cannot use historical sources to investigate reasons and perspectives of social organization. In practice, due to the above-mentioned uncertainty factors, it may more difficult to answer the question 'why'. The best practice could be to focus on the assessment procedures and work on environmental and geomorphological information in order to compare archaeological data with ancient land units. Following this approach we can use historical sources and in particular historical cartography, which can help us to distinguish ancient morphologies. These kinds of sources, integrated with remote-sensing data, can be very useful when we are dealing with territories dramatically transformed by anthropic actions such as, for instance, alluvial plains where reclamation activities have been undertaken. To sum up, in order to develop predicting-postdicting processes applied to prehistoric contexts it is essential to perform an analysis of land units that may preserve prehistoric evidence with the aim of reconstructing landscape characteristics, assessing evidence distribution, and individuating a 'prehistoric landscape surface' (Pizziolo 2012).

3 The procedure

The procedure we propose is composed of three stages. First, the prediction beginning with a deductive approach, as for instance: where can this type of settlement be in that area and in that period? Did they exploit that resource? Did they connect those settlements? Then, we make a cumulative cost surface on a GIS platform to run the prediction. The cost surfaces may be related to different variables, not just to the traditional cost of movement. Both natural and human factors are weighed up in different ways. All the outputs are analysed and verified with accurate fieldwork. A traditional survey should be supported by geophysics, remote sensing, and sample trenches. At the same time, we evaluate by how much the available dataset fits in with the prediction — the inductive stage of the procedure. It allows a further evaluation of both the prediction and the bias. Next, we make a new set of cumulative cost surfaces to achieve the best overlay with the observed data — the postdictive phase. We then ask why a certain settlement is located in a particular place, or why a specific resource was exploited (or not). We think this is the missing stage of traditional predictivity. By modelling the cost surface to fit in the observed data, we can get precious information about the relationship between the factors involved and their reciprocal weight.

This procedure is based on the traditional deductive/inductive model building, but it introduces the importance of data validation through both the field and laboratory validation processes. The approach is not oriented towards the assessment of the model performance through statistical tools (see e.g. Verhagen 2009) but is focused on a mixed quantitative-qualitative procedure.

This procedure stresses the validation of the model according to an intense field survey and validation process developed in the laboratory through a comparison of data observation and the creation of a cost surface, which is gradually improved through a process of approximation.

In this way we not only construct and test the model repeatedly, gaining reliability and stability (Kammermans and Wansleeben 1999: 226–9), but we use the best approximated cost surface to investigate which variables are important in the definition of the model itself. In the first phase the choice of variables follows general rules (deductive) and the resulting cost surface is a first qualitative estimation, which we are going to test with field survey and available data. The variables involved in the first estimation can be both environmental and cultural — in our experience we have found it highly profitable to use a wide range of variables. The output of our field test is the base for a new cost surface where the variables are related to one another according to an inductive approach. This cyclic process allows us to calibrate progressively the cost surface, thus suggesting which factors may affect the particular aspect we are investigating. In the case where two or more cost surfaces produce similar outputs, the archaeologist must choose which fits best with the historical framework of that specific context. The main difference between a quantitative-deterministic approach and a qualitative-indeterministic one is that we are aware that it is impossible to 'quantify' the exact weight of a variable in the way hard sciences can. Sometimes an output can be formally correct but historically unreliable — if not misleading — and therefore this is not what we are looking for. On the contrary, we criticize each output and discuss its scenario within the archaeological dataset. The output that includes the most of our present knowledge is the one we choose as our base to start the new cycle of the process (Fig. 2).

Cumulative cost surfaces have been successfully tested to model the least-cost path, but we think they are a flexible tool that can be used to forecast any type of cost (Arnoldus-Huyzendveld, Citter, Maccani 2013; Citter 2015). In fact, we can model the raster to simulate the cost to move within it, as well as the cost to exploit a given resource, or to found a given type of settlement. There are several advantages to using this rather simple tool instead of more sophisticated algorithms. We wish to emphasize two of them. First, because it is straightforward, most archaeologists can use it without the need of high mathematical skills, which are not the basis of their background knowledge. Second, it is flexible — it can be used for almost any kind of prediction — and it also does not require precise input data, something that archaeologists will never have. Highly sophisticated procedures are very sensible to short-range fluctuations of the input data. It is quite clear that material culture cannot produce the precision required by this procedure.

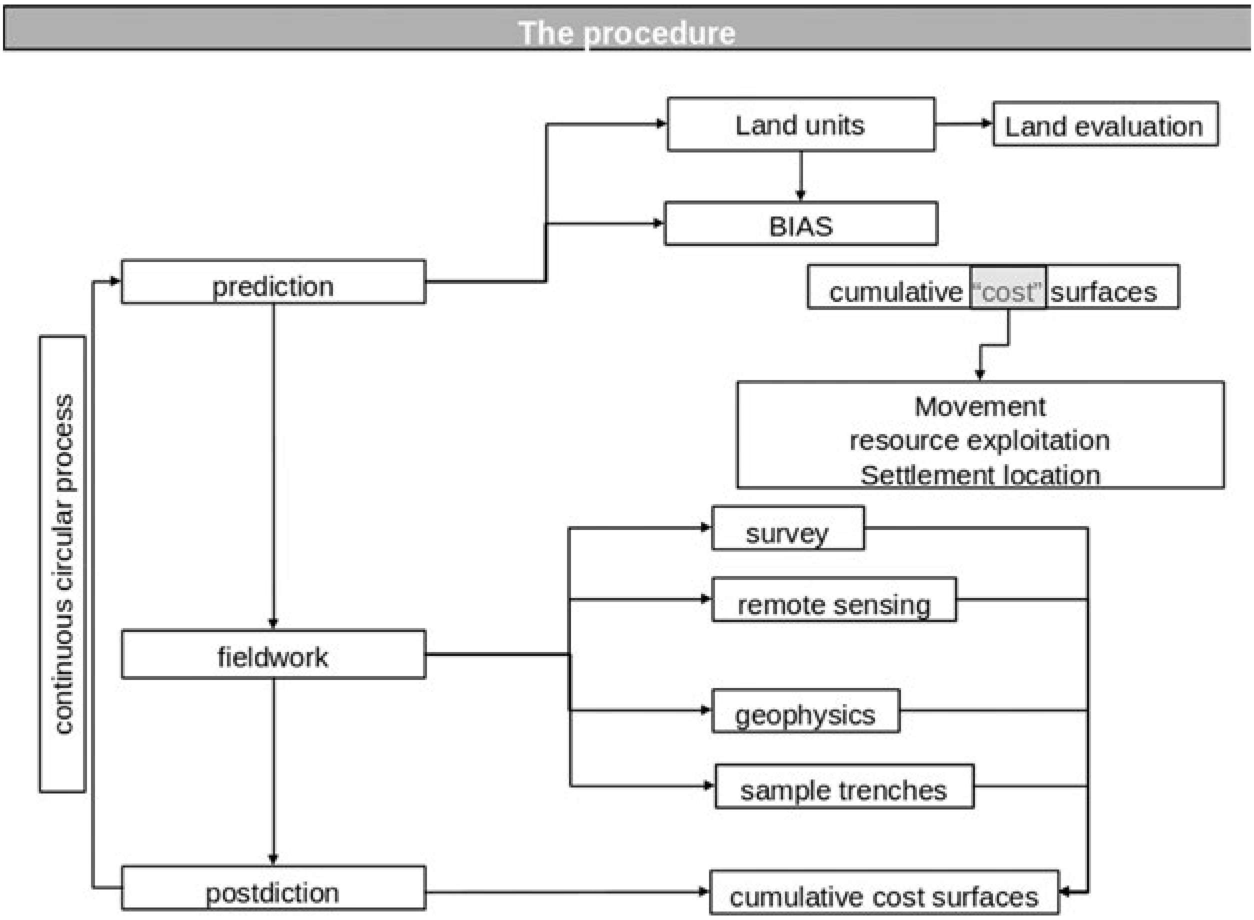

Fig. 2. Schema of prediction-postdiction procedure.

4 Case studies

4.1 Predictive maps: modelling the location of Grosseto's salt works

The Ombrone River delta (Tuscany) is located along the central-western coast of Italy and is composed of a lagoon plain, a sandy coastal belt, and a series of slightly higher internal coastal terraces (Arnoldus-Huyzendveld 2007). The town of Grosseto is located upon the latter. In historical times the plain was subject to intensive changes, such as the gradual infill and restriction of the lagoon by river sediments and a seawards expansion of the dune belt. For practical purposes, the terraces can be considered 'unchanged' background. We have no archaeological data about the salt works near Grosseto, but historical sources have shown that the collection of salt through evaporation must have been a major reason for the town's foundation and growth in the early Middle Ages (Citter, Arnoldus-Huyzendveld 2012). The location of the antique salt works is unknown as field survey and remote sensing are hampered by a thick cover of fluvial infill and modern land reclamation layers.

The prediction had the purpose of evaluating the most promising location for the remains of the salt works of the Roman period. We chose to use GIS spatial analysis with hydrology tools. These operations produce indications for reducing a vast plain to small areas, the potential of which is higher than anywhere else. These can be surveyed with geophysics, trenches and, in case of success, extended excavations. We had to consider the elevations and the extension of the former lagoon. We presumed the isolation of a lagoon bay through a transverse dam, in analogy with the Maccarese imperial salt works (Grossi *et al.* 2015).

The work consisted in subtracting from the present elevations a value based on the known data of the Roman surface level of the lagoon, to obtain the best approximation of the morphology of the former plain. Next, we determined, through calculation from a cumulative cost surface of flow direction and accumulation, the theoretical stream network. In order to model the location of the salt works we had to select a 'pour point', that is, a point where a specific basin has its final water outflow. Knowing that the sea level was about 1 m lower than the current level, we selected a pour point snapping on one of the streams at about that height. Moreover, it is located upon the border area of the lagoon, with the possibility of creating a connecting channel to the sea. The result has been an area of about 5 ha where, according to this model, salt collection in Roman times must have been most profitable.

4.2 Predictive maps: prehistoric landscape potentialities in the Grosseto Plain

The prehistoric dataset related to the Grosseto Plain has been strongly biased by environmental conditions. For this reason we are analysing sea-level changes that have significantly altered the Grosseto landscape in recent times, affecting settlement strategies of human groups from the Palaeolithic to the Bronze Age. The analysis of prehistoric landscape potentialities could provide new clues to predict site location, understand settlement strategies, and verify surface preservation. When the sea level had more or less reached its present height, the Pleistocene deposits accumulated in the central part of the plain were still surrounded by water and, as mentioned above, consequently these terraces are considered 'unchanged' background. Parts of Pleistocene deposits are also preserved in the marginal areas, in particular in the southern part of the plain. Moreover, these inlets and lagoons close to the Tuscan archipelago could have been used by Neolithic people (Volante 2007; 2012) crossing the Tyrrhenian and gradually penetrating the inland areas. One of the challenges of our research is to identify in today's landscape the shorelines and landing places that could have been exploited and crossed during the Neolithic period in the framework of maritime-inland communication.

Other problems of archaeological visibility concern Copper Age evidence, which is predominant inside caves and shelter areas. Our interpretation of the prehistoric landscape suggests that those Pleistocene deposits, free from reclamation activities and with a very low slope gradient, can be distinguished as areas that may have been 'walkable' surfaces during the Neolithic and Copper Age periods. Moreover, we expect that these areas would not have been affected by massive depositional actions after the Holocene prehistory. The use of historical cartography, drawn before the last reclamation activities, helps to define the shape of the ancient shorelines actually covered by reclamation deposits. Now, recent archaeological rescue activities and field survey investigations undertaken through both judgemental and random selections in the area confirm our model (Pizziolo, Volante 2015).

4.3 Predictive maps: modelling the location of salt works near Giuncarico, 6th to 10th c. AD

It is known from historical sources that there have been salt works in the neighbourhood of Giuncarico (NW of Grosseto), but they were never found. This castle is located in a hilly area, which is separated by terraces from the valley floor of the Bruna River and the former lagoon of Grosseto (Arnoldus-Huyzendveld, Citter 2014). We started from the present elevations in order to create a historical DEM and contour lines, and from soil characteristics for the landscape definition. In this case we presumed the construction of a series of basins for salt collection, due to the more recent age and the different environmental conditions. Landscape analysis proved that the salt works could not have been near the foothills, but at least 10 km further south. The results of this deductive qualitative model were so clear that it was not deemed necessary to use a cumulative cost surface, because the interpolation to evaluate the most likely coastline of the early medieval lagoon and the land units map were sufficient.

4.4 Postdictivity: the harbour basin of Claudius (1st c. AD)

Claudius extended two long moles into the sea. The outline of the harbour basin was detected by drilling as all relicts were covered by dune sand (Morelli *et al*. 2011). The hypothesis was recently put forward that the entire lagoon may not have been dredged, but that channels were excavated in the bottom and the coastal barrier was cut through to let the sea enter the lagoon (Arnoldus-Huyzendveld *et al*. 2015). Before the creation of the hexagonal harbour basin by Trajan, the coastline and the former lagoon of the higher dune area of Portus had already been used by Claudius.

The postdictive question is: why was Claudius' basin constructed in this particular part of the landscape? From the environmental viewpoint this is the only location north of the Tiber where the dune belt was narrow with a lagoon sitting behind it, but this cannot have been the only consideration at the time — there was also the need to connect the harbour over inland water routes to Rome.

4.5 Postdicting the via Aemilia Scauri

We have some indications of the route followed by this late Roman Republican infrastructure (further details in Citter 2007). We wanted to evaluate the factors that could be involved in the making of this specific road. This is a typical example of what we mean by postdiction: we do not have to guess the possibility of a connection between two factors — we know the road existed and we know its route almost as well. Therefore, the question we ask is, why does the route run in this way through this particular landscape? We made several evaluations with different weights of anthropic and environmental factors. Next, we evaluated which weighted cumulative cost surface produced the road, matching it with the actual routes to reach the highest score. Finally, we have indications of the factors that influenced the creation of this specific road (Citter, Patacchini, forthcoming).

Bibliography

Arnoldus-Huyzendveld, A. 2007. Le trasformazioni dell'ambiente naturale della pianura grossetana. In Citter, C., Arnoldus-Huyzenveld, A. (eds.), *Archeologia urbana a Grosseto. I. La città nel contesto geografico della bassa valle dell'Ombrone,* Biblioteca del Dipartimento di Archeologia e Storia delle Arti – Sezione archeologica Università di Siena, 16, p. 41-61. Firenze: Edizioni All'Insegna del Giglio.

Arnoldus-Huyzendveld, A., Citter, C. 2014. Site location and resources exploitation: predictive models for the plain of Grosseto. *Archeologia Medievale* XLI: 65-78.

Arnoldus-Huyzendveld, A., Turi, P., Morelli, C. 2015. Il paleoambiente di Monte Giulio e della parte nord-orientale del bacino portuale di Claudio. Available at: http://www.fastionline.org/docs/FOLDER-it-2015-324.pdf.

Bintliff, J., Kuna, M., Venclovà, N. 2000. *The Future of Surface Artefact Survey in Europe*, Sheffield, Sheffield Academic Press.

Citter, C. 2007. La città di Grosseto nel quadro della viabilità romana e medievale della bassa valle dell'Ombrone. In Citter, C., Arnoldus-Huyzenveld, A. (eds.), *Archeologia urbana a Grosseto I. La città nel contesto geografico della bassa valle dell'Ombrone,* Biblioteca del Dipartimento di Archeologia e Storia delle Arti – Sezione archeologica Università di Siena, 16: 156-98. Firenzel, Edizioni all'Insegna del Giglio.

Citter, C. 2015. Landscapes, settlements, and sustainability. In Chavarria, A., Reynolds, A., *Handbook of Landscape Archaeology*, PCA Studies 2: 239-58. Mantova, SAP.

Citter, C., Arnoldus-Huyzendveld, A. 2012. New approaches to old issues: the application of predictive maps in archaeology. A case study: modelling the location of Grosseto's salt works from 700 BC to AD 1200. *Medieval Settlement Research* 27: 1-11.

Citter, C., Arnoldus-Huyzendveld, A. and Maccani, C. 2013. Predicting site location through cost surfaces. A case study and a proposal. In Gualandi, M.L., Gattiglia, G., Anichini, F., Fabiani, F. (eds.), *Opening the past*, atti del convegno, Pisa: 5-10.

Citter C., Patacchini A. (forthcoming). Postdittività e viabilità: il caso della direttrice tirrenica. In Citter, C., Nardi, S., Stasolla, F. R. (eds.), *Tra la terra e il mare - La topografia del litorale del Lazio e della Toscana – Entre la terre et la mer. La via Aurelia et la topographie du littoral du Latium et de la Toscane. Atti del convegno, Paris, 6-7 giugno 2014*, Spoleto.

Fisher, C. T., Hill J. B., Feinman, G. M. (eds.) 2009. T*he Archaeology of Environmental Change. Socionatural Legacies of degradation and resilience*. Tuscon.

Grossi, M. C., Sivilli S., Arnoldus-Huyzendveld, A., Facciolo, A., Rinaldi, M. L., Ruggeri, D., Morelli, C. 2015. A complex relationship between human and natural landscape: a multidisciplinary approach to the study of the ancient saltworks in 'Le Vignole-Interporto' (Maccarese, Fiumicino – Rome). In Brigand, R., Weller, O. (eds.), *Archaeology of Salt. Approaching an invisible past*: 83-101. Leiden, Sidestone Press.

Kamermans, H., Wansleeben, M. 1999. *Predicitive Modelling in Dutch Archaeology, Joining Forces*. In Barcelò, J. A., Britz, I., Vila, A. (eds.)*, New techniques for old times, CAA98, Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 26th Conference*, *Barcelona*, March 1998, British Archaeological Reports International Series 757: 225-9. Oxford, Archaeopress.

Kamermans, H. 2013. Predictive modeling: a view from the ivory tower. In Gualandi, M. L., Gattiglia, G., Anichini, F., Fabiani, F. (eds.), *Opening the past, Atti del convegno, Pisa 2013*. Available at: http://mappaproject.arch.unipi.it/wpcontent/uploads/2011/08/Kamermans-Pisa-2013.pdf

Martin Civantos, J. M. 2012. Hydraulic Archaeology in South-East Spain Mountainous Landscapes. In Brogiolo, G. P., Angelucci, D. E., Colecchia, A., Remondino, F. (eds.), *APSAT 1. Teoria e metodi della ricerca sui paesaggi d'altura*: 51-74. Mantova, SAP.

Morelli, C., Marinucci, A., Arnoldus-Huyzendveld, A. 2011. Il Porto di Claudio: nuove scoperte. In Keay, S., Paroli, L. (eds.), *Portus and its Hinterland, recent archaeological research, Archaeological Monographs of the British School at Rome*: 47-65. Oxford, Oxbow.

Pizziolo, G. 2012. Prehistoric Peopling Process in the Holocene Landscape of Grosseto Area: Dealing with Uncertainty and Searching for Ancient Shorelines. In Kluiving, S. J., Guttmann-Bond, E. B. (eds.), *Landscape Archaeology between Art and Science. From a Multi- to an Interdisciplinary Approach.* Landscape And Heritage Series: 265-276. Amsterdam, Amsterdam University Press.

Pizziolo, G., Sarti, L. (eds.) 2015. *Predicting prehistory. Predictive models and field research methods for detecting prehistoric contexts, Proceedings of the International Workshop Grosseto (Italy), September 19-20, 2013.* Millenni 11. Firenze, Museo e Istituto fiorentino di preistoria 'Paolo Graziosi'.

Pizziolo, G., Volante, N. 2015. *Landscape changes and site discovery potential: predictive criteria and field survey strategies for prehistoric contexts*. In Pizziolo, G., Sarti, L. (eds.), *Predicting prehistory. Predictive models and field research methods for detecting prehistoric contexts, Proceedings of the International Workshop Grosseto (Italy), September 19-20, 2013.* Millenni 11: 133-51. Firenze, Museo e Istituto fiorentino di preistoria 'Paolo Graziosi'.

Redman, C. L. 2005. Resilience theory in archaeology. *American Anthropologist*, 107, 1: 70-5.

Van Leusen, M., Pizziolo, G., Sarti, L. (eds.) 2011. *Hidden Landscapes of Mediterranean Europe. Cultural and methodological biases in pre- and protohistoric landscape studies. Proceedings of the international meeting. Siena, Italy, May 25-27, 2007*, British Archaeological Reports International Series 2320. Oxford, Archeopress.

Verhagen, P. 2013. On the Road to Nowhere? Least Cost Paths, Accessibility and the Predictive Modelling Perspective, in Fusion of cultures. In Contreras, F., Farjas, M., Melero, F.J. (eds.), *Proceedings of the 38th Annual conference on computer applications and quantitative methods in archaeology*, (Granada, 2010), British Archaeological Reports Series 2494: 383-8. Oxford.

Verhagen, P. 2009. *Predictive Models put to the test*. In Kamermans, H., ven Leusen, M., Verhagen, P. (eds.), *Archaeological prediction and risk management*: 72-122. Leiden, Leiden University Press.

Verhagen, P., Whitley, T. 2012. Integrating Archaeological Theory and Predictive Modeling: a Live Report from the Scene. *Journal of Archaeological Method and Theory* 19: 49-100.

Volante, N. 2007. *Neolitico ed Età del Rame*. In Citter, C., Arnoldus-Huyzenveld, A. (eds.), *Archeologia urbana a Grosseto I. La città nel contesto geografico della bassa valle dell'Ombrone,* Biblioteca del Dipartimento di Archeologia e Storia delle Arti – Sezione archeologica Università di Siena 16: 122-7.

Volante, N. 2012. Loc. Podere Elvira, Comune di Civitella Paganico – Preistoria. In Agricoli, G., Barbieri, G., Cavallo, T., De Benedetti, M., Magno, A., Tuci, D., Turchetti, M. A., Volante, N. (eds.), Rilevamenti archeologici lungo la E78 tra Campagnatico e Civitella Paganico (GR): contributo per una carta archeologica della provincia di Grosseto. *Notiziario della Soprintendenza per i Beni Archeologici della Toscana* 8: 89-92.

Predicting and Postdicting a Roman Road in the Pre-pyrenees Area of Lleida (Spain)

Antonio Porcheddu
porcheddu.antonio@gmail.com
Universitat de Lleida, Spain

Abstract: This paper aims to illustrate an analysis of an ancient road, considered as Roman, in the Àger Valley, located on the Spanish side of the Pre-Pyrenees. The analysis uses the continuously evolving methodology of predictive archaeology and the emerging 'retrodictive' (or postdictive) approach. The starting point was to perform a reconstruction of the path based on the available documentary and archaeological evidence. A second step focused on the application of a GIS analysis with a least-cost path algorithm to predict the better route between two given points and over a weighted cost surface. The final step was to compare the reconstructions and to apply the retrodictive approach. This allowed a reflection and understanding of the causes that may have influenced both the setting and the evolution of the path.

Keywords: Àger, Spain, Landscape archaeology, Predictive and postdictive archaeology, Least-cost path

Introduction

In scientific literature for north-east Spain, studies on late Roman and medieval secondary roads are scarcer than those on main routes of transportation.[1] This is mainly due to a limited quantity of available written sources and to a lower material visibility of the remains. Indeed, minor roads were built of a lower quality and frequently disappeared leaving no trace, or were completely transformed, due to their volatile structure. In this sense, this contribution aims to propose a possible way to study the ancient secondary paths, approaching them from a specific predictive and retrodictive methodology. The test area will be a path traditionally considered as Roman, which connected the Àger Valley to the plain of Lleida (Spain).

Looking at the area of research it is possible to identify some geomorphological features. The presence of the rivers Noguera Pallaresa on the eastern side and Noguera Ribagorçana on the western side, with the two related valleys, denotes two possible macro-access corridors. The specific morphology, apart from these valleys, makes it otherwise difficult to move along a north–south direction.

The historical role of the Àger Valley during the proto-historic and Roman periods is unknown. There are only a few examples of material visibility and no specific studies were carried out. Presently, only weak hypotheses based on sporadic and non-contextualized findings are available, and they are related to local historical traditions, but we have more information about the later Islamic period (7th–10th c.). It is useful for scientific purposes from the 11th century thanks to documentary sources and also to a large amount of material evidence, especially churches and fortifications. During the Middle Ages, the Àger Valley became one of the central places in the frontier between the Islamic territory of the Lleida Taifa in the south and the Christians counties in the north, which were gaining more power and expanding their domains from the Pyrenees to the south.

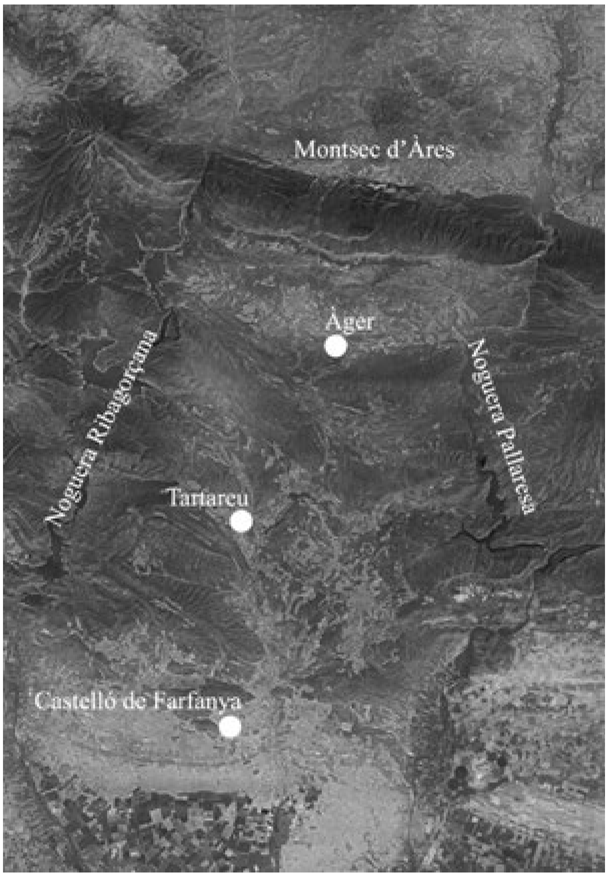

Fig. 1.

[1] For a linear review of the study of ancient Catalan roads see first Riu 1993: 27–43; Bolòs 1993: 3–26; more recently Carreras and De Soto 2008; 2009. In general, all these papers consider the main routes of transportation but exclude secondary paths because of the scale involved. The more recent paper by Güimil-Fariña and Parcero-Oubiña (2015) dealing with the north-west side of Iberian Peninsula routes, shows this trend, as the authors write, 'We are not dealing here with fluid, unstable and easily changing forms of mobility, but with a context where a strong discipline was imposed over the landscape. This also produced a significant ensemble of material remains that constitute a rich source of evidence.' Our paper deals with the opposite case.

The path in this analysis is traditionally considered to be of Roman origin; excavations carried out during the construction of a recent road, informally confirmed this hypothesis, but no results have yet been published.[2] The aim of this paper, however, is not to find the actual chronology of the path, but to understand the accessibility from the plain to the valleys and find a suitable path, discussing the connections with the historical and archaeological sources.

A way to achieve these objectives is to determine by 'trial and error' a computed model of the path based on the least-cost path (LCP) algorithm that best fits the hypothesized track. A least-cost path, which recently increased the number of its applications, is based on the concept that in general people and animals tend to make the least effort to complete a task. In this case, to reach a place starting from a specific point, the LCP models a path over a cost surface that tries to reduce the energy expenditure as much as possible. It is evident that modelling an adequate cost surface is crucial for a reliable modelling. As stated by Herzog, 'with the LCP software currently available, LCP calculations can be applied tentatively to identify the factors governing the route layout connecting two points in ancient time' (2013: 199). The final discussion of this paper will thus be centred on the understanding of the importance of every parameter to the generation of the path. It is clear that during the formation of a road, not only physical and geographical parameters matter, cultural and economic needs are also involved. The choice of an LCP is due to the fact that when we do not have an absolute and explicit cultural cause that determined the shape of the road, we can only suppose that the design depended on the energy saved and on the least effort necessary to join two or more places.[3]

1 Methodology

Although it is very difficult to reconstruct a path simply using a predictive model, it is useful to narrow down the different possibilities by applying a least-cost path algorithm on a cost surface.

From the scientific literature, we can generally consider two main typologies of cost-surface application for predictive models: a) the individuation for the best path between two given points; and b) the more explorative models of the mobility basin, which estimate all the alternatives of movement inside a given area.[4] In our case, the choice involved the first option because of the nature of the studied object and the main target of our research.

The cost surface was implemented with ArcGis Desktop software. In addition, the application of the least-cost path algorithm was carried out with the same software using a specific toolbox[5] that computes the cost distance in every direction over a raster surface between two determined points, and then creates an optimum cost path in a vector format.

The work was organized in three stages. The first took a more traditional approach. It intended to evaluate the path by referring to the descriptions left by Antoni Gallardo (1934: 26–27). The second included the generation of an optimum path by applying a least-cost path algorithm on a cost surface. The third focused on comparing both results and interpreting the variability of the path by slightly changing the parameters of the cost surface, adding data layers and considering alternative attractors and detractors, in order to build a model that fitted the reconstructed path by 'trial and error'. In this context, an attractor is a parameter that influenced the initial location or the evolution of the path.[6] These procedures characterize a retrodictive approach. It consists of a widening of the interpretation phase, in order to test the computed results using the historical data available and questioning why some parameters are more relevant than others. The final objective of a retrodictive approach is to discuss what the logic behind past choices was, and if it was different from the present logic.

2 Area, Dataset and Cost Surface

As usually occurs, the heterogeneity of human activities over the landscape makes it more difficult to extract plausible ancient pathways, especially where the economic expansion generated a huge amount of recent modifications. Indeed, rural area alterations became more invasive after the Second World War. As far as Spain is concerned, especially in very marginal areas, as Àger was, this occurred later, indeed not until the end of the Spanish dictatorship in the 1970s and the subsequent industrial and economic expansion. The most recent human features such as highways and others substantial changes in the landscape were filtered out by using ortho-rectified aerial photographs from 1946 and 1956 and archival information.

The choice of limits within the investigation area depended mostly on the landscape geomorphology and on specific historical interests. Although it is possible to anticipate that the entire path was connected to a network of roads from the plain of Lleida to the Pyrenees, we chose as a starting point the castle of Castelló de Farfanya and as an arrival point the village of Àger. From the historical sources we can be certain that the route passed from this point and may have been connected to others routes to the plain of Lleida. Moreover, analysing a network of paths with an LCP is possible but is a more complex operation than a single point-to-point exploration, and this type of application is far from the purpose of this paper.

The cost surface we modelled for the application of the LCP is an accumulated cost surface (ACS) moulded by four main cost components: slope, soil type, geological risks, and hydrographic network.

The base map for the slope component of the cost surface is a lidar-derived digital elevation model downgraded to 5 m per cell. A map of geological risks from the Institute of Catalan

2 For a synthesis of the various chronologies of the Àger Valley see Fité Llevot 1985. For more information about the frontier between Christian and Muslims, see Sabaté 1996.

3 This was recently discussed by Güimil-Fariña and Parcero-Oubiña (2015): 'Dotting the joins': a non-reconstructive use of Least Cost Paths to approach ancient roads. The case of Roman roads in the NW Iberian Peninsula, Journal of Archaeological Science, 54, 2015, pp. 31–44.

4 For a review of these techniques, see Llobera, Fábrega-Álvarez, Parcero-Oubiña 2011: 843–51.

5 Carlo Citter and Antonia Arnoldus-Huyzendveld implemented the toolbox for ArcGIS. The specific features of this tool are explained in detail in Citter and Arnoldus-Huyzendveld 2011: 87.

6 A discussion on the attractors is considered in Citter, Arnoldus-Huyzendveld 2011: 87.

Cartography and Geology, at a scale of 1:25000, was used to analyse threats such as rock fall, landslides, and torrential flux. These kinds of threats can influence, during time, the path of a road, changing its shape even if the energy cost is not the optimum. In a diachronic perspective especially, they can generate several modifications to the path and contribute to constrain the road even more to the natural environment.

The soil type was another cost component. It was important to avoid types of soil that could not guarantee a stability for the path. Again, the Institute of Catalan Cartography and Geology posseses a good dataset for the soil types that facilitated the implementation on the GIS platform.

Another relevant datum is the hydrographic network. The entire river network was mapped and rasterized. The surface obtained was crucial for the understanding of the development of the track inside the territory. On one side, rivers can be obstacles to human mobility, either because of the difficulty of crossing them or because they are not easily navigable. Nevertheless, a river in a mountainous landscape often creates the easiest access through a territory — its valley. The weights assigned to the water net raster are not uniform because we wanted to consider the watercourse typology. Not all the rivers are active during the entire year, the majority are only seasonal rivers. Furthermore, even today in the Pre-Pyrenees of Lleida, many seasonal rivers, called 'barrancos', serve as paths for transhumance.

For the retrodictive phase, it has been useful to map some attractors that could have influenced the path as water springs and natural wells. The information on these data was obtained using topographic maps.

No cultural or social components were used for modelling the cost surface. Although this can appear to be less realistic, as stated above, we do not have an explicit cultural phenomenon that could have influenced the shape of this path, but this is not too great a problem for our purpose (as stated in others similar works and discussions on the modelling of a realistic cost surface). Herzog, citing some examples, reported that 'the only social or cultural cost factors that have so far been regularly considered in LCP calculation are connected with visibility issues' (2013: 186). In addition, in the same paper Herzog stated the conclusions of Bell (Bell *et al*. 2002), 'topographic features are the most static and reliable elements of the landscape, and they propose using a topographic model as a foundation upon which additional models can be constructed.'[7]

3 Reconstruction of the historical path

In 1934 Antoni Gallardo published an article describing the 'Roman road of Àger'. Since then, this path has been considered as Roman; this became a unanimously accepted conclusion without any stronger evidence than the author's word. Presently the visible part of this road is about 2.5 km long and is located in the hill named Coll d'Àger.

This is in fact quite fortunate, because it gives the possibility of testing a predictive model on an existing feature and evaluating the chosen parameters.

[7] Herzog 2013: 186. The statement is taken from Bell *et al.* 2002: 169–86.

Fig. 2.

Using the archaeological and written evidence, as well as oral sources, it has been possible to evaluate a possible reconstruction of the path from Àger to Castellò de Farfanya. A 2.5 km stretch of this path is still visible from the Pont d'en Rosell, a bridge also considered of Roman origins, to Port d'Àger and corresponds to the last stretch towards the village. In 1934 Antoni Gallardo published an article in the *Butlletí del Centre Excursionista de Catalunya* in which he described and drew the path, considering this road as Roman. He also described remains of the road next to Fontdepou[8] and another part next to the Mas de Talet, a rural settlement.[9] The other locations cited by Gallardo are Tartareu and the Farfanya Valley. From the aerial photographs, it is possible to observe a stratification of roads next to the Coll d'Àger. The current road from Balaguer to Àger was built in 2006 and is a modification of a road built at the beginning of the 20th century in order to create the artificial reservoirs at Canelles. During the construction of the 2006 road, another stretch of the former path appeared next to Port d'Àger and, although the emergency intervention has not been published, we could glean from material evidence and oral testimonies that the path also passed under the present road. The outcome of this analysis is

[8] This place name literally means 'water spring from a well'; it could prove interesting when evaluating the role of water springs in the development of the path.

[9] The word 'Mas' derives from the Latin word mansius, possibly indicating a rural settlement.

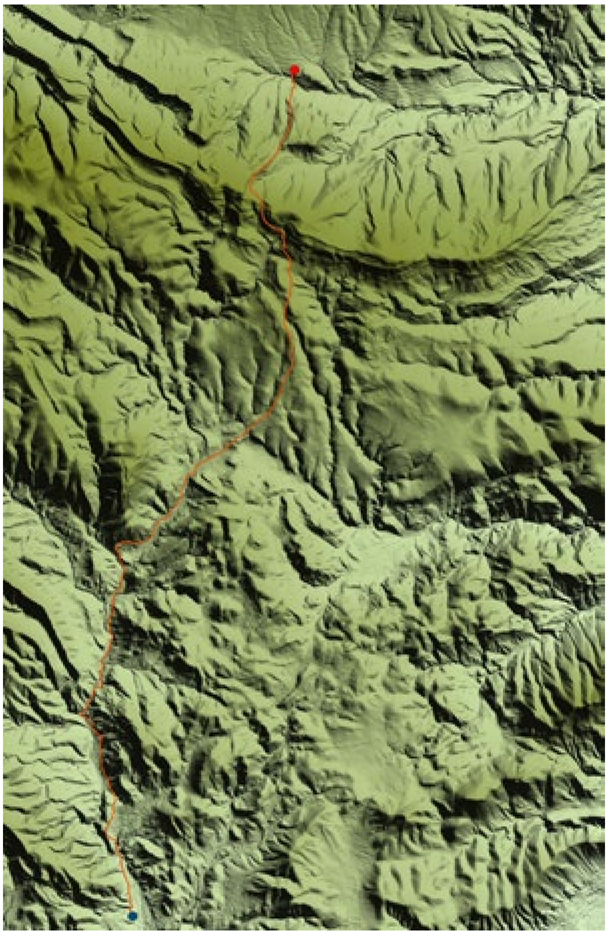

Fig. 3.

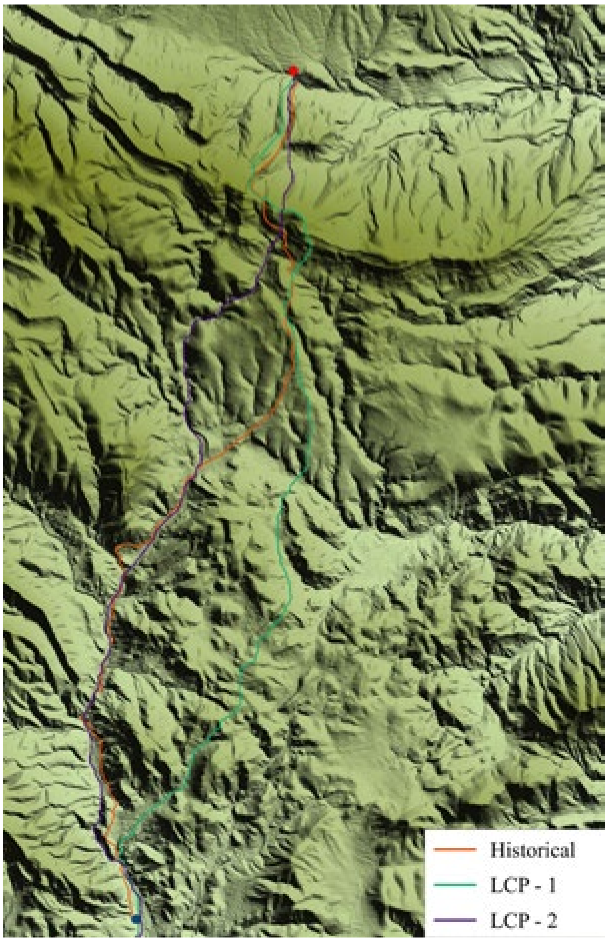

Fig. 4.

the reconstruction of a 20 km path from Àger to Fontdepou, Vilamayor, Tartareu, and Castelló de Farfanya.

4 Predictive and postdictive analysis: the results

For the computation of the accumulated cost surface we decided to concentrate on the slope values. The cost for the slope was computed from the function of pedestrian mobility, specifically following the procedure published in 2011 by Citter and Arnoldus.[10] We then computed a series of LCPs using the Esri ArcGIS software. For each LCP we slightly modified the parameters and tried to obtain the best fit of the computed model over the hypothesized track.

In the first attempt of least-cost path computation, the cost surface was calibrated giving priority (lower values of cost) on factors such as slope and geological risk and underestimating rivers, springs, and others attractors. This allowed ua to determine how much the slope influenced the development of the path on the region. The source point was Castelló de Farfanya and the target point was the village of Àger. The slope was classified in nine classes representing all the possible steep variations present in the raster. In order to model a realistic human mobility, it was necessary to give a higher cost value to the steepest slopes and to allocate the minor cost in a range from 0 to 18%. The choice of a realistic modelling of the cost depending on the slope is usefully discussed by Llobera and Sluckin (2007), where they base their computation on the metabolic effort to climb and descend a slope.[11] The nine classes received the following classification: 0–5%, 5–7%, 7–11%, 11–15%, 15–18%, 18–22%, 22–26%, 26–40%, 40–65%, with the related cost value of 1, 2, 3, 5, 7, 20, 45, 65, and 100. All the remaining values were eliminated from the raster. We calculated that in the plain areas, the cost would be lower, but in fact, the selection of the study area made the quantity of plain surface almost absent.

With these data, we created a first cost surface also giving a relative weight to every single raster: 40% for the slope, 30% for geological risks, 20% for soils, and 10% for rivers.

To evaluate quantitatively the correspondence between the historical path and the computed path, we used the buffer zone method suggested by Goodchild and Hunter.[12] With this method, we computed a buffer of 100 m around the historical road and then measured the percentage of each LCP lying inside the buffer?.

After performing the first least-cost path, the resulting track was very similar to the reconstructed path for the first 2 km and the last 2.5 km over a total length of about 20 km, therefore

[10] Citter and Arnoldus-Huyzendveld 2011: 86–99.

[11] Llobera and Sluckin 2007: 206–17.
[12] Goodchild and Hunter 1997: 299–306.

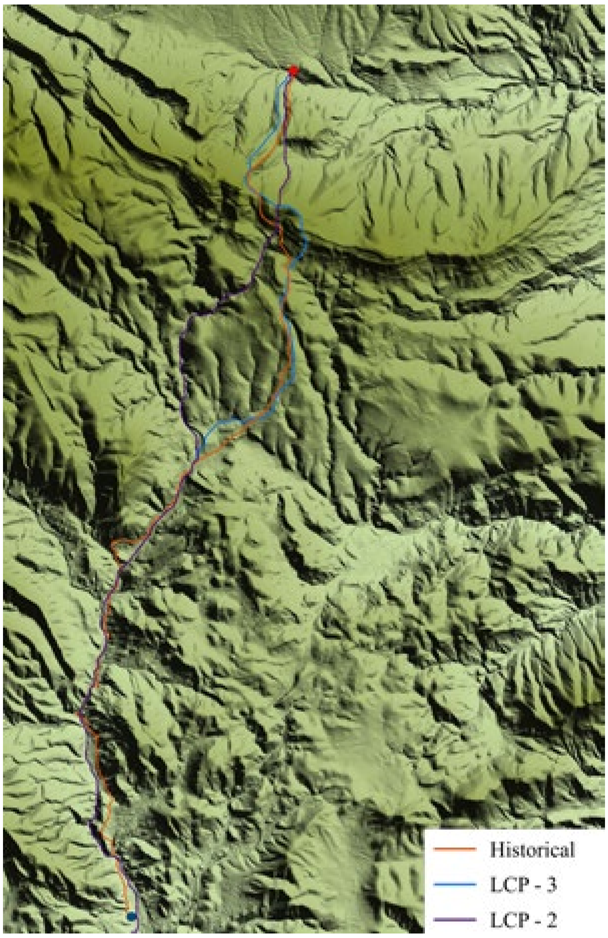

Fig. 5.

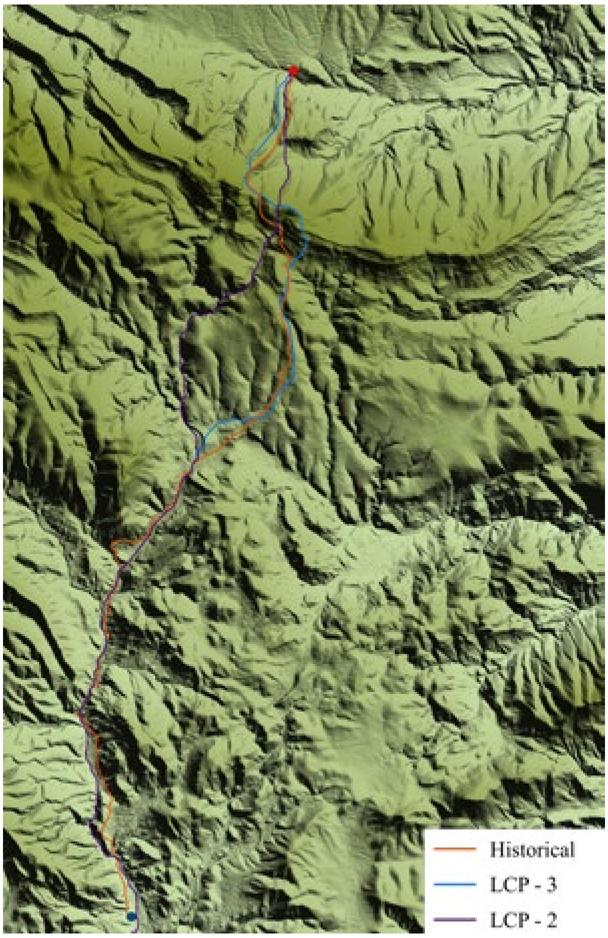

Fig. 6.

22.5% of the total length. In the central stretch of the track, there was no settlement or archaeological evidence that could justify the path itself and the slope played the most important role.

For the second attempt, we added some attractors and considered the water supply from rivers and natural springs. In general this computation covered more of the path that we proposed as reconstruction, and especially the first 10 km. By carefully analysing the reconstructed path, it was evident that in the last 10 km there was no trace of rivers, only sporadic springs. Although in general the path was better than that of the first attempt, the last stretch diverged more from the reconstruction. In this case we improved this coincidence to about 50% of the total length.

Another trial was undertaken to refine the calculation of the path by splitting the area in two parts and analysing them separately. For the southern part, the result was satisfactory; there was no need to make any changes. For the northern part, a useful choice was to change the weights of the attractors and the slope. This third attempt generated the best result. It gave an overall correspondence of about 15 km over 20 km (75%), inside a buffer of 100 m, which can be considered as a satisfactory result for an analysis of this kind.

5 Conclusions

From an interpretive point of view, this study could be read as follows: a) without any doubt, the main reason for the development of a road over a mountainous area lies in the slope; this is also the only tangible evidence when we do not possess substantial sources of information; b) nonetheless, the water supply worked as an important attractor when considered at an appropriate distance from the path.

Applying a postdictive approach to this kind of analysis could help to understand which factors may have influenced the twists and turns of a road. It is important to remember that a path has a long life and changes quite often, so it is almost impossible, especially in the case of marginal areas such as Àger, to obtain a perfect reconstruction. In more general cases, the approach by 'trial and error' could help to discover the logic behind the shape of the track, although we know that we cannot base a study in a totally environmentally deterministic way. The building of a settlement could reinforce the stability of a path or even attract a distant route to it, but a natural disaster such as a landslide could generate a permanent change. In this example, it has been shown how the simple presence of water can completely change a path in a mixed area. It is conceivable that after the plain and faced with multiple solutions, the most suitable way to reach the mountain was through a valley (the

Valley of Farfanya) with a water supply and an easy straight route, as it continues today.

The traditional reconstruction was based on the archaeological evidence and written sources. The computer helped us to consider more factors, such as the importance of the water supply. Considering only the slope factor for a heterogeneous landscape could produce a multiplicity of accessibility solutions that would not be satisfactory for our purpose. We know that human decisions may not follow mathematical logic and that more than one factor is involved in the creation of a path. Indeed, not only is energy saving to be considered but also all the features related to a certain type of travel in a certain period in history. In addition, the use of the path in the course of time must be discussed and may change its evolution.

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Bibliography

Bolòs, J. 1993. La xarxa viària catalana a l'alta edat mitjana. Una aproximació des de la cartografía. *Anuario de Estudios Medievales* 23: 3-26.

Bell, T., Wilson, A., Wickham, A. 2002. Tracking the Samnites: Landscape and Communications Routes in the Sangro Valley, Italy. *American Journal of Archaeology* 106: 169-86.

Carreras, C. and De Soto, P. 2008/2009. La red de comunicaciones romana en Cataluña: actualización y metodología. *Anas*, 21-22.

Citter, C. Arnoldus-Huyzendveld, A. 2011. *Uso del suolo e sfruttamento delle risorse nella pianura di Grossetana nel medioevo.* Salerno, Artemide.

Fité Llevot, F. 1985. *Reculls d'historia de la Vall d'Àger*, Àger.

Gallardo, A. 1934. Una vía romana al coll d'Ager. *Butlletí del Centre Excursionista de Catalunya* XLIV: 26-7.

Goodchild, M. F., Hunter, G. J. 1997. A simple positional accuracy measure for linear features. *International Journal of Geographical Information Science* 11: 299-306.

Güimil-Fariña, A. and Parcero-Oubiña, C. 2015. 'Dotting the joins': a non-reconstructive use of Least Cost Paths to approach ancient roads. The case of Roman roads in the NW Iberian Peninsula, *Journal of Archaeological Science* 54: 31-44.

Herzog, I. 2013. The potential and limits of optimal path analysis. In Bevan A. and Lake M., (eds.), *Computational Approaches to Archaeological Spaces*: 186. Left Coast Press.

Llobera, M. and Sluckin T. J. 2007. Zigzagging: theoretical insights on climbing strategies. *Journal of Theorical Biology* 249: 206-17.

Llobera, M., Fábrega-Álvarez, P., Parcero-Oubiña, C. 2011. Order in Movement a GIS approach to accessibility. *Journal of Archaeological Science* 38: 843-51.

Riu, M. 1993. Els Camins Catalans. Analisi Arqueològica dels seus vestigis. *Anuario de Estudios Medievales* 23: 27- 43.

Sabaté, F. 1996. *L'expansió territorial de Catalunya (segles IX-XII): Conquesta o repoblació*? Lleida, Pagès.

Predict and Confirm:
Bayesian Survey and Excavation at Three Candidate Sites for Late Neolithic Occupation in Wadi Quseiba, Jordan

Philip M.N. Hitchings(1)
p.hitchings@utoronto.ca

Peter Bikoulis(1)
peter.bikoulis@mail.utoronto.ca

Steven Edwards(2)
steven.edwards@mail.utoronto.ca

Edward B. Banning(1)
ted.banning@utoronto.ca

[1] Department of Anthropology, University of Toronto, Canada
[2] Department of Near and Middle Eastern Civiliations, University of Toronto, Canada

Abstract: In 2012 and 2013, a team from the University of Toronto conducted survey of the Wadi Quseiba drainage in northwest Jordan. This survey's main goal was to discover evidence of Late Neolithic habitation and landscape use, which typical archaeological surveys in the region very rarely find. To improve the efficiency and frequency with which sites are located, we experimented with Bayesian optimal allocation methods, originally designed for naval searches during the 1940s. The survey's design began with a predictive model in a GIS environment in which we assigned prior probabilities to landscape elements thought most likely to have survived the severe alteration of the landscape that has occurred since the Neolithic in this highly eroded region. Optimal-allocation algorithms, performed iteratively on the basis of each day's survey results, guided the allocation of survey effort to spaces with high probability densities, given past survey coverage. After two survey seasons, we conducted small-scale excavations in 2014 on "candidate sites" located during survey. This paper will discuss the survey methods and briefly touch on the results of these excavations, which verified that two "candidates" were Yarmoukian and Wadi Rabah Late Neolithic sites.

Keywords: Survey, Bayesian allocation, Jordan, Neolithic, Geoarchaeology

1 The Problem

The rationale behind the field project that is the focus of this paper is the strong likelihood that Neolithic sites are vastly under-represented in Jordan's archaeological inventory. This under-representation carries with it the risk that current interpretations of Neolithic development and ways of life, including patterns and changes in settlement and economic activity, are highly skewed by those few sites that have been located — mostly by accident — to date. The Late Neolithic and transition to the Chalcolithic suffer particularly from this under-representation (Banning *et al*. 1994).

Several factors contribute to this problem. For many decades, Near Eastern archaeologists showed greater interest in other periods, focusing on questions such as the beginnings of agriculture at the very beginning of the Neolithic or on social and political developments in the Bronze Age and later. Another notable factor is the inherent difficulty of locating small, relatively ephemeral sites that appear to constitute most of the archaeological inventory of the Late Neolithic. Compared to the 'megasites' of the Pre-Pottery Neolithic B or the large urban sites of the Iron Age, the small farmsteads that may characterize the Late Neolithic are more difficult to locate and identify. Yet another is the nature of typical archaeological surveys in Jordan; many of these surveys have been low in intensity, had large gaps in coverage, or had crews that lacked expertise in the identification of prehistoric material culture. The influence of geological factors is also very important. In the deeply dissected territories bordering the Jordan Rift Valley, erosion has destroyed many parts of the Neolithic physical landscape while burying much of what remains under colluvium and alluvium (Field and Banning 1996; Hitchings *et al*. 2013). Consequently, a large proportion of Neolithic sites owe their discovery, not to systematic surveys, but rather to accidental exposure during road construction and similar development activities (Banning 2015). Our experiments with survey methods represent an attempt to overcome some of these issues and to fill gaps in our knowledge of Neolithic prehistory, especially Late Neolithic settlement activity, by improving our opportunities for the discovery of small, early Holocene archaeological sites in the modern landscape. This is accomplished with the implementation of new survey techniques that are developed with the particular goal of improving the detection of rare sites or those otherwise difficult to locate. This goal differs from that of archaeologists who tend to apply the most commonly used survey techniques. Most often these archaeologists seek to provide representative samples of some target population. Instead, we present here a method intended for use in seeking to detect particular site types rather than a representative sample. This may be thought to increase bias toward one type of site at the expense of others. Our goal, however, is to correct the bias that is often inherent in the most commonly applied methods of archaeological

Fig. 1. View of terraces in Wadi Quseiba with a modern channel now well below the early Holocene valley floor. Polygon 117 is the terrace at far right.

survey, which often fail to account for the impacts of landscape changes that affect the detectability of certain site types and in fact bias the perceived distributions of archaeological materials towards those that are most obtrusive and thus most readily located.

1.1 Problems Inherent in the 'Landscape'

In such a geologically active area as northern Jordan, the modern physical landscape bears at best a very loose similarity to that of the early Holocene. The gradual disappearance of Lake Lisan in the Late Pleistocene and early Holocene, along with tectonic activity, has led to the continual dropping of base drainage levels, and this has in turn caused deeper incision of the valleys that drain into the Jordan River. Old valley floors have been cut away, leaving only small remnants as terraces stranded some way up the valley walls (Fig. 1; cf. Vita-Finzi 1964; Cordova 2007; Maher 2011). Sediments removed from upper parts of these drainages have been redeposited downstream as alluvium on top of older surfaces, and steepening of the valley walls, in conjunction with Holocene deforestation, have caused colluvium to bury, sometimes deeply, the stream terraces that border the modern channel. In addition to these natural geological processes, anthropogenic alterations to the physical landscape can have similar effects. On the one hand, post-Neolithic agricultural practices can help to reveal archaeological remains, as when ploughing turns up artefacts, and large-scale earth-moving, as in road construction, and sometimes reveal buried archaeological sites. On the other, both agricultural practices and bulldozing to create new field terraces can effectively erase large portions of the ancient landscape, with effects somewhat similar to erosion. We argue that it is wasteful of survey effort to search places where erosion and deposition, or for that matter modern development, have made it impossible to find Neolithic deposits when the discovery of Neolithic sites is the main goal.

1.2 Problems of Visibility and Obtrusiveness

Some kinds of sites, such as large, Early Bronze Age tells, are highly obtrusive, especially where they stand out on a flat plain, and exhibit dense scatters of pottery on their surfaces. Earlier Neolithic sites typically show no more than scatters of lithics on the modern surface unless erosion or construction activity has dug into Neolithic deposits to expose some of the substantial architecture characteristic of the period. Late Neolithic sites, meanwhile, are usually much less obtrusive than either of these site types, exhibiting at best extremely low densities of pottery and lithics, the former sometimes being poorly preserved and difficult to identify, the latter consisting mainly of 'expedient' flakes that do not readily allow their assignment to any particular period.

To complicate things further, vegetation cover, in addition to the alluvium and colluvium mentioned in the last section, can severely impede the visibility of these low-density scatters.

1.3 Problems of Survey Method and Coverage

Archaeological surveys methods have received a good deal of attention both with regard to protocols for proper selection of survey units, often by some form of random, or stratified sampling to ensure realistic samples of some archaeological population, and also for proper transect or shovel test spacing (e.g. Plog *et al*. 1978; Ammerman 1981; Krakker *et al*. 1983; Nance 1983; Banning 2002; Banning *et al*. 2006). During pedestrian or surface survey, archaeological surveyors will typically place parallel transects across some set of geometrically shaped spaces, walk across them, and collect or record their finds of artefacts. If they find none, the assumption is often made that space is 'clear' of archaeologically interesting material and surveyors move on. Few projects resurvey a small sample of previously surveyed spaces to see if they may have missed anything.

There are lots of problems with this approach, some of which have been recognized in the past, although efforts to correct them have not necessarily followed. One major issue is that of transect spacing when investigating for archaeological materials that do not fall into the highly obtrusive category such as the tells, or other highly visible architectural remains mentioned above. If we take into consideration the spacing of archaeological surveyors as they walk along their transects in combination with both their effective 'sweep widths' (Banning *et al.* 2011) and the size of the geometrically shaped spaces that they happen to be surveying, it becomes clear that it is often the case that the proportion of any given space that is effectively surveyed is quite small. The proportion that is missed, in turn, is quite large. This leads to the conclusion that the assumption that a space, once surveyed, is clear of archaeologically interesting material is probably a false one. This assumption, however, tends to discourage reinvestigation of areas and is most likely to be good at finding only the most abundant and most obtrusive kinds of archaeological material. Another issue is the all too common mistake of ignoring the very real differences in geology and visibility that occur across the surveyed regions, and the effects that these will have on the different levels of coverage required for the ability to determine the existence of archaeological material on them.

2 Optimizing our Chances of Discovery

In Wadi Quseiba, northern Jordan, our main goal was to find Late Neolithic sites, which are difficult to find and identify. Secondarily, we wanted to find other late prehistoric sites from the Epipalaeolithic to the Early Bronze Age (*c.*15,000 to

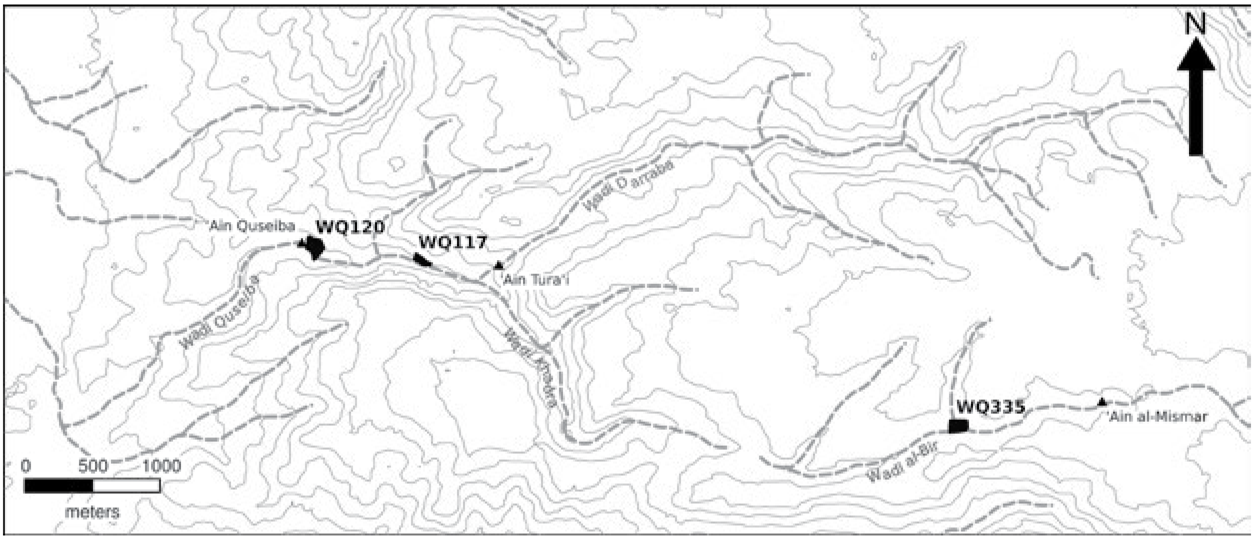

Fig. 2. Map of Wadi Quseiba's drainage basin showing the three 'candidate sites' WQ 120, WQ 117, and WQ335, as well as three of the springs in the area, marked by small triangles.

5000 years ago). In order to improve our chances of finding these more elusive kinds of sites, we employ a very different approach than the traditional, grid-based one.

2.1 The Predictive Model

Unlike typical surveys with geometrical survey units, we use satellite imagery and a GIS to define polygons that correspond to landforms that we suspect are remnants of the valley floor that have survived down-cutting since the Neolithic (Fig. 2). Most of these are now terraces stranded some distance above the modern wadi channels. Using basic elements of Bayesian probability modelling, as some authors have previously suggested (Nicholson *et al.* 2000; Banning 2002), we assigned prior probabilities to these polygons on the basis of previous experience and geoarchaeological work in nearby Wadi Ziqlab (Field and Banning 1996; Maher and Banning 2002; Maher 2011), and with emphasis on factors that appeared to be influences on Neolithic settlement in Wadi Ziqlab. For example, these remnants have higher probabilities when they are near springs or at the confluences of tributaries, since those were typical Neolithic choices in Wadi Ziqlab. Relatively low slope was another relevant factor, because areas with low grade would probably have been conducive to both settlement and agricultural activities. The addition of more recent colluvium, however, has often increased the slope on terraces that could have Neolithic remains, making it necessary to take this factor into consideration too.

We used these initial estimated probabilities to allocate our first survey effort in each portion of the survey region, and then updated the model in light of our results and survey coverage.

2.2 Optimal Allocation of Search Effort

After assigning these polygons prior probabilities of containing Neolithic sites based on expert knowledge — mainly gained in Wadi Ziqlab — these probabilities became the basis for the first iteration of survey. The calculations for this allocation take into account the measured areas of the survey polygons, the distance travelled by each surveyor, and the effective sweep width of the survey team. Collection and timely processing of such data benefitted greatly from the use of tablet computers (iPads) running FileMaker Go™ software, since it was necessary to update our probability estimates on a daily basis.

In a particular sub-region of our total survey territory, allocation of search effort to each eligible polygon is related to the logarithms of their probability densities (r), that is, the prior probability that the polygon contains Neolithic material divided by the polygon's area:

$$\square_i = \log r_i - \frac{1}{A}(\log A_1 \log r_1 + \log A_2 \log r_2 + \cdots + \log A_n \log r_n) + f/A \qquad (1)$$

where f_i is the amount of survey effort in space i, r_i is the probability density of space i, A_i is the area of space i, A is the total area of all survey areas, and f is the total amount of survey effort available (generally the number of metres we can expect all surveyors to walk in a day) (Banning 2002). The United States Navy originally developed this allocation algorithm in the 1940s to aid the search for German U-boats but it is now used for search and rescue, especially at sea. We use it to guide the amount of survey effort, measured in metres of transect walked, that we devote to each polygon. Some spaces get no survey at all, while others receive significant amounts of survey, even if they have already been surveyed before.

Next, we take seriously the likelihood that even very proficient surveyors are far from perfect detectors and we measure the likely success of our completed survey with sweep widths. These allow us to assess the probability — given the amount of effort we have expended and various environmental factors — that we have failed to detect archaeological targets that occur within a surveyed polygon. We discuss this in more detail elsewhere (Banning *et al.* 2011; Stewart *et al.*, this volume) but, in plain English, Effective Sweep Width (W) is the width

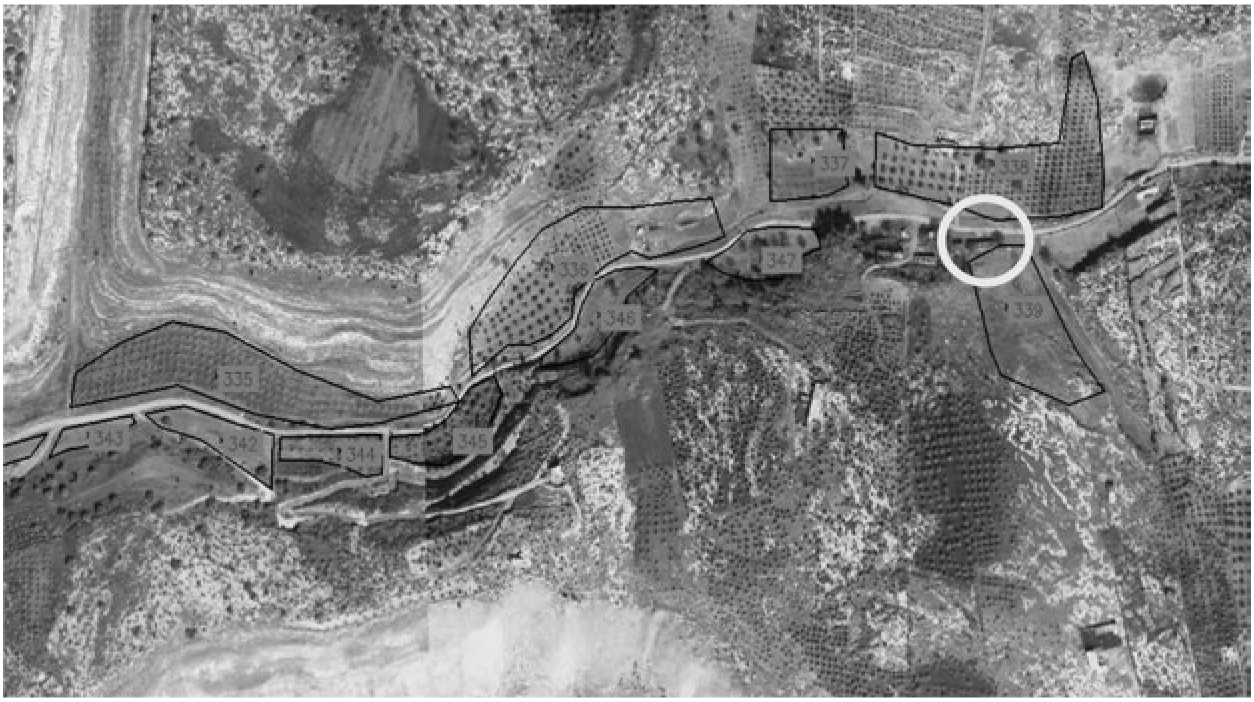

Fig. 3. Landforms or 'polygons' with significant probability of being remnants of the early Holocene valley floor in one portion of the Wadi Quseiba Project's survey territory, Wadi al-Bîr. Note the spring (in the circle) to the right and the confluence of tributary streams at far left.

of a band within which the number of artefacts we fail to detect is equal to the number we find outside that band. Survey coverage is the product of sweep width and the total length of all transects walked, divided by polygon area.

The main implication for our predictive model is that the probability that any space contains archaeological residues of interests declines after we survey it without finding anything, but not necessarily by very much. The Bayesian approach and updated estimates of our survey coverage to date allow us to assess that posterior probability. The posterior probability after an 'unsuccessful' set of transects can sometimes be higher, just because of interactions with other polygons whose probabilities went up or down by various amounts, but typically the probabilities decline with increasing survey effort without finding anything (Fig. 3). The transect lines gradually accumulate, intersecting at oblique angles to maximize coverage.

Given new probability estimates each time we resurveyed any portion of the survey region, reapplying the Bayesian allocation formula in an iterative fashion has real effects. Take polygon 335, for example. It has many characteristics that would allow us to assign it high prior probability, being near a spring and at a confluence and having fairly low slope. Yet several iterations of survey allocation, in which we found no artefacts on this terrace at all, caused its posterior probability to decline, but not low enough to prevent further resurvey. On our fourth set of transects on this polygon (also the last day of survey!), we found several Neolithic sherds and a couple of lithics and ground-stone fragments. This made polygon 335 a good candidate for a Late Neolithic site.

Carrying out the iterative modelling with revised probabilities to make allocations of additional effort gradually increased our total coverage, with posterior probability steadily declining until it abruptly rose to an estimate near 1.0 on the last increment of survey.

3 Testing the Candidate Sites

A year after our last survey, we returned to conduct test excavations at three 'candidates' for sites at polygons 120, 117, and 335.

The first of these, at polygon 335, confirmed that it was a Late Neolithic site of the 'Wadi Rabah' culture, probably representing the remains of a small settlement damaged by modern arboriculture. Among the finds in one of the excavation units was a Late Neolithic surface with an upturned mortar, but no substantial architecture (Fig. 4). Other units revealed surfaces with stone features of unknown purpose and many of the units yielded flint sickle elements and pottery with distinct Wadi Rabah features, including distinctive incised decoration in some cases.

At polygon 117, the test excavations also confirmed a Yarmoukian site dating a little earlier in the Late Neolithic than the Wadi Rabah one at polygon 335, despite deep colluvium. There, most of the 1 x 2 m test units found only low densities of Yarmoukian artefacts in a very deep colluvium, but units closer to the toe of the slope, where colluvium was shallower and erosion of the terrace edge was a factor, revealed parts of several large pits, some of which could be pit-dwellings. One of these contained a large ash-filled feature, one had several mud bricks lining one edge of the pit, and all three contained dense

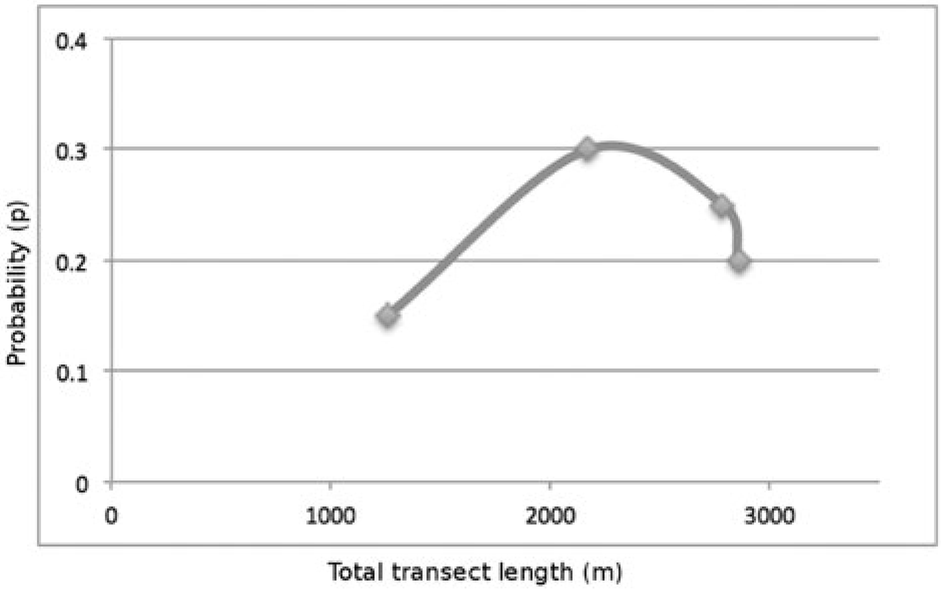

FIG. 4. CHANGES IN THE PROBABILITY ESTIMATE IN ONE SURVEY POLYGON WITH INCREASING ALLOTMENTS OF SURVEY, AS MEASURED IN METRES WALKED.

FIG. 5. NEOLITHIC SURFACE IN UNIT J11 AT POLYGON 335. NOTE THE UPTURNED MORTAR SITTING ON THIS SURFACE (BOTTOM OF PICTURE).

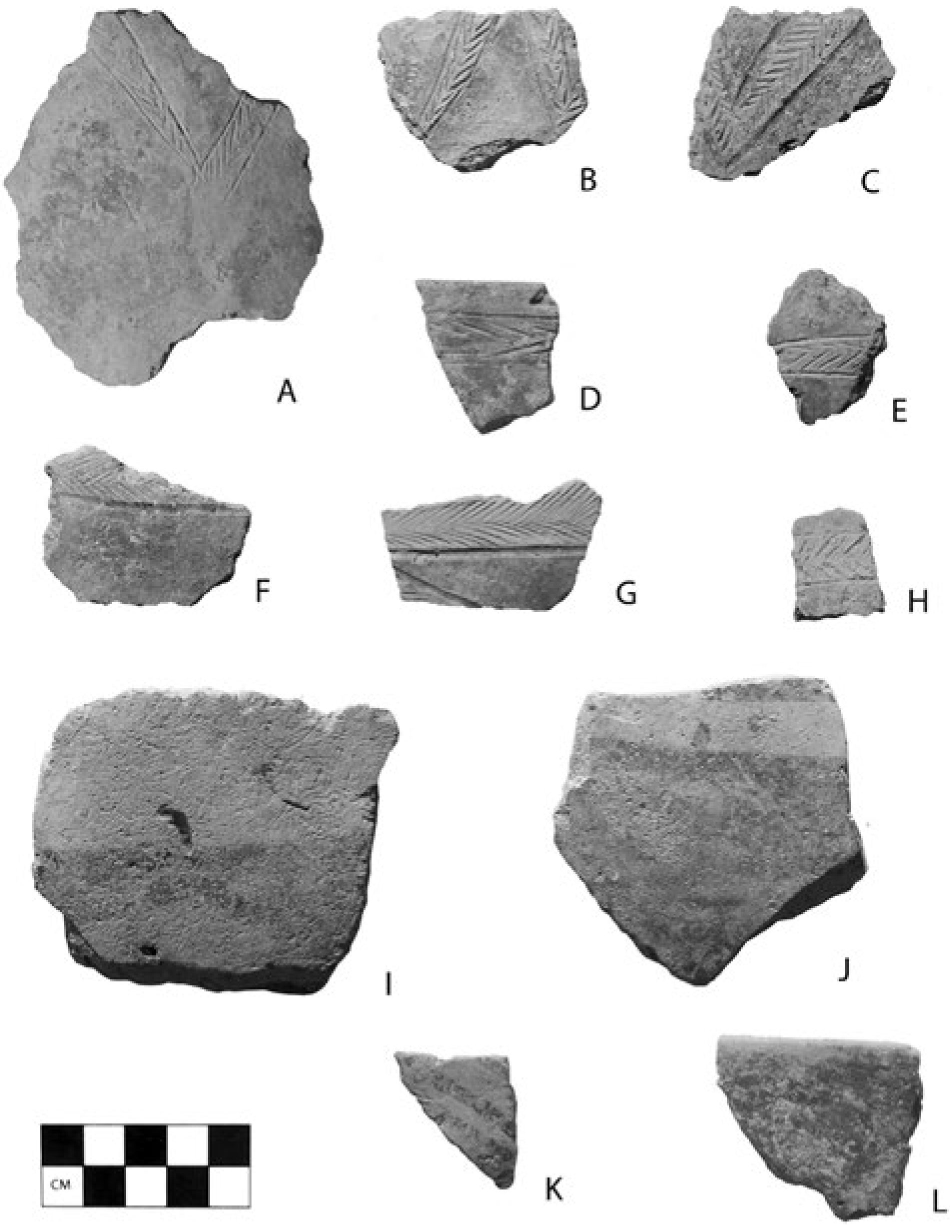

Fig. 6. Examples of decorated Yarmoukian pottery from polygon 117 in Wadi Quseiba.

concentrations of Yarmoukian artefacts, including distinctive decorated pottery (Fig. 5) and a broken stone figurine.

Another candidate site at polygon 120, next to a major spring, is less certainly identified, but appears to belong to the Pre-Pottery Neolithic (PPNB). It exhibits many long blades and some bladelets in its lithic assemblage and only pottery of the Iron Age and later. Our test excavations did not reach undisturbed Neolithic deposits here, probably because they are buried under colluvium and a substantial Iron Age occupation, but the high blade:flake ratio and lack of pre-Iron Age pottery suggests that there is a PPNB site here. Only further, and larger, excavations could confirm this.

Over two field seasons, we refined our methods somewhat and had some success in finding Neolithic and possible Neolithic site locations, or 'candidates'. In addition to the site already mentioned, subsequent tests confirmed a Yarmoukian site dating a little earlier in the Late Neolithic, with two pit-houses as well as many lithics and pottery and a broken stone figurine. Another candidate is less certainly identified, but appears to belong to the Pre-Pottery Neolithic.

4 Conclusions

Our experiments with sweep widths and Bayesian optimal allocation of survey effort have proved quite promising.

They have yielded more efficient use of survey resources by focusing survey, sometimes repeatedly, on spaces that are most likely to result in the discovery of archaeological materials of the greatest interest, even when these are ephemeral and hard to see. Use of this method allowed us to identify several 'candidate sites' in places that might never have been noticed through traditional survey methods based on walking parallel transects across arbitrary rectangular survey squares. Indeed, subsequent tests of 'candidates' by excavation confirmed that at least two of these were Late Neolithic sites. Given how unobtrusive these sites are, it is quite unlikely that they would ever have been found in a conventional survey.

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Bibliography

Ammerman, A. J. 1981. Surveys and archaeological research. *Annual Review of Anthropology* 10, 1: 63-88.

Banning, E. B. 2002. *Archaeological Survey*. New York, Kluwer Academic/Plenum Publishing.

Banning, E. B. 2015. Settlement shifts and site visibility. Where are the Neolithic sites? In Finlayson, B. and Makarewicz, C. (eds.), *Settlement, Survey, and Stone: Essays on Near Eastern Prehistory in Honour of Gary Rollefson*: 91-9. Berlin: ex oriente.

Banning, E. B., Hawkins, A. L., Stewart, S. T. 2006. Detection functions for archaeological survey. *American Antiquity* 71, 4: 723-42.

Banning, E. B., Hawkins, A. L., Stewart, S. T. 2011. Sweep widths and the detection of artefacts in archaeological survey. *Journal of Archaeological Science* 38: 3447-58.

Banning, E. B., Rahimi, D., Siggers, J. 1994. The Late Neolithic of the southern Levant: Hiatus, settlement shift or observer bias? The perspective from Wadi Ziqlab. *Paléorient* 20, 2: 151-64.

Cordova, C. 2007. *Millennial Landscape Change in Jordan: Geoarchaeology and Cultural Ecology*. Tucson, University of Arizona Press.

Field, J. and Banning, E. B. 1998. Hillslope processes and Archaeology in Wadi Ziqlab, Jordan. *Geoarchaeology* 13: 595-616.

Hitchings, P. M. N., Abu Jayyab, K., Bikoulis, P., Banning, E. B. 2013. A Bayesian approach to archaeological survey in north-west Jordan. *Antiquity* 87: project gallery. Available at: http://antiquity.ac.uk/projgall/hitchings336/

Koopman, B. O. 1980. *Search and Screening: General Principles with Historical Applications*. New York, Pergamum Press.

Krakker, J. J., Shott, M. J., Welch, P. D. 1983. Design And evaluation of shovel-test sampling in regional archaeological survey. *Journal of Field Archaeology* 10, 4: 469-80.

Maher, L. 2011. Reconstructing paleolandscapes and prehistoric occupation of Wadi Ziqlab, northern Jordan. *Geoarchaeology* 26, 5: 649-92.

Maher, L., and Banning, E. B. 2002. Geoarchaeological survey and the Epipalaelithic in northern Jordan. *Antiquity* 76: 313-4.

Nicholson, M., Barry, J., Orton, C. 2000 Did the burglar steal my car keys? Controlling the risk of remains being missed in archaeological surveys. Paper presented at the Institute for Field Archaeology conference, Brighton, April 2000. http://eprints.ucl.ac.uk/2738/1/2738.pdf.

Stone, L. D. 1975. *Theory of Optimal Search*. New York, Academic Press.

Vita-Finzi, C. 1964. Observations on the late Quaternary of Jordan. *Palestine Exploration Quarterly* 95: 19-33.

Predicting Survey Coverage through Calibration: Sweep Widths and Survey in Cyprus and Jordan

Sarah T. Stewart(1)
salstew@gmail.com

Edward B. Banning(2)
ted.banning@utoronto.ca

Steven Edwards(3)
steven.edwards@mail.utoronto.ca

Philip M.N. Hitchings(2)
p.hitchings@utoronto.ca

Peter Bikoulis(2)
peter.bikoulis@mail.utoronto.ca

[1] Archaeology Centre, University of Toronto, Canada
[2] Department of Anthropology, University of Toronto, Canada
[3] Department of Near and Middle Eastern Civilizations, University of Toronto, Canada

Abstract: Many archaeological surveys make the assumption that a single field walk by a survey team is sufficient to determine whether a space does or does not contain archaeological materials. Making retrodictive statements about site distributions or locational preferences relies on the accuracy of this assumption. We instead take the approach that the probability of detecting artefacts by field walking is less than 1.0 and use calibration surveys to calculate the survey teams' 'sweep widths'. Our calibrations took place in typical fields in which we 'seeded' artefacts in known locations, but otherwise simulated actual survey conditions. Sweep widths, in combination with knowledge of the total length of transects walked, then allow us to calculate survey coverage. In prehistoric surveys in the Tremithos Valley, Cyprus, and Wadi Quseiba, Jordan, continually updated estimates of coverage and its effect on the probability that survey areas contained undetected sites were crucial elements in survey planning, execution, and evaluation.

Keywords: Survey, coverage, Cyprus, Jordan, Neolithic

1 Survey Regions

The Wadi Quseiba Project conducted surveys in several wadis that drain into the Jordan Valley west of the town of Taiyyiba, in northern Jordan (Fig. 1). The survey's main goal was to locate and identify late prehistoric sites, and particularly Epipalaeolithic, Neolithic, and Chalcolithic sites, which tend to be under-represented in typical surveys in Jordan. During this survey, we experimented with new approaches, including use of a predictive model that takes into account the vast changes to the physical landscape that have occurred since the Late Neolithic (Hitchings *et al.*, this volume), and use of Bayesian optimal allocation to focus our survey efforts on spaces where we are likely to have the greatest success at detecting sites of interest. This latter process depended on our having reasonably accurate measures of our survey coverage of each space, as each iteration of the optimal allocation involved updating prior probabilities in light of our results to date, i.e. the probability that a space contained undetected archaeological materials of interest given the total amount of coverage.

The Tremithos Neolithic Survey Project is a pedestrian survey of sections of the Tremithos River Valley in south-central Cyprus. The river runs from the Troodos foothills south-east to the sea, just west of Larnaca. The goal of the project is to identify the potential for early Neolithic use of the valley to access the resource-rich areas in the Troodos foothills to the north, particularly the abundant and high-quality chert sources. Previous survey work identified numerous chert sources and stone tool scatters from the eastern foothills region and into the headwaters of the Tremithos River Valley system. Geochemical analyses (Neutron Activation Analysis) indicate that there are clear links between specific sources, scatters, and an Early Neolithic (PPNA) site in the Troodos foothills (Stewart 2004, 2006; McCartney *et al*. 2006, 2007, 2008, 2010, 2012; Manning *et al*. 2010). The research conducted in the Tremithos Valley extends this knowledge to a river system that could have provided a plausible transportation route from the sea to this central area. To date, we have identified numerous stone tool scatters, including a large Neolithic site on a major confluence and a possible very early Neolithic site (P229, see below) located on a spur above the river.

As in the Wadi Quseiba Survey, the Tremithos Neolithic Survey Project has employed Bayesian optimal allocation of survey effort, so again it was critical to be able to estimate coverage and to update these estimates daily.

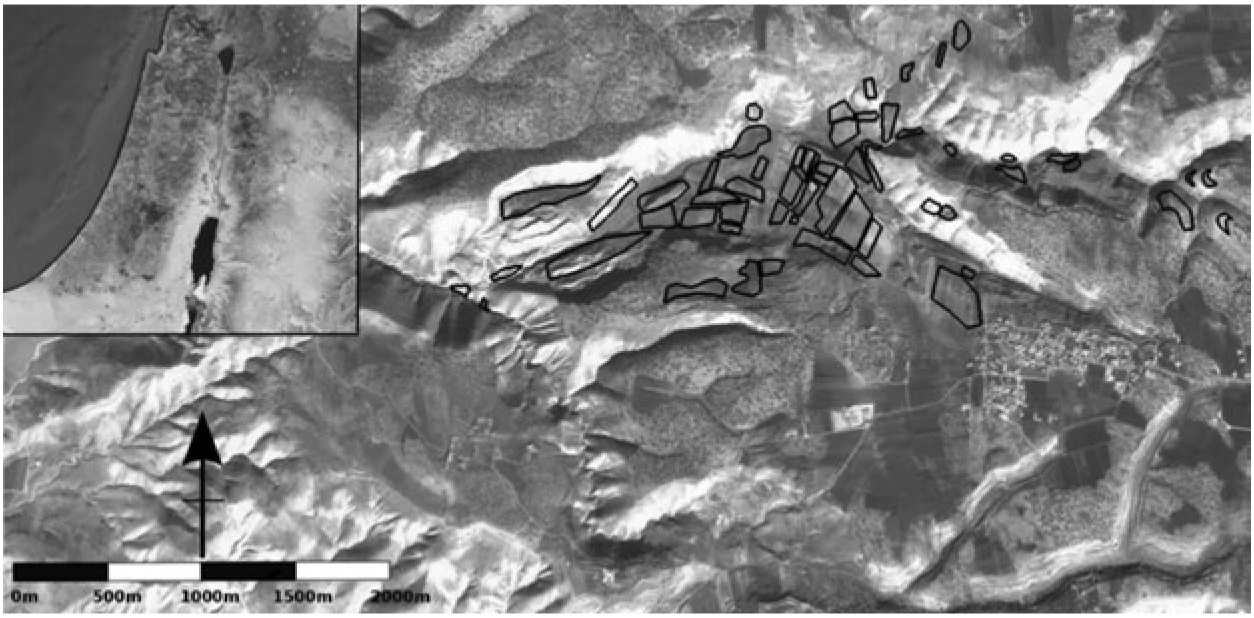


Fig. 1. Aerial view of Wadi Quseiba, Jordan. The wadi contains several springs, and drains into the Jordan Valley to the west. Survey areas are outlined in black.

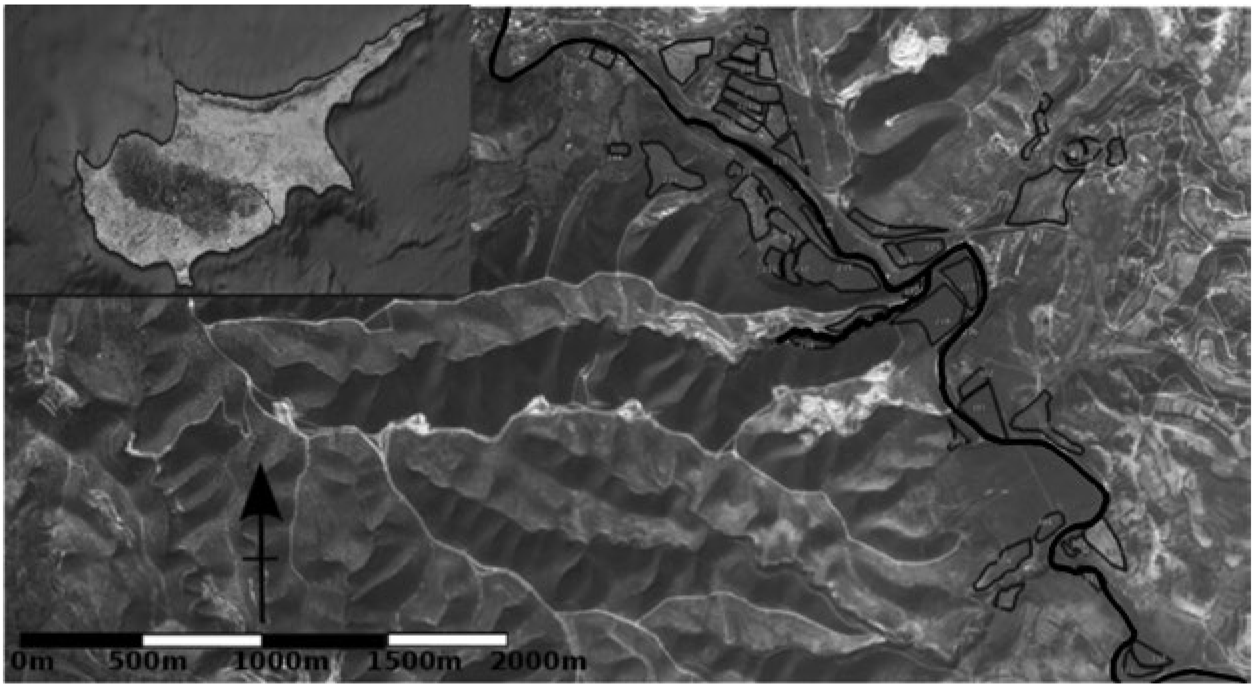
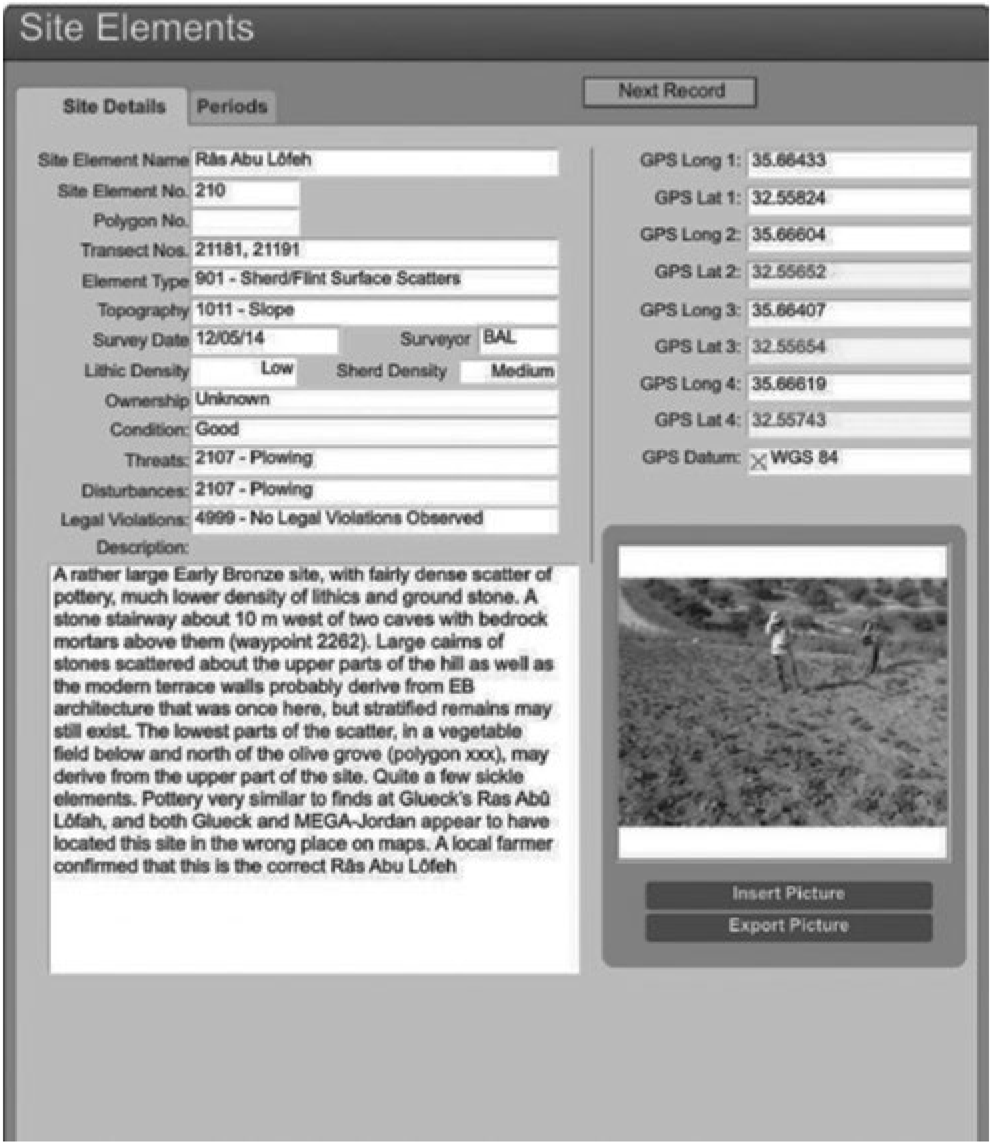


Fig. 2. Aerial view of the Tremithos River, Cyprus. The river flows south-east where it drains into the Mediterranean. Survey areas are outlined in black.

2 Data Collection

Both the Wadi Quseiba Project and the Tremithos Neolithic Survey adopted a paperless format for data collection. Each surveyor is assigned an iPad equipped with a custom FileMaker Go™ database. This method has several advantages. Team members can integrate image and geospatial data directly into the database using the iPad's front-facing camera and on-board GPS. This means the surveyor does not have to carry a separate camera or hand-held GPS unit while surveying.

Moreover, having all transect data input digitally in the field means that data processing can begin immediately. This is particularly important since each day's results are used to modify coverage estimates to use in updating probabilities


Site Elements

Site Details | Periods

Next Record

Site Element Name	Râs Abu Lôfeh
Site Element No.	210
Polygon No.	
Transect Nos.	21181, 21191
Element Type	901 - Sherd/Flint Surface Scatters
Topography	1011 - Slope
Survey Date	12/05/14
Surveyor	BAL
Lithic Density	Low
Sherd Density	Medium
Ownership	Unknown
Condition:	Good
Threats:	2107 - Plowing
Disturbances:	2107 - Plowing
Legal Violations:	4999 - No Legal Violations Observed

GPS Long 1:	35.66433
GPS Lat 1:	32.55824
GPS Long 2:	35.66604
GPS Lat 2:	32.55652
GPS Long 3:	35.66407
GPS Lat 3:	32.55654
GPS Long 4:	35.66619
GPS Lat 4:	32.55743
GPS Datum:	WGS 84

Description:

A rather large Early Bronze site, with fairly dense scatter of pottery, much lower density of lithics and ground stone. A stone stairway about 10 m west of two caves with bedrock mortars above them (waypoint 2262). Large cairns of stones scattered about the upper parts of the hill as well as the modern terrace walls probably derive from EB architecture that was once here, but stratified remains may still exist. The lowest parts of the scatter, in a vegetable field below and north of the olive grove (polygon xxx), may derive from the upper part of the site. Quite a few sickle elements. Pottery very similar to finds at Glueck's Ras Abû Lôfah, and both Glueck and MEGA-Jordan appear to have located this site in the wrong place on maps. A local farmer confirmed that this is the correct Râs Abu Lôfeh

Insert Picture

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FIG. 3. SCREENSHOT OF ONE OF THE DIGITAL RECORDING FORMS FROM THE WADI QUSEIBA PROJECT, IN FILEMAKER GO™.

for all subsequent survey allocation in a given survey unit (polygon).

3 Detection Functions and Sweep Width

The measure that we use for the detection probability of artefacts is effective sweep width (W). This is a measure that relates detectability to the perpendicular distance, or range, away from the centre of a survey transect. Although we can model the relationship between range and probability of target detection in a number of ways (Fig. 4), our experience has shown excellent fit to an exponential range function of the form,

$$p(r) = be^{-kr^2} \quad (1)$$

where is the probability of detection at range r in metres, is the y-intercept (expected detection right on the transect), is the exponential constant (approximately 2.718), is a constant that summarizes effects on detectability, is the range, and describes the steepness of falloff in detectability (see Koopman 1980: 64).

3.1 Calculating Sweep Width

We fit our data from calibration transects (described below) to the exponential detection function using non-linear regression and then integrate the area under the curve to find sweep width. A more intuitive way to characterize effective sweep width is as the range within which the number of artefacts that fail to be detected is equal to the number of artefacts found outside it (Fig. 5; Banning *et al.* 2011; Cooper *et al.* 2003: 18–24; Frost 1999a: 7; Koopman 1980: 65–66). In a map view, a surface survey along a particular distance might, for example, find 88 out of 100 artefacts that lie within 2 m of the transect centre and 12 artefacts outside that range (Fig. 4c).

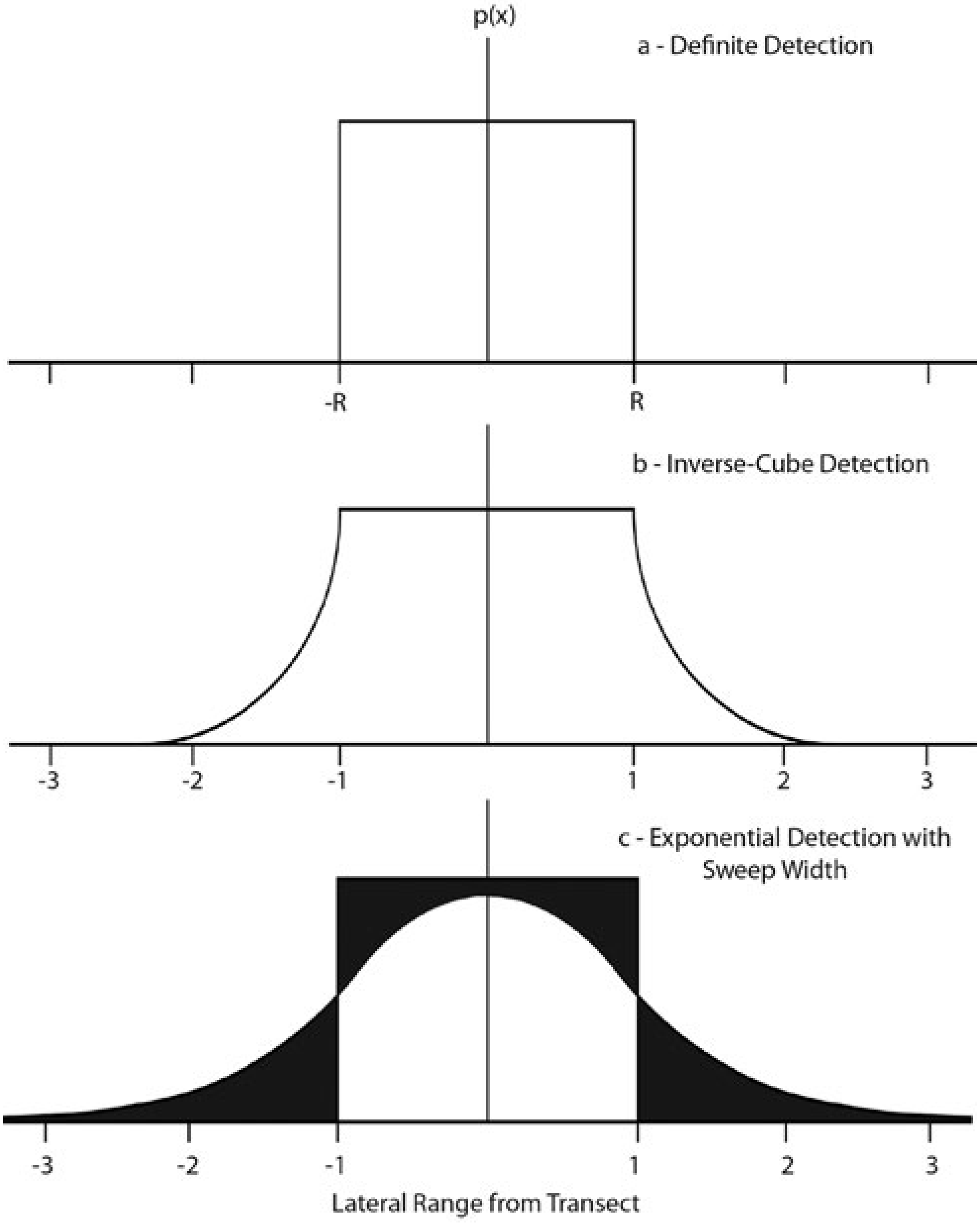


Fig. 4. With definite detection (a), all artefacts within the range (R) are detected, but those lying outside the range are not detected. Inverse-cube detection (b) allows for a decreasing probability of detection as range increases. Combining exponential detection with sweep width (c) is an improvement on both detection functions (see below). The shaded area above the curve and within R1 represents the artefacts not detected within that range, and it is equal to the shaded area beyond R1, which represents artefacts detected beyond R1.

3.2 What is Coverage?

Once we have sweep width (W), it is easy to assess coverage as it is just the total area 'swept' divided by the area of the surveyed space:

$$C = (W*L)/A \qquad (2)$$

where C is coverage, W is sweep width, L is the total length of all transects in A, and A is the total area of the surveyed space (Koopman 1980; Stone 1975; Frost 1999b).

3.3 Sweep Width with Calibration

In order to determine the appropriate 'sweep widths', it was necessary to establish a measure of our team's effectiveness at identifying artefacts in fields with different types of ground cover. To do this, we conducted a series of tests that simulated actual survey conditions. We seeded several test areas with potsherds and lithic debitage of varying sizes and materials (local chert and clay vessels) that would be similar to those one would expect to find in typical prehistoric contexts, having first examined the fields to ensure that no 'real' prehistoric or

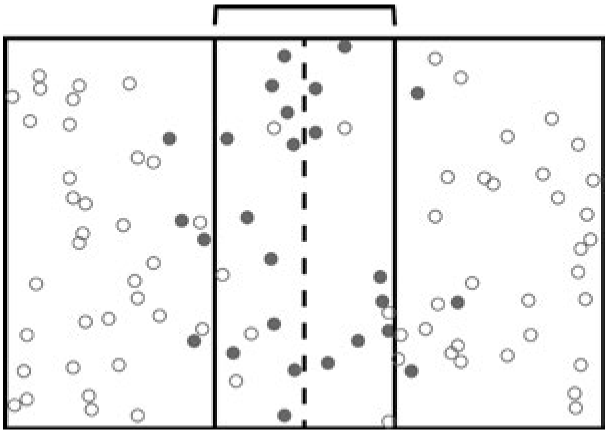


Fig. 5. Hypothetical transect showing effective sweep width (bracket). Undetected artefacts within the effective sweep width are equal to the number of detected artefacts outside the band; filled circles = detected artefacts; open circles = undetected artefacts.

other artefacts were present. For seeding, we assigned artefacts to either large (*c*.6–8 cm) or small (*c*.2–4 cm) categories. These we randomly distributed within a grid measuring 150 m long by 40 m wide (Fig. 6), but only the centre line of the grid was marked with 50 m tapes.

In Cyprus, we placed the experimental artefacts at random in two different fields, one a recently ploughed field, and the other an agricultural field with short wheat stubble. In Jordan, the test fields included a pasture with sparse vegetation and bare rock, a ploughed field planted at *c*.5 m intervals with young guava trees, a ploughed olive grove, with trees spaced about 5 m apart, and a field with approximately equal portions of harvested field with chaff, pasture with sparse oak trees, and rocky pasture with sparse shrubby vegetation, such as capers. Each surveyor then walked 150 m transects in these fields, while recording their finds on an iPad. Surveyors conducted multiple passes along this transect in the centre of the field, to obtain a large enough sample size, recording their finds as they went (Fig. 7). Each time a team member thought he or she saw an artefact, they recorded the type of artefact, their distance along the tape, and their estimate of the artefact's distance to the left or right of the transect line.

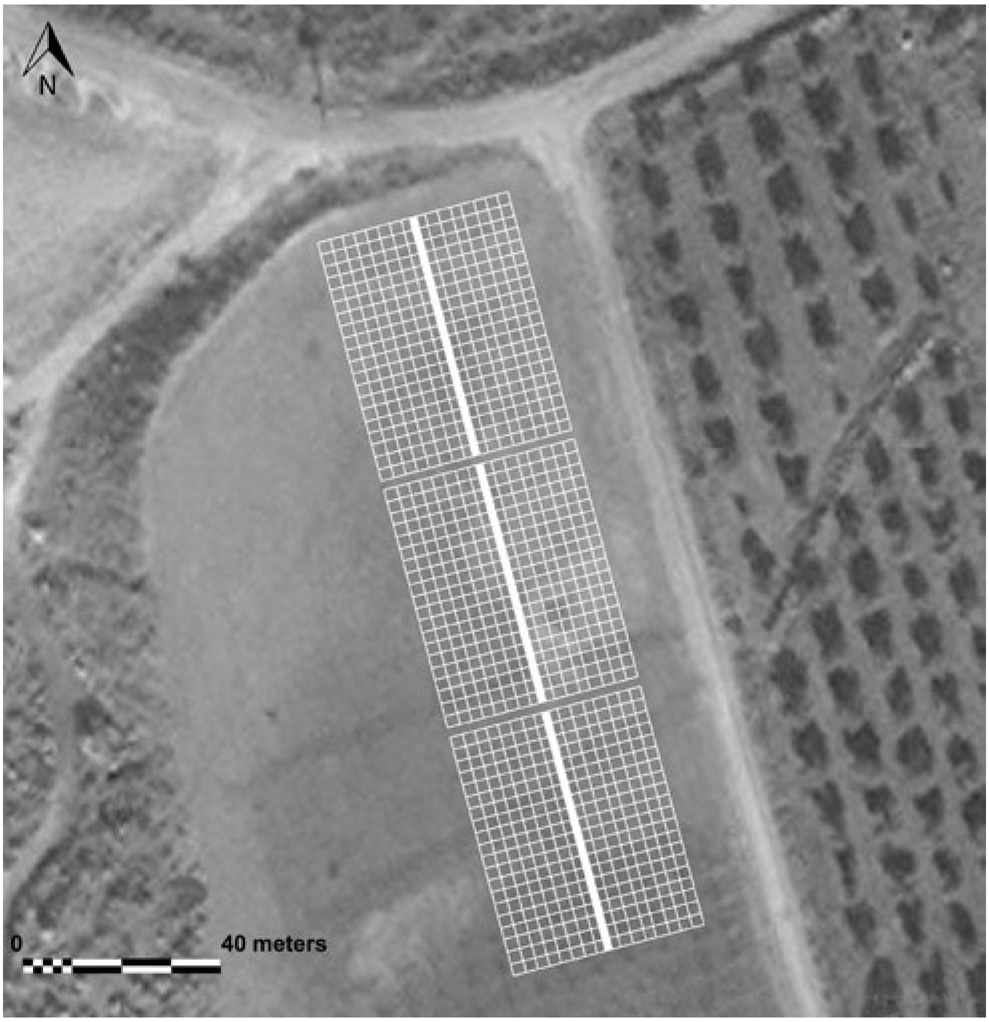
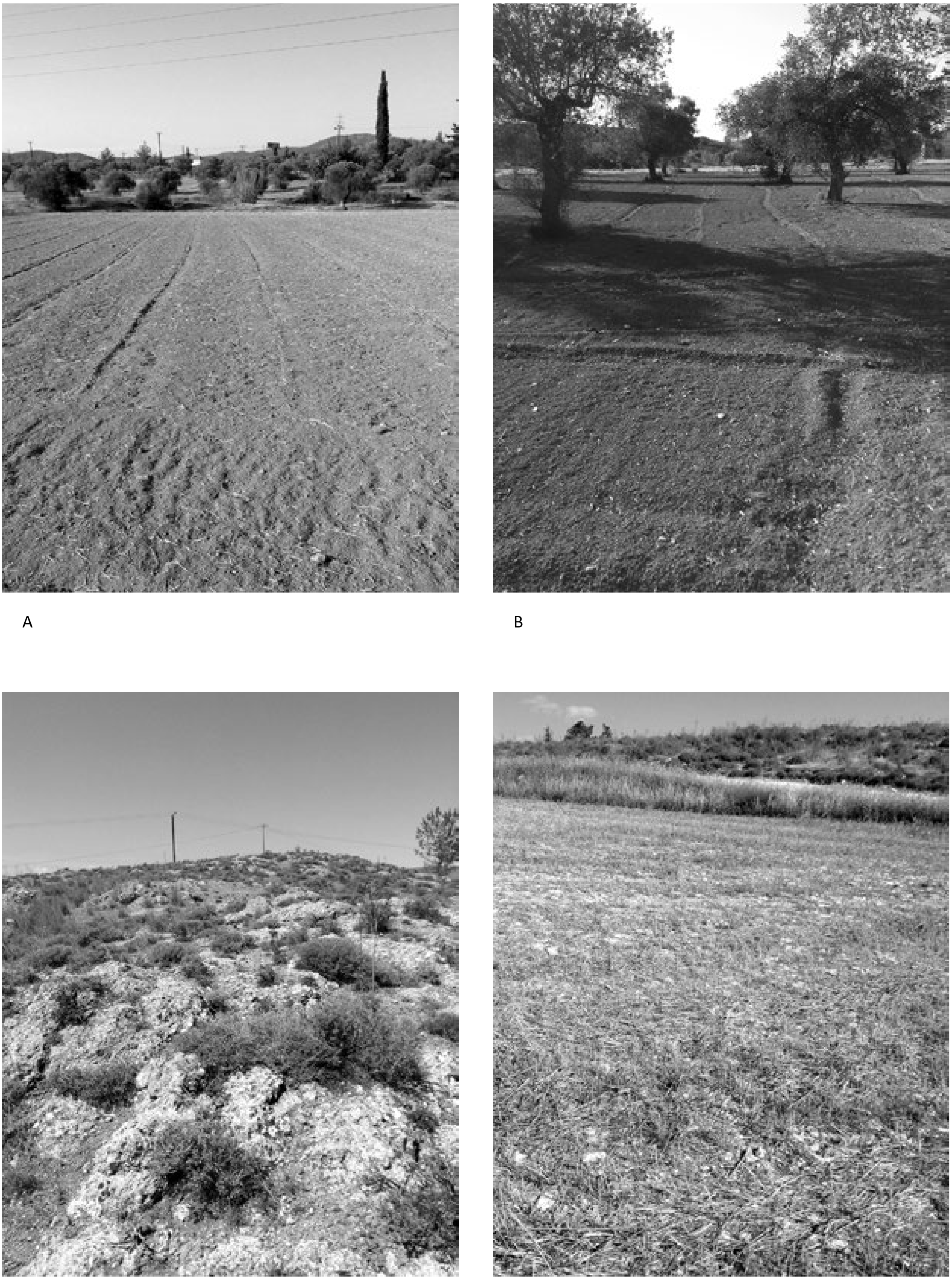


Fig. 6. Example of a calibration field. The total length of the grid is 150 m, divided into three 50 m segments. The width of the grid is 40 m (20 m on each side). The grid was only marked by tapes down the centre line.

Fig. 7. Example of a calibration record in FileMaker Go™, showing possible artefact detections (bottom), as well as transect information such as location and duration (top left)

The data collected from these test runs was then used to determine the number of successful detections that resulted from each calibration run, and these were used cumulatively to calculate average sweep widths for the entire team. As we did several such calibration runs over the course of each survey, this allowed us both to improve our estimates of sweep width over time and, importantly, to estimate the approximate coverage to date for any given survey area.

A wide range of factors can affect detection probabilities, including time of day, direction of walk, and surveyor experience. One of the most important factors is ground cover. Calibration should take place in a variety of conditions in order to determine more accurately an appropriate sweep width. Calibration should also take place as close to the actual survey as possible, to duplicate accurately personnel and environmental conditions.



A B C D

Fig. 8. Several examples of ground cover types commonly encountered while surveying in Cyprus and Jordan. In our survey areas, we frequently encountered (a) ploughed fields, (b) olive/fruit groves, (c) bare rock, and (d) fields with stubble.

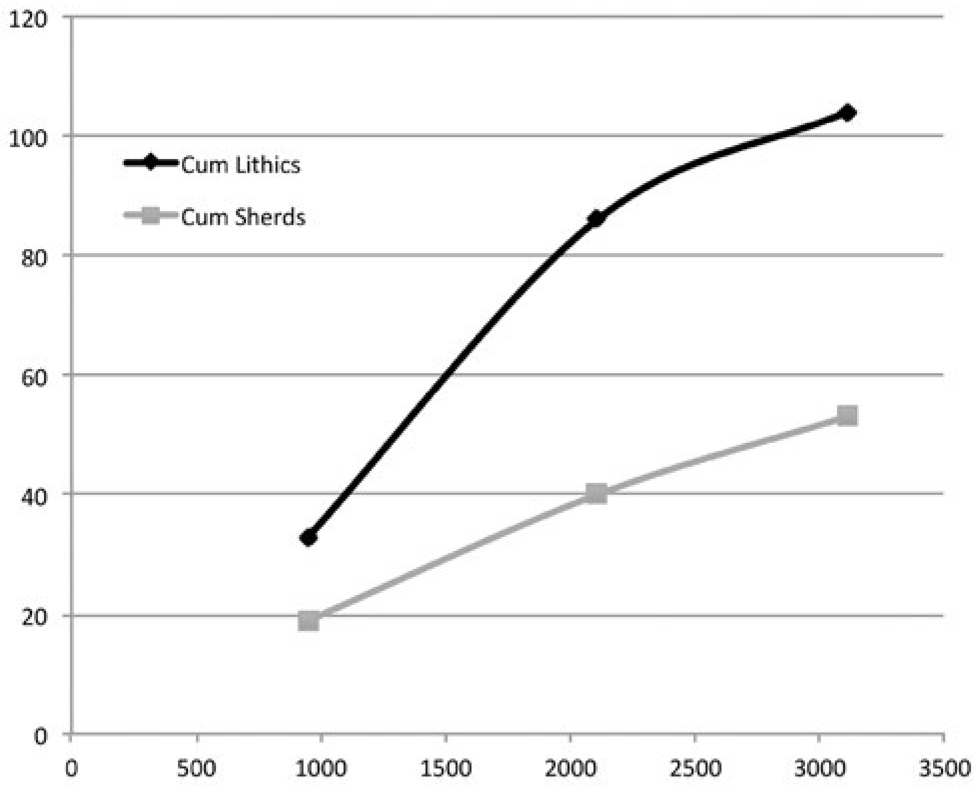


Fig. 9. Chart showing the relationship of the total effort (in metres walked, x-axis) to cumulative detection of artefacts (y-axis) in Polygon 229, an elongated terrace on the right bank of the Tremithos River, Cyprus. The polygon was surveyed on three different days. Coverage has a linear correlation with effort walked (as it is distance walked times W/A). Notice how detection of lithics has already begun to level off.

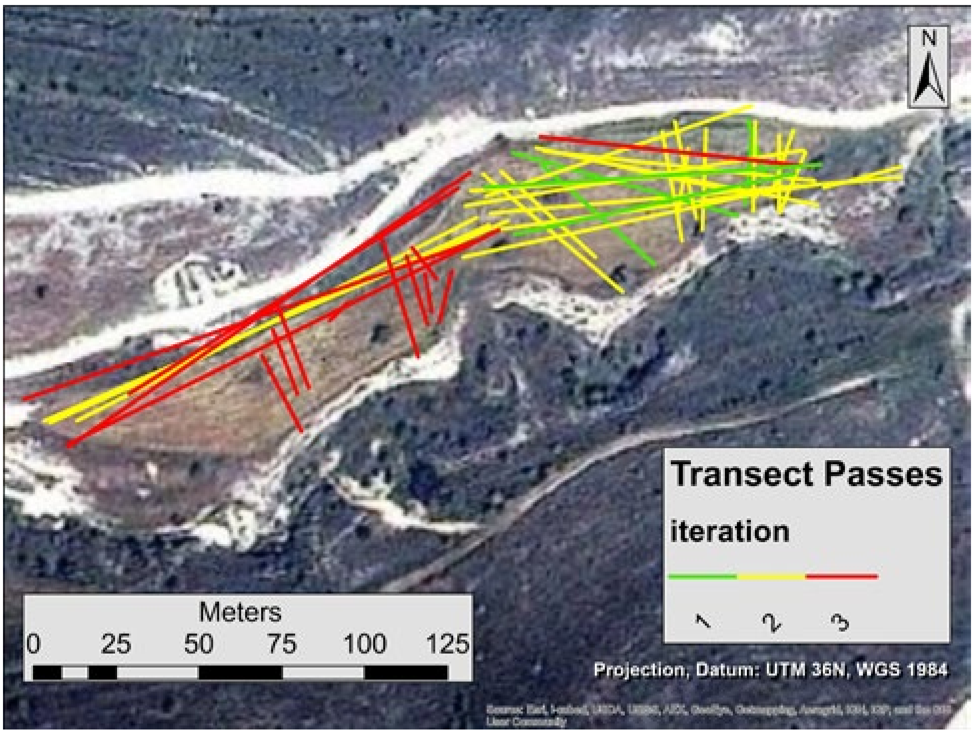


Fig. 10. Satellite view of Polygon 229 showing locations of all transects. Transects colours differentiate transects from the three different days that this polygon was surveyed.

4 Results

Our methods for measuring sweep width allowed us to evaluate increasing coverage of each survey polygon. As we discuss further in another paper (Hitchings *et al.*, this volume), this in turn allows us to assess whether we have investigated a space sufficiently to determine whether or not it is likely to be a site.

For example, Polygon 229 is an elongated agricultural field extending over an area of about 7381 m^2. Knowing that our calibrated sweep width for this kind of ground cover was roughly 1.8 m, we were able to calculate that our survey coverage for this area was only 23% after the first survey but, after three days of work and 3106 m total transect length, it had increased to about 76%.

The three survey runs across this polygon, having resulted in the recovery of 56 diagnostic lithic artefacts consistent with early Neolithic technology as well as non-diagnostic finds, allow us to designate P229 as a probable site, now named Ayia Anna-Phramena 2. It thus merits further survey and test excavation to determine if there are intact deposits suitable for further investigation.

5 Conclusions

In both surveys in northern Jordan and south-central Cyprus, calculation of estimated sweep widths on the basis of calibrations on prepared test fields was a critical component in our estimation of gradually increasing survey coverage, which in turn informed our iterative survey strategy (Hitchings *et al.*, this volume). Once the fields are prepared in areas nearly devoid of 'real' artefact scatters but representative of expected visibility conditions, and given appropriate software and spreadsheet set-up, it is relatively easy to accumulate data and analyse them to provide fairly realistic estimates of the thoroughness of archaeological surveys by field walking.

Bibliography

Banning, E. B., Hawkins, A. L., Stewart, S. T. 2006. Detection functions for archaeological survey. *American Antiquity* 71, 4: 723-42.

Banning, E. B., Hawkins, A. L., Stewart, S. T. 2010. Detection functions in the design and evaluation of pedestrian surveys. In Niccolucci, S. and Hermon, S. (eds.), *Beyond the Artefact: Digital Interpretation of the Past. Proceedings of the 32nd Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Prato Italy,13-17 April 2004*: 123-4. Budapest, Archaeolingua.

Banning, E. B., Hawkins, A. L., Stewart, S. T. 2011. Sweep widths and the detection of artefacts in archaeological survey. *Journal of Archaeological Science* 38: 3447-58.

Cooper, D. C., Frost, J. R., Robe, R. Q. 2003. *Compatibility of Land SAR Procedures with Search Theory*. US Department of Homeland Security, United States Coast Guard Operations (G-OPR), contract no. DTCG39-00-D-R-00009. Alexandria, VA, Potomac Management Group, Inc.

Frost, J. R. 1999a. *Principles of Search Theory. Part I: Detection*. Fairfax, VA, Soza and Company, Ltd.

Frost, J. R. 1999b. *Principles of Search Theory. Part II: Effort, Coverage and POD*. Fairfax, VA, Soza and Company, Ltd.

Hitchings, P. M. N., Abu Jayyab, K., Bikoulis, P., Banning, E. B. 2013. A Bayesian approach to archaeological survey in north-west Jordan. *Antiquity* 87: project gallery. Available at: http://antiquity.ac.uk/projgall/hitchings336/

Koopman, B. O. 1980. *Search and Screening: General Principles with Historical Applications*. New York, Pergamum Press.

Manning, S. W., Mccartney, C., Kromer, B., Stewart, S. T. 2010. The earlier Neolithic in Cyprus: recognition and dating of a Pre-Pottery Neolithic A Occupation. *Antiquity* 84: 693-706.

Mccartney C., Manning, S. W., Sewell, D., Stewart, S. T. 2006. Elaborating Early Neolithic Cyprus (EENC) Preliminary Report on the 2005 Field Season. *Report of the Department of Antiquities, Cyprus*: 39-59.

Mcartney, C., Manning, S. W., Sewell, D., Stewart, S. T. 2007. The EENC 2006 field season: Excavations at Ayia Varvara-Asprokremnos and survey of the local early Holocene landscape. *Report of the Department of Antiquities, Cyprus*: 27-44.

Mccartney, C., Manning, S. W., Rosendal, S., Stewart, S. T. 2008. Elaborating Early Neolithic Cyprus (EENC) Preliminary report on the 2007 field season: Excavations and Regional Field Survey at Ayia Varvara-Asprokremnos. *Report of the Department of Antiquities, Cyprus*: 67-86.

Mccartney, C., Manning, S. W., Sewell, D., Stewart, S. T. 2010. New Perspectives On The Early Holocene Landscape In Cyprus. In Finlayson, B., Warren, G. (eds.), *Landscapes in Transition*. Levant Supplementary Series 8: 133-146. Oxford, Oxbow Books.

Mccartney, C., Manning, S. W., Stewart, S. T. 2012. Ayia Varvara-Asprokremnos : Excavations, Radio-carbon Dating and Geo-Chemical Analysis of Chert Sources. *Report of the Department of Antiquities, Cyprus*: 77-94.

Stewart, S. T. 2004. Hill and Vale: Understanding Prehistoric Lithic Use in Cyprus. In Peltenburg, E. and Wasse, A. (eds.), *Neolithic Revolution: New Perspectives on Southwest Asia Based on Recent Discoveries in Cyprus*. Levant Supplementary Series 1: 123-132. Oxford, Oxbow Books.

Stewart, S. T. 2006. *Walking in Cyprus: Ancient landscapes and Modern Bias*. Unpublished PhD thesis, Department of Anthropology, University of Toronto.

Stewart, S. T., Morden, M. E. (in press). The Idalion Survey Project. In GABER, P. (ed.) *Idalion III: The Terrace of the East Acropolis, Moutti tou Avrili, and Special Studies*. Annual of the American Schools of Oriental Research. Boston, American Schools of Oriental Research.

Stone, L. D. 1975. *Theory of Optimal Search*. New York, Academic Press.

Estimating The 'Memory of Landscape' to Predict Changes in Archaeological Settlement Patterns

Philip Verhagen(1), Laure Nuninger(2), Frédérique Bertoncello(2), Angelo Castrorao Barba(3)

[1] Vrije Universiteit Amsterdam, The Netherlands
[2] CNRS – University of Bourgogne Franche-Comté, Besançon, France)
[3] University of Siena, Italy

Abstract: In this paper, we present a method to calculate a 'land use heritage map' based on the concept of 'memory of landscape'. Such a map can be seen as one variable among others influencing site location preference, and can be used as input for predictive models. The computed values equate to an index of long-term land use intensity. We will first discuss the method used for creating the land use heritage map, for which kernel density estimates are used. We will then present the use of these land use heritage maps for site location analysis in two study areas in SE France. Earlier analyses showed that the influence of the natural environment on settlement location choice in the Roman period is limited. In contrast, land use heritage seems to have a stronger influence on the placement of new settlements. We will discuss the implications for predictive modelling of settlement patterns.

Keywords: Predictive modelling, settlement pattern analysis, socio-cultural variables, memory of landscape, heritage map

Introduction

The IHAPMA project[1] (Nuninger *et al*. 2012a; Verhagen *et al*. 2013) aimed to perform cross-regional comparison and predictive modelling of the location of rural Roman settlements by analysing both environmental and socio-cultural factors influencing site location in two areas of southern France (Argens-Maures and Vaunage), and in the region of Zuid-Limburg in the Netherlands. For this purpose, we developed a protocol that can be easily implemented for different regions and time periods, using contextual analysis, statistical comparison, and predictive modelling of site location as the primary tools to gain a better understanding of cross-regional diachronic patterns of occupation. It distinguishes between environmental factors (such as slope, aspect, and solar radiation), socio-environmental factors (such as visibility and accessibility), and socio-cultural factors (such as the duration of previous occupation and hierarchical network structures; Fig. 1).

In this paper, we will focus on the duration of previous occupation as a site location factor, and use the sub-model we developed to compute a map of 'land use heritage' (Nuninger *et al.*, in press) to analyse the effect of 'memory of landscape' on settlement location choice. For this, we defined the concept of 'memory of landscape' at a very basic level of meaning, taking into consideration that the occupation of archaeological settlements also reflects human investment in the surrounding area. When rural communities settle somewhere, they reshape the landscape by delimiting parcels, clearing woodlands, draining wet areas, improving the quality of the soil, etc. We can therefore assume that the duration of rural settlement occupation constitutes an index of long-term land use intensity, which may be considered as an opportunity for new settlers to benefit from these previous investments. This index is calculated in the sub-model for every location of the studied areas using a kernel operator. The resulting map of 'land use heritage' is then included in the global predictive model as a variable. The aim is to estimate the weight of social investment in the landscape and its effect on subsequent settlement location choices.

After a general overview of the research context, the paper will focus on the sub-model used to compute the map of land use heritage. We will use the resulting map to perform site location analysis and predictive modelling, discuss the results and explore the perspective for a comparative approach.

1 Research context: duration of previous occupation and land use heritage

1.1 Duration of previous occupation

Many archaeological rural sites in France, dating from the 2nd c. BC to the 7th c. AD, show a discontinuous occupation with clear phases of abandonment followed by reoccupation after one or more generations. In cases where the site itself is not reoccupied, new settlements may be created in its surroundings, in the area that was previously exploited. This type of historical pattern came to light through field surveys in the 1980s and was more recently proved by extensive rescue excavations, such as for example in northern France. These discoveries highlight a certain continuity of land use, even if some settlements are abandoned. New occupations and new landscape structures may indicate socio-economic changes or new ways of life (Hamerow 2012), but the successive occupations in the surroundings of a former settlement point to a higher value of managed landscapes. As such, the surroundings are not only a set of natural characteristics that are more or less interesting for a community to settle, but they become a real landscape, that is, a historical object which includes the investments of previous generations on the land. From this point of view we can think in terms of 'memory of landscape', considering that

[1] 'Introducing the human (f)actor in predictive modelling for archaeology'.

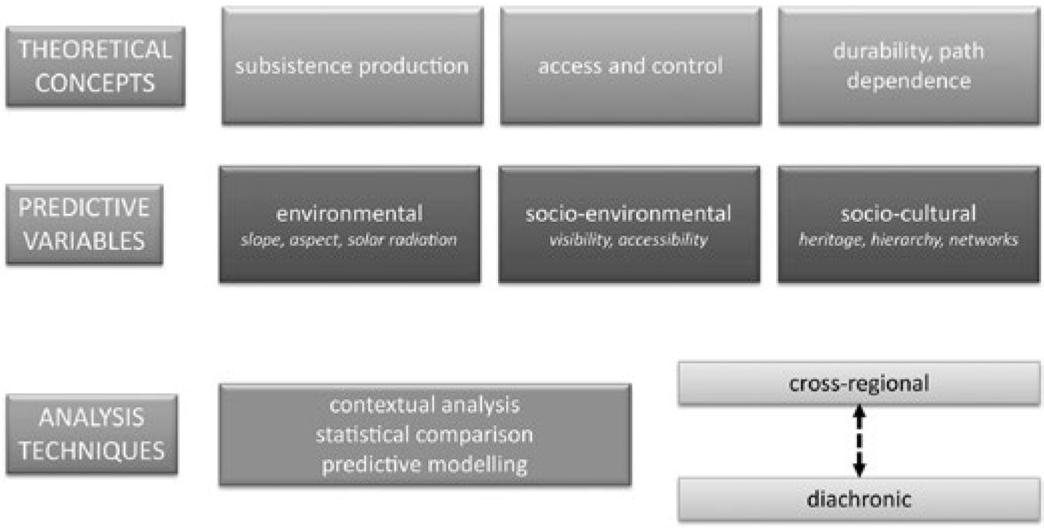


Fig. 1. Building blocks of the IHAPMA predictive modelling protocol.

past activities are embedded in the land used by generations of people and recognized as a heritage by contemporaneous communities (Nuninger *et al*. 2012b; Favory *et al*. 2012).

1.2 The concept of 'land use heritage' and predictive modelling

This concept provides an opportunity to reconsider predictive models and their heuristic power for settlement pattern characterisation over time. Predictive modelling methods were often criticized in the past because of the dominance of environmental characteristics, which was considered reductionist and in a way 'effectively de-humanising the past' (Wheatley 2004). In addition, predictive modelling was considered to be anti-historical since the correlation between behaviour and environmental characteristics is taken into account as a contemporary phenomenon, while 'in reality, the behaviour and activities that structure the spatial patterns in archaeological landscapes are just as much a product of historical as contemporary factors' (2004). And lastly, predictive modelling was criticized because it is 'concerned only with sites and fails to take broader theoretical developments about off-site activity into account' (Kay and Witcher 2009).

In our view, using the value of 'land use heritage' as a socio-environmental factor in predictive modelling offers a new way to 're-humanise' the past and to take into account the historical process of pattern construction. Indeed, for each location in the landscape at a certain point in time, we assume that settlement location preferences are not only guided by natural advantages, but by previous human investment to improve the land for agro-pastoral activities and consequently make it more attractive for a community to settle. The historical process is effectively taken into account as the model uses, for each period of one century, the previous occupations as a variable. We need to highlight here the importance of a good database to define such a variable, with a high spatial (systematic field surveys) and chronological resolution (precision of the settlements' dating).

It is important to note that predictive modelling is used here as a tool to explore the archaeological data in order to assess the factors influencing the location choice of rural settlements and their ability to perpetuate. Under no circumstances, should the IHAPMA models be considered as tools to predict the presence of archaeological sites for heritage management purposes. In addition, we have to specify that no ideas of social transmission are embedded in the concept of 'land use heritage'. This variable is one index among others that can be used to qualify landscape without any cultural considerations. Such a choice can be debated, but in this case it is justified by the objective to perform inter-regional and diachronic comparisons, which must be based on a common analysis protocol.

2 Specifying the computational model

For the creation of a new settlement we have to consider the potential attractiveness of the degree of anthropization, as well as the potential competition for land. In geography and ecology, anthropization is defined as the transformation of spaces, landscapes, or natural environments through human action. Settling close to an area with a high degree of anthropization potentially offers better opportunities to develop a new exploitation because it can benefit from the landscaping created by previous occupations. If the occupation of a location continues, however, then a new settlement cannot be established in or close to this location.

In order to compute the value of 'land use heritage' for each location in the landscape we have used a moving window with a kernel density function. The rationale and specifics for the computational modelling of the 'land use heritage' are explained in more detail in Nuninger *et al.* (in press). In this paper, we only provide the basic calculations involved.

Within the surroundings of a location A, a number of settlements (B–E) are found, dating from various periods (Fig. 2). Basically, for location A, the 'heritage' is a function of the geographical distance to the previous occupations located in its neighbourhood — B, C, D, and E — as well as the duration of these previous settlements. For each input cell location, a statistic of the heritage values within a specified neighbourhood is therefore computed, based on the number and duration of previous settlements.

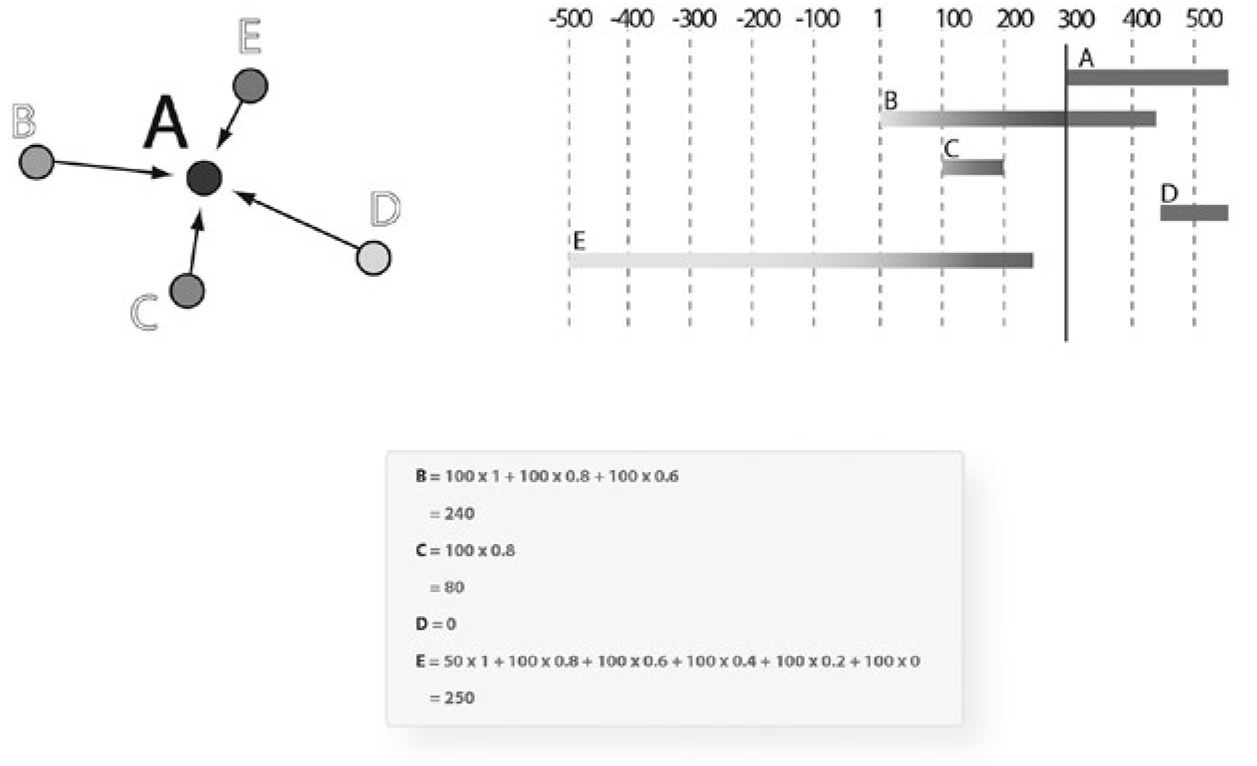


Fig. 2. Calculation of the temporal weighting of 'land use heritage' for a hypothetical settlement A. The duration of occupation of each settlement within A's surroundings is weighted according to the temporal distance, and then summed to a total value of land use heritage of 240 + 80 + 250 = 570 for settlement A.

2.1 Spatial weighting

From a practical point of view, we have modelled this principle using a distance decay function within a radius of 1000 m, corresponding to the area exploited by a settlement and its immediate surroundings. The distance decay function was implemented using a kernel matrix, based on the Epanechnikov kernel weighting function (Silverman 1986; Epanechnikov 1969). We want to stress here that this function was only chosen as a model to represent the spatial influence of 'land use heritage', and is therefore not used in its classical sense of a statistically optimized smoothing function.

The Epanechnikov-function produces a relatively large smooth surface around each location with a rapid fall-off on the edges. For a set of sites, it thus produces large smooth surfaces with few irregularities between sites. Assuming a continuity of land use between neighbouring sites, a surface density that is as regular as possible is best suited to our goals.

2.2 Temporal weighting

Since we are studying rural, agro-pastoral settlements, we assume that farmers worked the land, maintained terraces, and cleared land, among other things. When the land is abandoned, nature takes over, and the value of the land will decrease from an agro-pastoral point of view. To take into account this progressive degradation, each of the settlements B–E is weighted according to its duration of occupation, relative to the start of settlement A's occupation. The weight of duration will decrease by 0.2 per century, implying that after five centuries the influence of previous occupation will no longer be considered (Fig. 2).

3 Application and results

3.1 Comparing new settlement distribution and land use heritage

We compared the distribution of new settlements to the resulting land use heritage maps for two study areas in southern France, the Argens-Maures region (Var, Provence region) and the Vaunage region (Gard, Languedoc region). For these regions, the dating of sites is sufficiently precise to distinguish period ranges per century. The land use heritage value was computed for each century between the 2nd c. BC and the 5th c. AD and corresponds to the heritage value at the very beginning of each century. Then, we reclassified the raw land use heritage value into five classes:

HER0 - no heritage

HER1 - low heritage

HER2 - medium heritage

HER3 - high heritage

HER4 - very high heritage

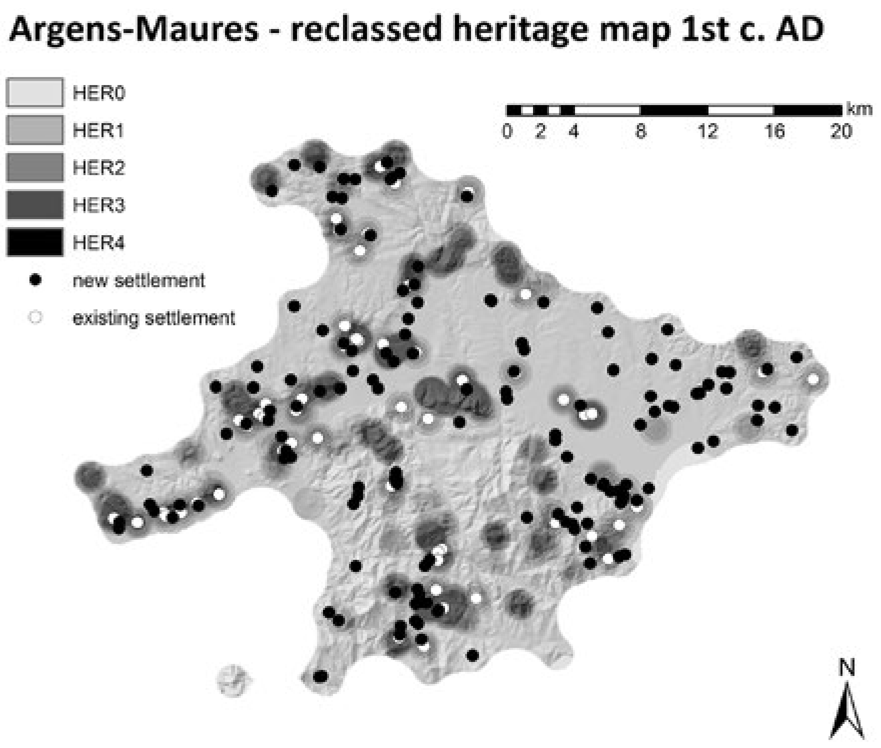


Fig. 3. Reclassified land use heritage map of the Argens-Maures region for the 1st c. AD, with archaeological sites. 'Existing settlements' are locations already occupied in the 1st c. BC, with continuing occupation in the 1st c. AD.

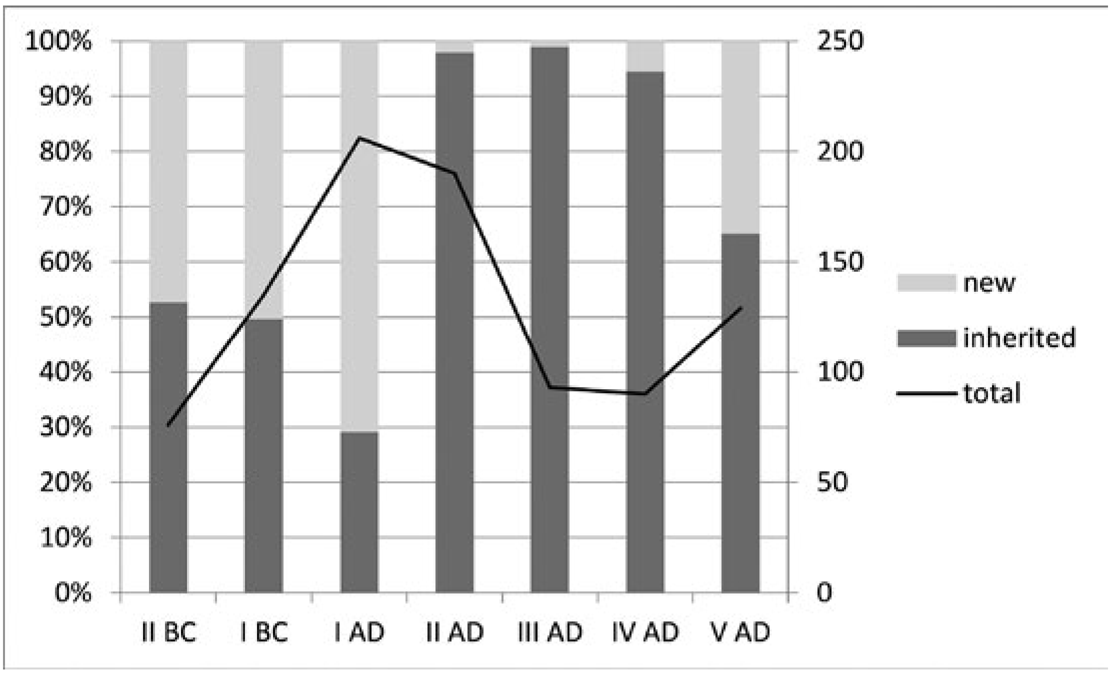


Fig. 4. Development of settlement numbers per century for the Argens-Maures region.

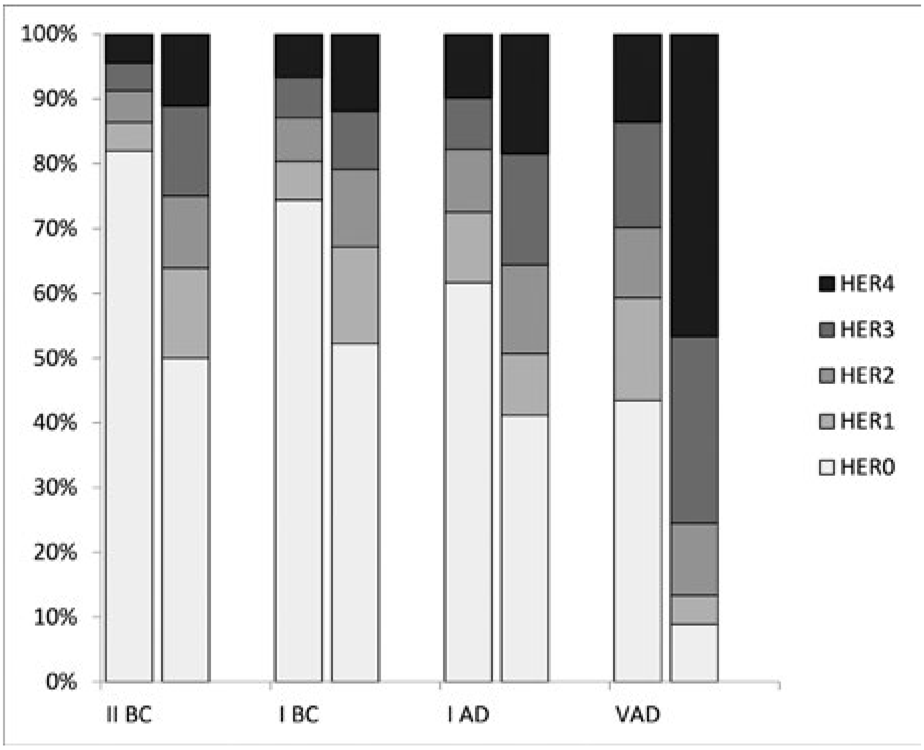


Fig. 5. Histogram comparing the expected (left bar) and observed (right bar) proportions of new settlements for each time period and heritage class for the Argens-Maures region.

In order to compare between periods and with other areas, the reclassification is based on the quantile method, for positive land use heritage values. This creates similar statistical distributions for all periods, allowing us to compare the relative ranges of inherited land use intensity, whatever their absolute value. Figure 3 shows an example of a reclassified heritage map.

We analysed the distribution of new settlement locations in the Argens-Maures region for the 2nd c. BC, 1st c. BC, 1st c. AD, and 5th c. AD. During the 2nd, 3rd, and 4th c. AD a drastic decrease in settlement density is observed, so the analysis could not be performed for those centuries (Fig. 4). Table 1 and Figure 5 show the results of the analysis for the remaining centuries. The χ^2 values all point to a settlement distribution that is significantly influenced by the land use heritage variable (p-values all < 0.0001). The tendencies are not extreme, however, as can be observed from the relative gain values per heritage category. In all analysed centuries, new settlements are under-represented in no-heritage (HER0) areas (relative gains from -0.21 to -0.34). The situation is different, however, for areas with (very) high heritage values (HER3 and HER4). During the 2nd and 1st c. BC there is no clear tendency to favour areas with a high heritage value. The attractiveness of high- and very high-heritage areas increases during the 1st c. AD. This becomes clearer during the 5th c. AD, where especially class HER4 shows a marked positive relative gain (0.33). The 5th c. AD therefore shows the strongest contrast in settlement preference, with clear negative gains in classes HER0 and HER1 and positive gains in classes HER3 and HER4. This clear tendency to favour areas with high heritage is partly explained by the fact that 37.7% of the settlements created during the 5th c. AD reoccupy previous settlements that were deserted, usually during the 2nd c. AD. But the newly created settlements (which do not reoccupy a previous settlement site) also show the same tendency to favour areas with high heritage values: 50% of them are created in a very high-heritage area (HER4) and 64% altogether in classes HER3 and HER4.

In the Vaunage region, we also observe a strong decrease in settlement densities after the 1st c. AD, but in this case the recovery already starts in the 4th c. AD (Fig. 6). Consequently, the analysis could not be performed for the 2nd, 3rd, and 5th c. AD. Table 2 and Figure 7 show the results of the analysis for the remaining centuries. Again, the χ^2 values all point to a settlement distribution that is significantly influenced by the land use heritage variable (p-values all < 0.001), but the tendencies are somewhat different than those for the Argens-Maures region. The no-heritage areas (HER0) are under-represented in all periods (relative gains between -0.37 and -0.15), but less so for the 1st and 4th c. AD (relative gains between -0.18 and -0.15). We can observe that in the 2nd c. BC new settlements have a clear preference for class HER3 (relative gain 0.29), but not for the very high heritage HER4 area (relative gain 0.05). In the 1st c. BC, new settlements tend to prefer both the HER3 and HER4 areas (relative gains 0.14 and 0.30). In the 1st c. AD, new settlements do not seem to have a preference for any particular heritage value. In the 4th c. AD, however, we observe a strong tendency for new settlements to favour areas with very high heritage (HER4; relative gain 0.40), while the other zones all have negative gains. This pattern of reoccupation of previous settlement locations is quite similar to what is observed in the Argens-Maures region in the 5th c. AD.

Tab. 1. This table shows, for each class of land use heritage in the Argens-Maures region, and for each analysed century, the number of observed new settlements compared to expected ones, and their proportions (denoted p_S and p_A). The χ^2 value indicates the difference between observed and expected values, normalized by the expected ones. An increasing χ^2 value indicates a higher degree of dependence between settlement creation and the land use heritage class. Its statistical significance is represented by the p-value. Three indicators of the strength of location preference are given in the last three columns: Kvamme's gain ($1 - p_A/p_S$; Kvamme, 1988), indicative value (p_S/p_A; Deeben *et al.* 1997) and relative gain ($p_S - p_A$; Wansleeben and Verhart 1992).

2nd century BC								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	18	29,501	0,500	0,819	4,484	-0,64	0,61	-0,32
1	5	1,592	0,139	0,044	7,295	0,68	3,14	0,09
2	4	1,757	0,111	0,049	2,864	0,56	2,28	0,06
3	5	1,537	0,139	0,043	7,801	0,69	3,25	0,10
4	4	1,613	0,111	0,045	3,535	0,60	2,48	0,07
Total	**36**				**25,978**			
p-value					0,000			
1st century BC								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	35	49,817	0,522	0,744	4,407	-0,42	0,70	-0,22
1	10	4,011	0,149	0,060	8,944	0,60	2,49	0,09
2	8	4,501	0,119	0,067	2,721	0,44	1,78	0,05
3	6	4,192	0,090	0,063	0,780	0,30	1,43	0,03
4	8	4,480	0,119	0,067	2,766	0,44	1,79	0,05
Total	**67**				**19,619**			
p-value					0,001			
1st century AD								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	60	90,018	0,411	0,617	10,010	-0,50	0,67	-0,21
1	14	15,897	0,096	0,109	0,226	-0,14	0,88	-0,01
2	20	14,130	0,137	0,097	2,439	0,29	1,42	0,04
3	25	11,555	0,171	0,079	15,646	0,54	2,16	0,09
4	27	14,401	0,185	0,099	11,022	0,47	1,87	0,09
Total	**146**				**39,343**			
p-value					0,000			
5th century AD								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	4	19,514	0,089	0,434	12,334	-3,88	0,20	-0,34
1	2	7,173	0,044	0,159	3,731	-2,59	0,28	-0,11
2	5	4,895	0,111	0,109	0,002	0,02	1,02	0,00
3	13	7,314	0,289	0,163	4,419	0,44	1,78	0,13
4	21	6,104	0,467	0,136	36,355	0,71	3,44	0,33
Total	**45**				**56,841**			
p-value					0,000			

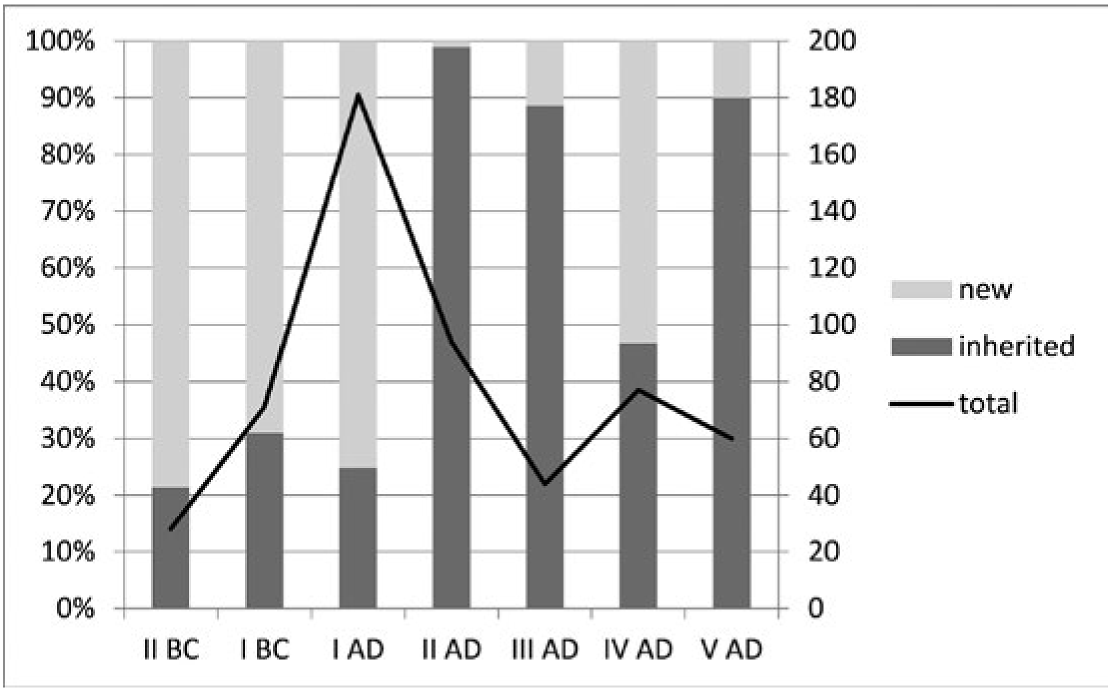


FIG. 6. DEVELOPMENT OF SETTLEMENT NUMBERS PER CENTURY FOR THE VAUNAGE REGION.

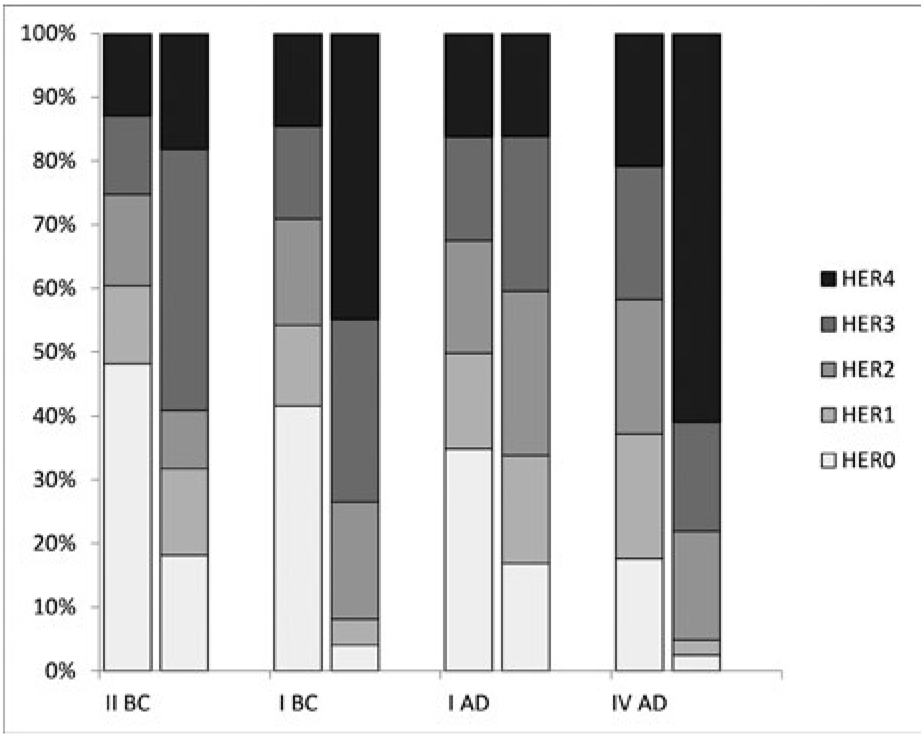


FIG. 7. HISTOGRAM COMPARING THE EXPECTED (LEFT BAR) AND OBSERVED (RIGHT BAR) PROPORTIONS OF NEW SETTLEMENTS FOR EACH TIME PERIOD AND HERITAGE CLASS FOR THE VAUNAGE REGION.

Tab. 2. This table shows, for each class of land use heritage in the Vaunage region, and for each analysed century, the number of observed new settlements compared to expected ones, and their proportions.

2nd century BC								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	4	10,598	0,182	0,482	4,107	-1,65	0,38	-0,30
1	3	2,682	0,136	0,122	0,038	0,11	1,12	0,01
2	2	3,165	0,091	0,144	0,429	-0,58	0,63	-0,05
3	9	2,711	0,409	0,123	14,591	0,70	3,32	0,29
4	4	2,844	0,182	0,129	0,470	0,29	1,41	0,05
Total	**22**				**19,635**			
p-value					0,001			
1st century BC								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	2	20,368	0,041	0,416	16,564	-9,18	0,10	-0,37
1	2	6,197	0,041	0,126	2,842	-2,10	0,32	-0,09
2	9	8,189	0,184	0,167	0,080	0,09	1,10	0,02
3	14	7,105	0,286	0,145	6,691	0,49	1,97	0,14
4	22	7,141	0,449	0,146	30,919	0,68	3,08	0,30
Total	**49**				**57,097**			
p-value					0,000			
1st century AD								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	23	47,373	0,169	0,348	12,540	-1,06	0,49	-0,18
1	23	20,396	0,169	0,150	0,333	0,11	1,13	0,02
2	35	23,996	0,257	0,176	5,046	0,31	1,46	0,08
3	33	22,207	0,243	0,163	5,246	0,33	1,49	0,08
4	22	22,029	0,162	0,162	0,000	-0,00	1,00	-0,00
Total	**136**				**23,164**			
p-value					0,000			
4th century AD								
Heritage value	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
0	1	7,218	0,024	0,176	5,357	-6,22	0,14	-0,15
1	1	8,033	0,024	0,196	6,158	-7,03	0,12	-0,17
2	7	8,634	0,171	0,211	0,309	-0,23	0,81	-0,04
3	7	8,557	0,171	0,209	0,283	-0,22	0,82	-0,04
4	25	8,558	0,610	0,209	31,591	0,66	2,92	0,40
Total	**41**				**43,697**			
p-value					0,000			

3.2 Comparing land use heritage and environmental context

In order further to analyse the effect of land use heritage on the location of new settlement, site locations were also compared to an environmental context map, based on combined slope, aspect, and solar radiation values within a 250 m circular neighbourhood around each grid cell (Verhagen *et al*. 2013). Preferences for environmental contexts in the Argens-Maures region are relatively weak for all analysed periods (reflected in modest values of χ^2), with the exception of the 1st c. AD, when we can observe a clear preference for south-facing, moderately sloping terrain (Tab. 3). In the Vaunage region, preferences are not very strong either, although we can observe in all periods a general avoidance of sloping terrain, and a preference for slightly to moderately sloping, south-facing terrain (Tab. 4; note that the classification for both regions does not reflect the same environmental contexts).

Both land use heritage and environmental context were then combined in a predictive model that was created using the MaxEnt software package (Phillips *et al*. 2004; 2006; Phillips and Dudík 2008; Elith *et al*. 2011). MaxEnt is a general-purpose predictive modelling tool, designed to work with presence-only data, such as archaeological sites. It is based on the principle of minimizing the relative entropy (dispersedness) between the probability densities estimated from the sample data and

Tab. 3. This table shows, for each environmental class in the Argens-Maures region, and for each analysed century, the number of observed new settlements compared to expected ones and their proportions. The characterization of the environmental classes is as follows: 1 – flat and slightly sloping, moderately warm, S- and E-facing; 2 – slightly and moderately sloping, warm, S-facing; 3 – steeply sloping, very cool, W-, N-, and E-facing; 4 – steeply sloping, very cool and very warm, E-, S-, and W-facing; 5 – steeply sloping, very warm, S-facing. NB: these classes represent the environmental characteristics within a 250 m neighbourhood around each grid cell.

2nd century BC								
Environmental class	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
1	4	3,372	0,111	0,094	0,117	0,16	1,19	0,02
2	4	9,349	0,111	0,260	3,060	-1,34	0,43	-0,15
3	10	8,444	0,278	0,235	0,287	0,16	1,18	0,04
4	9	8,715	0,250	0,242	0,009	0,03	1,03	0,01
5	9	6,119	0,250	0,170	1,356	0,32	1,47	0,08
Total	36				4,829			
p-value					0,305			
1st century BC								
Environmental class	Observed new settlements	Expected new settlements	ps	pa	x2	Kvamme's gain	Indicative value	Relative gain
1	3	6,276	0,045	0,094	1,710	-1,09	0,48	-0,05
2	28	17,399	0,418	0,260	6,459	0,38	1,61	0,16
3	9	15,715	0,134	0,235	2,870	-0,75	0,57	-0,10
4	17	16,220	0,254	0,242	0,037	0,05	1,05	0,01
5	10	11,389	0,149	0,170	0,169	-0,14	0,88	-0,02
Total	67				11,245			
p-value					0,024			
1st century AD								
Environmental class	Observed new settlements	Expected new settlements	ps	pa	x2	Kvamme's gain	Indicative value	Relative gain
1	10	13,676	0,068	0,094	0,988	-0,37	0,73	-0,03
2	79	37,915	0,541	0,260	44,521	0,52	2,08	0,28
3	16	34,246	0,110	0,235	9,721	-1,14	0,47	-0,12
4	22	35,346	0,151	0,242	5,039	-0,61	0,62	-0,09
5	19	24,818	0,130	0,170	1,364	-0,31	0,77	-0,04
Total	146				61,633			
p-value					0,000			
5th century AD								
Environmental class	Observed new settlements	Expected new settlements	ps	pa	x2	Kvamme's gain	Indicative value	Relative gain
1	2	4,215	0,044	0,094	1,164	-1,11	0,47	-0,05
2	16	11,686	0,356	0,260	1,593	0,27	1,37	0,10
3	13	10,555	0,289	0,235	0,566	0,19	1,23	0,05
4	7	10,894	0,156	0,242	1,392	-0,56	0,64	-0,09
5	7	7,649	0,156	0,170	0,055	-0,09	0,92	-0,01
Total	45				4,770			
p-value					0,312			

from the landscape. While there is some debate regarding its utility for precise predictions (Peterson *et al*. 2007; Kondo *et al*. 2012), it is a convenient tool to compare the contribution of different variables to prediction results. A useful feature is that it can also integrate measures of reliability of data coverage through so-called bias maps. In the case of the Argens-Maures region, we have therefore introduced a measure of reliability of the data according to the intensity of investigation and the field survey conditions (soil visibility) by attributing a weight of 1, 2, and 3 to areas with increasing quality of survey (no or partial survey or bad visibility conditions, systematic survey with medium visibility conditions, and systematic survey with optimal visibility conditions; Bertoncello *et al*. 2012; Fig. 8). For the Vaunage region, such a correction was not necessary since the whole area was surveyed systematically.

Tab. 4. This table shows, for each environmental class in the Vaunage region, and for each analysed century, the number of observed new settlements compared to expected ones and their proportions. The characterization of the environmental classes is as follows: 1 – slightly and moderately sloping, moderately cool, N- and W-facing; 2 – sloping, no particular preference for solar radiation or aspect; 3 – moderately sloping, warm, S-facing; 4 – flat, moderately cool, no particular preference for aspect; 5 – flat to slightly sloping, moderately warm, S-facing. NB: these classes represent the environmental characteristics within a 250 m neighbourhood around each grid cell.

2nd century BC								
Environmental class	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
1	4	3,802	0,182	0,173	0,010	0,05	1,05	0,01
2	2	5,340	0,091	0,243	2,089	-1,67	0,37	-0,15
3	5	5,274	0,227	0,240	0,014	-0,05	0,95	-0,01
4	4	4,941	0,182	0,225	0,179	-0,24	0,81	-0,04
5	7	2,642	0,318	0,120	7,188	0,62	2,65	0,20
Total	**22**				**9,481**			
p-value					0,050			
1st century BC								
Environmental class	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
1	5	8,469	0,102	0,173	1,421	-0,69	0,59	-0,07
2	7	11,894	0,143	0,243	2,014	-0,70	0,59	-0,10
3	16	11,747	0,327	0,240	1,540	0,27	1,36	0,09
4	7	11,006	0,143	0,225	1,458	-0,57	0,64	-0,08
5	14	5,885	0,286	0,120	11,191	0,58	2,38	0,17
Total	**49**				**17,623**			
p-value					0,001			
1st century AD								
Environmental class	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
1	24	23,505	0,176	0,173	0,010	0,02	1,02	0,00
2	15	33,011	0,110	0,243	9,827	-1,20	0,45	-0,13
3	41	32,603	0,301	0,240	2,163	0,20	1,26	0,06
4	32	30,547	0,235	0,225	0,069	0,05	1,05	0,01
5	24	16,333	0,176	0,120	3,599	0,32	1,47	0,06
Total	**136**				**15,668**			
p-value					0,003			
4th century AD								
Environmental class	**Observed new settlements**	**Expected new settlements**	**ps**	**pa**	**χ2**	**Kvamme's gain**	**Indicative value**	**Relative gain**
1	7	7,086	0,171	0,173	0,001	-0,01	0,99	-0,00
2	7	9,952	0,171	0,243	0,876	-0,42	0,70	-0,07
3	13	9,829	0,317	0,240	1,023	0,24	1,32	0,08
4	4	9,209	0,098	0,225	2,947	-1,30	0,43	-0,13
5	10	4,924	0,244	0,120	5,233	0,51	2,03	0,12
Total	**41**				**10,079**			
p-value					0,039			

The predictive modelling results for the Argens-Maures region clearly show that land use heritage has a higher contribution to the predicted probabilities than environmental context (Tab. 5). We can observe a change through time, however, with land use heritage gradually decreasing in importance from the 2nd c. BC to the 1st AD. In the 5th c. AD, however, land use heritage becomes extremely dominant. This pattern largely conforms to what is observed from analysing the distribution of new settlements compared to the land use heritage and environmental context maps. The accuracy of prediction, as measured through the Area Under Curve (AUC) statistic, is only poor to fair for the first three periods, but it is good for the 5th c. AD. For the Vaunage region, the results are very similar, although in the 1st c. BC we observe a stronger influence of land

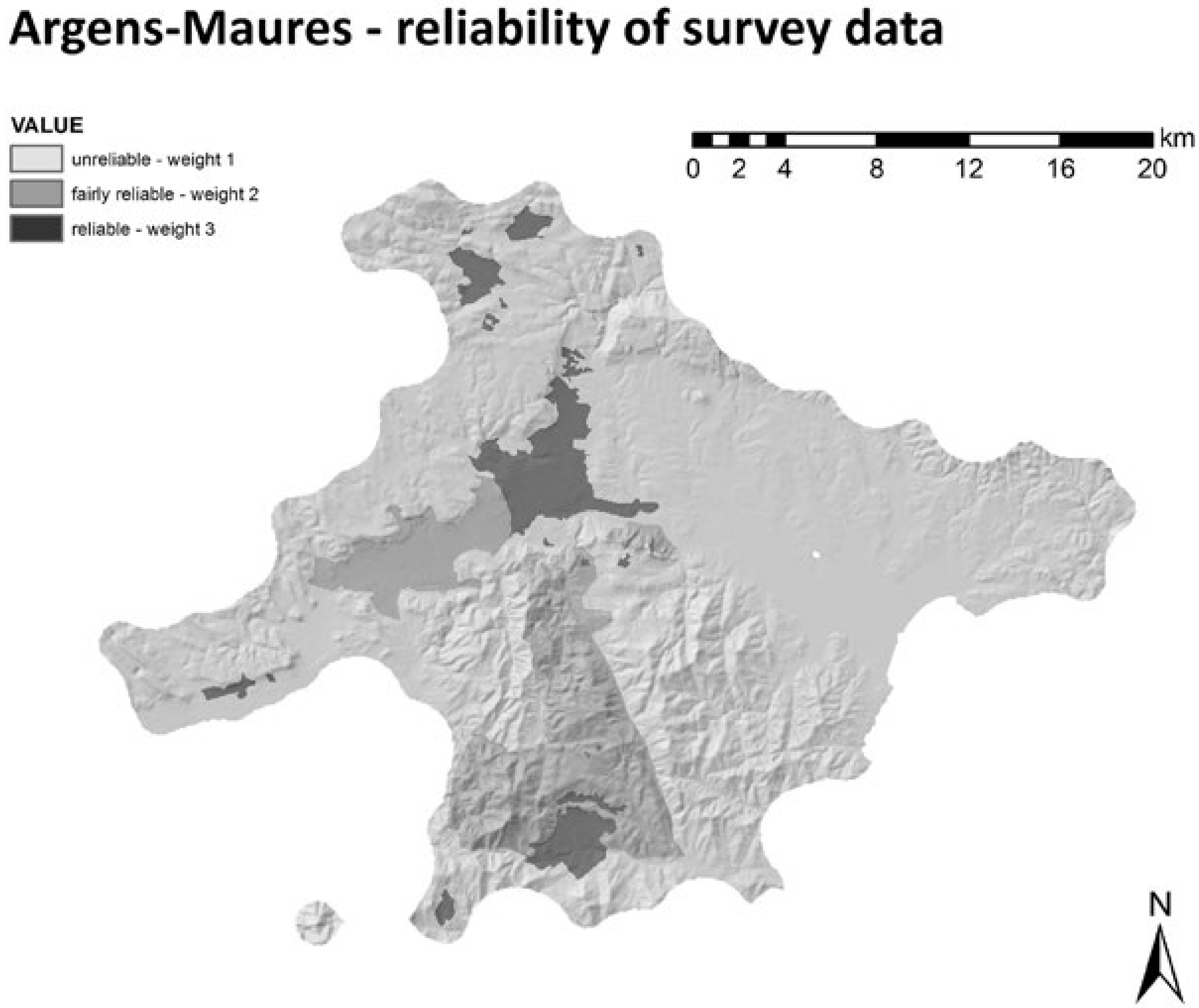


FIG. 8. MAP SHOWING THE RELIABILITY OF ARCHAEOLOGICAL SURVEY IN THE ARGENS-MAURES AREA. A LARGE PROPORTION OF THE 'NO-HERITAGE' AREA IS FOUND IN ZONES OF LOW RELIABILITY.

use heritage than in the Argens-Maures region (Tab. 6), and the accuracy of predictions is somewhat higher. In the Vaunage, this specific situation can be explained by the diffusion of small settlements around the pre-existing *oppida* from the 2nd c. BC and especially during the 1st c. BC (Nuninger 2004). By comparison, the Argens-Maures region shows a very limited occupation during the Iron Age, at least before the 2nd c. BC, even when taking into account survey bias and chronological uncertainty (Bertoncello 1999).

When including the reliability of field survey in the prediction for the Argens-Maures region, the contribution of land use heritage clearly decreases, and it is no longer the dominant factor in the 1st c. AD. The temporal trend is still the same, however, and the accuracy of prediction does not change very much. The reduction of the importance of land use heritage for the prediction results can be explained by the fact that this variable is dependent on the known density of settlement. In areas that are poorly surveyed, the real settlement density will be higher than what is known from the survey record, not just because of the lower area coverage, but also because of the potential preferential discovery of larger and more conspicuous sites. Hence, land use heritage values in these areas will be underestimated. In the predictive model, this could lead to over-emphasizing the avoidance of no-heritage areas by new settlements.

4 Discussion and perspectives

The preliminary results presented here were obtained when testing the workability of the model and should be interpreted with caution. The Iron Age (8th to 3rd c. BC) in the Argens-Maures region is probably less well studied than the Roman period, so the resulting heritage values for the 2nd and 1st c. BC might be underestimating the importance of previous occupation. Nevertheless, the results are striking in showing that settlement creation in the later Roman period exhibits a clear preference for areas with high to very high heritage values, which we could interpret as a sign of path dependency. Moreover, land use heritage seems to be a more important location factor for new settlement than the environmental context in most periods, but since the predictive power of the models is not very high, we can suspect that other factors are involved as well. Soil type, for example, was not included in the

Tab. 5. Predictive modelling results for the Argens-Maures region, with and without bias filter.

	Model without bias filter	Environment (%)		Model with bias filter		
Period	Contribution of heritage (%)	Contribution of environment (%)	AUC	Contribution of heritage (%)	Contribution of environment (%)	AUC
2nd c. BC	73,6	26,4	0,719	63,0	37,0	0,688
1st c. BC	62,3	37,7	0,672	54,5	45,5	0,667
1st c. AD	56,4	43,6	0,694	32,3	67,7	0,695
5th c. AD	91,7	8,3	0,793	88,2	11,8	0,797

Tab. 6. Predictive modelling results for the Vaunage region.

	Model without bias filter	Environment (%)	
Period	Contribution of heritage (%)	Contribution of environment (%)	AUC
2nd c. BC	70,4	29,6	0,772
1st c. BC	84,6	15,4	0,813
1st c. AD	53,8	46,2	0,672
4th c. AD	89,1	10,9	0,772

analysis presented here, and could potentially be an important site location factor for rural settlements.

Another important result of the analysis is, as anticipated, that it allows for cross-regional comparison. Relatively subtle patterns of occupation dynamics in the Argens-Maures and Vaunage regions now become clearer, telling us more about the differences and similarities in the trajectories of both regions, which can be related to the general development of Roman occupation in the south of France. The strong decrease in the number of settlements after the 1st c. AD is well attested in many regions (Favory *et al*. 1999; Van der Leeuw *et al*. 2003; Gandini *et al*. 2008) and the results from the Archaeomedes project promoted a new reading of territorial dynamics in the Late Roman Empire. Instead of reflecting a political and economic crisis coupled to land abandonment and environmental degradation, the large-scale abandonment of sites might reflect a process of restructuration and stabilisation of the settlement pattern (Durand-Dastès *et al*. 1998). The choice for particular land areas is the result of this restructuration and does not necessarily imply a contraction of the exploited areas, which can be managed from fewer locations (Favory *et al*. 1999; Tourneux 2000; Fovet 2005). In other words, when settlement is contracting at the end of the Early Roman Empire, the remaining sites are located in preferential contexts, and the latest phases of creation (the 4th and 5th c. AD, also attested in many other regions) correspond to a firmer choice for particular environmental contexts (Nuninger *et al*. 2012a). This could explain the strong path dependency of the settlements created during the 4th and 5th c. AD, as they would thus benefit both from previous landscaping and anthropization of the area, and from the best environmental conditions selected by the earliest settlements. This process of stabilisation of the settlement configuration is now supported with a new argument by the calculation and analysis of land use heritage presented here, at least in the Vaunage and Argens-Maures regions, but it still needs to be demonstrated on a larger scale.

The ‘land use heritage’ model itself also deserves more thorough discussion and experimenting. The concept, in its current definition, potentially conflates two variables. In the case of an abandoned settlement, the land use heritage equates to the heritage of the abandoned settlement location and its surroundings. In the case of continuation of occupation, however, the location of the settlement itself is not available for occupation, and land use heritage is only relevant for the surroundings of the settlement. In the current model, no distinction can be made between these situations, making it impossible to analyse if we are dealing with reoccupation of an abandoned settlements, or with occupation in the surroundings of existing and/or abandoned settlements. An annular neighbourhood, for example, might make more sense in this case.

The modelling protocol, which was developed in ArcGIS, is still under construction, and progress has been relatively slow, since it is based on independent research efforts in three different institutes. Nevertheless, we aim to make it publicly available as soon as possible as a set of toolboxes that can be used by anyone interested, and that can be adapted to the specific characteristics of particular regions and/or time periods. In the longer term, however, we want to move towards an Open Source solution that would make it easier for other users to add functionality.

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Bibliography

Bertoncello, F. 1999. *Le peuplement de la basse vallée de l'Argens et de ses marges (Var) de la fin de l'Âge du Fer à la fin de l'Antiquité*. Unpublished PhD thesis, Aix-en-Provence, Université de Provence I.

Bertoncello, F., Fovet, E., Gandini, C., Trément, F., Nuninger, L. 2012. The spatio-temporal dynamics of settlement patterns from 800 BC to 800 AD in Central and Southern Gaul: models for an interregional comparison over the long term. In Gandini, C., Favory, F., Nuninger, L. (eds.), *Settlement Patterns, Production and Trades from the Neolithic to the Middle Ages. Archaedyn, Seven Millennia of Territorial Dynamics, Final Conference, Dijon, 23-25 June 2008*: 51-64. Oxford, Archaeopress.

Deeben, J., Hallewas, D., Kolen, J., Wiemer, R. 1997. Beyond the crystal ball: predictive modelling as a tool in archaeological heritage management and occupation history. In Willems, W., Kars, H., Hallewas, D. (eds.), *Archaeological Heritage Management in the Netherlands. Fifty Years State Service for Archaeological Investigations*: 76-118. Amersfoort, Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Durand-Dastès, F., Favory, F., Fiches, J.-L., Mathian, H., Pumain, D., Raynaud, C., Sanders, L., Van Der Leeuw, S. 1998. *Des oppida aux métropoles. Archéologues et géographes en vallée du Rhône*. Paris, Anthropos.

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J. (2011) A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* 17: 43–57.

Epanechnikov, V. A. 1969. Non-Parametric Estimation of a Multivariate Probability Density. *Theory of Probability and Its Applications* 14: 153–8.

Favory, F., Girardot, J.-J., Nuninger, L., Tourneux, F.-P. 1999. Archaeomedes II: une étude de la dynamique de l'habitat rural en France méridionale, dans la longue durée (800 av. J.-C. – 1600 ap. J.-C.). *AGER* 9: 15-35.

Favory, F., Nuninger, L., Sanders, L. 2012. Integration of geographical and spatial archaeological concepts for the study of settlement systems. *L'Espace Géographique* 4: 295–309.

Fovet, E. 2005. Dynamique spatiale du peuplement et analyse des ressources agro-pastorales dans le bassin de Combas et le vallon de l'Aigalade (Gard, France), du Bronze final au bas Moyen Age. In

Berger, J.-F., Bertoncello, F., Braemer, F., Davtian, G., Gazenbeek. M. (eds.), *Temps et espaces de l'Homme en société, analyses et modèles spatiaux en archéologie. Actes des XXVe Rencontres internationales d'archéologie et d'histoire d'Antibes, 21-23 Octobre 2004*: 499-503. Sophia-Antipolis, APDCA.

Gandini, C., Bertoncello, F., Gauthier, E., Nuninger, L., Trément, F. 2008. Hierarchical Typology and Settlement Patterns Modelling at Interregional Scale. In Posluschny, A., Lambers, K. and Herzog, I. (eds.), *Layers of Perception. 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Apr 2007, Berlin, Germany*. Bonn: Dr. Rudolf Habelt GmbH.

Hamerow, H. 2012 *Rural Settlements and Society in Anglo-Saxon England*. Oxford, Oxford University Press.

Kay, S. J. and Witcher, R. E. 2009. Predictive Modelling of Roman Settlement in the Middle Tiber Valley. *Archeologia e Calcolatori* 20: 277-90.

Kondo, Y., Omori, T., Verhagen, P. 2012. *Developing predictive models for palaeoanthropological research: a preliminary discussion (Technical Report 12-001)*. Tokyo, Department of Computer Science, Tokyo Institute of Technology.

Kvamme, K. L. 1988. Development and Testing of Quantitative Models. In Judge, W. J. and Sebastian, L. (eds.), *Quantifying the Present and Predicting the Past: Theory, Method, and Application of Archaeological Predictive Modelling*: 325-428. Denver, U.S. Department of the Interior, Bureau of Land Management Service Center.

Nuninger, L. 2004. Understanding the protohistorical territorial heritage by means of Iron Age settlement system analysis in GIS: a case study in the eastern Languedoc (France). In Fischer Ausserer, K., Börner, W., Goriany, M., Karlhuber-Vöckl, L. (eds.), *Enter the Past. The E-way into the four Dimensions of Cultural Heritage. CAA 2003, Computer Applications and Quantitative Methods in Archaeology*: 286-9. Oxford, Archaeopress.

Nuninger, L., Verhagen, P., Bertoncello, F., Castrorao Barba, A. (in press). Estimating 'land use heritage' to model changes in archaeological settlement patterns. *Proceedings of the Third International Landscape Archaeology Conference 2014, 19-20 September 2014, Rome.*

Nuninger, L., Verhagen, P., Tourneux, F.-P., Bertoncello, F., Jeneson, K. 2012a Contextes spatiaux et transformation du système de peuplement: approche comparative et predictive. In Bertoncello, F. and Braemer, F. (eds.), *Variabilités environnementales, mutations sociales. Nature, intensités, échelles et temporalités des changements*: 139-154. Sophia-Antipolis, APDCA.

Nuninger, L., Bertoncello, F., Favory, F., Fiches, J.-L., Raynaud, C., Girardot, J.-J., Mathian, H., Sanders, L. 2012b. Peuplement et territoire dans la longue durée: retour sur 20 ans d'expérience. In Archambault De Beaune, S. and Francfort, H.-P. (eds.), *L'archéologie en mouvement: hommes, objets et temporalités*: 150-7. Paris, CNRS Éditions Alpha.

Peterson, A. T., Papeş, M., Eaton, M. 2007. Transferability and model evaluation in ecological niche modeling) a comparison of GARP and Maxent. *Ecography* 30: 550-60.

Phillips, S. J., Dudík, M., Schapire, R. E. 2004. A maximum entropy approach to species distribution modeling. *Proceedings of the twenty-first International Conference on Machine Learning*: 655–62. New York, ACM Press.

Phillips, S. J., Anderson, R. P., Schapire, R. E. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190: 231–59.

Phillips, S. J., Dudík, M. 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31: 161–75.

Silverman, B. W. 1986. *Density Estimation for Statistics and Data Analysis*. London, Chapman and Hall.

Tourneux, F.-P. 2000. *Modes de représentation des paysages*. Unpublished PhD thesis, Besançon, Université de Franche-Comté.

Van Der Leeuw, S., Favory, F., Fiches, J.-L. (eds.) 2003. *Archéologie et systèmes socio-environnementaux. Études multiscalaires sur la vallée du Rhône dans le programme Archaeomedes*. Paris, CNRS Éditions.

Verhagen, P., Nuninger, L., Tourneux, F.-P., Bertoncello, F., Jeneson, K. 2013. Introducing the human factor in predictive modelling: a work in progress. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I., Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 379-88. Amsterdam, Amsterdam University Press, p.

Wansleeben, M. and Verhart, L. B. M. 1992. The Meuse Valley Project: GIS and site location statistics. *Analecta Praehistorica Leidensia* 25: 99-108.

Wheatley, D. 2004. Making space for an archaeology of place. *Internet Archaeology* 15. Available at: http://dx.doi.org/10.11141/ia.15.10 [Accessed: 1 july 2015].

On Their Way Home ...
A Network Analysis of Medieval Caravanserai Distribution in the Syrian Region, According to an 1D Approach

Augusto Palombini(1)
augusto.palombini@itabc.cnr.it

Cinzia Tavernari(2)
cinzia.tavernari@agu.edu.tr

1 CNR – ITABC, National Research Council – Institute of Technologies Applied to Cultural Heritage,
2 Abdullah Gul University

Abstract: The common theory on caravanserais states that they were built at one-day's march distance from each other. Such a pattern may fit some situations, but it does not seem to be present in Syria during the Ayyubid (1174–1260 CE) and Mamluk periods (1260–1517 CE), when most of the region's caravanserais were founded. Caravanserais built during these periods do not seem to follow a precise pattern of distribution along the communication axis of Syria and, as a result, the logic that underlines their distribution remains unclear. The authors face the problem through a GIS-based, network analysis approach that takes into account the building period of each structure and the one-dimensional criterion of distance to its nearest neighbour, also considered in relation to the closeness to urban centres. The results of the analysis are then compared to the historical Syrian caravan networks. The outcomes show interesting aspects both in terms of understanding the route organization, and of predictive methods for focusing on areas where structures not yet located may be expected.

Keywords: Spatial archaeology, "Caravanserais, GIS, Syria, Middle Ages, Network analysis.

Introduction

Spreading throughout the Muslim world since the beginning of the Islamic period, wayside caravanserais have functioned for many centuries as sheltered stopovers providing lodging and security to all travellers (Fig. 1). The impressive diffusion of this institution clearly shows that caravanserais fulfilled a key role in society in relation to travel and trade; they represent the specific response developed by the Islamic world to travellers' needs. Despite such considerations, caravanserais remain inadequately studied and understood, particularly when considered as a network. In fact, even in regions such as Turkey and Iran where the study of caravanserais can boast a significant record of research, the overwhelming majority of the studies have focused on the architecture of these buildings, mainly trying to work out a periodization of these edifices based on their layout (e.g. Erdmann 1961; Kiyani and Kleiss 1995). Rare studies that do consider caravanserais as a complex system do exist, but their approach leaves aside geographical considerations to focus mainly on historical issues, such as the question of patronage (see Cytryn-Silverman 2010 for an example). An MA thesis dealing with the caravanserais of Central Anatolia appears to be the only attempt to approach caravanserais as a network of stopovers in relation to the road communication system using computer-based analyses (Ertepinar-Kaymakci 2005). A dissertation was proposed in 2009 (Tate 2009) aimed at widening the scope of the previous MA thesis by using a more comprehensive GIS approach as well as the methods of landscape archaeology, but the PhD was never completed (Scott Branting, personal communication). No study such as those mentioned above exists for the Syrian region, or more correctly Bilād al-Šām, whose caravanserais never attracted much of the scholars' attention.

Fig. 1. Khan al-'Arus: the caravanserais built by Salah al-Din in 1181 CE on the Damascus-Aleppo road (Photo: C. Tavernari)

1 The geographical and historical framework

The geographical region that from the Middle Ages until the 20th century was known as Bilād al-Šām was formed by Jordan, Syria, Israel, Palestine, and the southern part of Turkey up to the Taurus Mountains (Fig. 2).

The choice of the historical framework mainly depends on the information available on caravanserais. Within the framework of the intended study, it is essential to be able to locate the caravanserais quite precisely on the field and, at least, assign their construction to a particular period if not date. The scarce

Fig. 2. The historical region known as Bilād al-Šām until the 20th century (Map: C. Tavernari).

Fig. 3. The distribution of the 72 wayside caravanserais built during the Ayyubid (1174–1260 CE) and Mamluk (1260–1517 CE) period in the region of Bilād al-Šām (Map: C. Tavernari).

and scattered information available for the first centuries of the Islamic period (i.e. 8th–12th century), prevent any analysis of caravanserais as a system of stopovers along the roads. Starting from the beginning of the Ayyubid period (1174–1260 CE) both material and historical data are more largely available and it appears plausible that, whatever the number of earliest wayside caravanserais, their construction noticeably increased under the Ayyubids (Constable 2003: 75–76), a tendency that continued during the following Mamluk era (1260–1517 CE). The Ottoman conquest of Bilād al-Šām in 1517 CE saw the dawn of a new political and economic order in the region, thus representing a coherent chronological boundary for the present study. The 12th–16th centuries not only represent a pivotal period for the study and comprehension of the caravanserai phenomenon in Bilād al-Šām, but also constitute a moment of significant political upheavals in the region, due to the crusaders' presence and the Mongol invasion followed by the establishment of an aggressive empire at the eastern frontier of Bilād al-Šām.

2 The roads and caravanserais of Bilād al-Šām

The geopolitical situation of Bilād al-Šām during the 12th–16th century and its evolution most likely also affected the communication networks, which transformed accordingly. The development of the road network mainly towards the Euphrates and the regions to the east of it during the 12th–13th century probably follows the firm establishment of the crusaders' kingdoms along the coasts of the Mediterranean and the expansion of the Ayyubid empire towards more peaceful eastern lands. Under Mamluk rule, during the second half of the 13th century, the end of the crusaders' occupation on the Levantine coast combined with the dreadful Mongol invasion from Asia seemingly prompted a westward reorientation of the communication networks.

The construction pattern of the 72 wayside caravanserais built in Bilād al-Šām during the end of 12th and the beginning of the 16th century (Fig. 3) largely appears to reflect the changes of the region's communication network, shifting from the Syrian steppe to the shores of the Mediterranean (e.g. Tavernari 2011). If this phenomenon is quite evident, it is difficult, on the other hand, to understand the caravanserais' pattern of distribution in detail. To the naked eye, their distribution is irregular and so far, it has not been possible to identify the factors that regulated their implantation at a precise location along the roads. No element common to all sites has been identified at this stage of the research, not even the presence of a source of water (e.g. fountain, cistern, river, etc.).

3 Aims and methods

Spatial pattern analysis models are well known in archaeology, well before the introduction of GIS and computer science (e.g. Hodder and Orton 1975) in the discipline. In recent years, the diffusion of such software-aided approaches has led to complex methodologies that mainly involve cost surface and viewshed

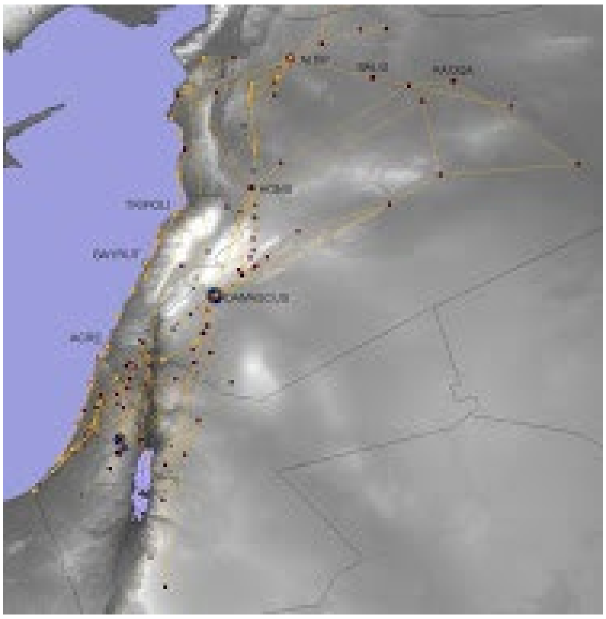

Fig. 4. The network of caravanserais and urban areas in the region of Bilād al-Šām during the Ayyubid (1174–1260) and Mamluk (1260–1517) periods (Map: A. Del, C. Tavernari).

analysis (Van Leusen 1999) but we considered that, due to the characteristics of the research object and to the absence of GIS analyses on Syrian caravanserais, the research should focus on a simplified, one-dimensional approach to distance analysis.

The creation of a network and the choice of its nodes represented the first step of the research work (Fig. 4)

Dealing with such a stratified historical context as the one presented above, we could not build a single network but had to single out coherent networks of structures to conduct a significant historical analysis. In such a perspective, we built a timeline covering from 1200 CE to 1600 CE that we partitioned in 50 years' time slices, and we ordered all caravanserais in this timeline according to their construction date (as precisely as it is known) and assuming (according to the sources) an average life of 100 years for Ayyubid caravanserais, and a long-lasting existence well into the Ottoman era for Mamluk ones. The caravanserais that could not be located have been excluded from the dataset of buildings used for this work. The results led to the selection of 1200 CE and 1450 CE as the most representative and copious phases for the inquiry (Tab. 1). Successively, the two distinct sets of caravanserais (1200 CE and 1450 CE) were isolated and projected on a map together with the most significant urban areas of the region that undoubtedly served as stopovers along the main roads (e.g. Damascus, Aleppo, Gaza, Hama, etc.) during the considered period. Two different networks were created, whose nodes represented the stopovers in 1200 CE and in 1450 CE, and we superimposed them to the historic routes of the region as known from the sources.

A further selection was then carried out to obtain results that are more reliable. For each period (i.e. 1200 CE and 1450 CE), we tried to choose the best-documented route both from the point of view of the historic network and of the number of caravanserais that could have served as stopovers along each communication axes. The Damascus-Aleppo route for the 1200 CE phase and the Damascus-Khan Yunus route for the 1450 CE phase appeared to satisfy both conditions. These routes also represent two of the most important communication axes of Bilād al-Šām. The historic tracks of these roads have been reconstructed on the basis of the works of Qalqašandī (1963) and Ibn Ǧi'ān (1922) for the 15th century and Ibn Ǧubayr for the 13th century (Ibn Ǧubayr 2003). The latter was a secretary to the ruler of Granada who in 1183 CE decided to perform the pilgrimage (hajj) to Mecca. As a secretary to the Mamluk sultan Qaytbay, in 1477 CE Ibn Ǧi'ān accompanied his master on a journey across the Mamluk lands to inspect the conditions of the fortresses meant to prevent a predictable Ottoman attack. Qalqašandī also worked at the Mamluk court; he was a clerk who compiled all the itineraries followed by the royal postal couriers.

It is important to stress the difference between the historic networks and the networks of caravanserais and urban areas that we have reconstructed. Historic networks report a precise sequence of stopovers and two different sources, albeit approximately contemporary such as Qalqašandī and Ibn Ǧi'ān, can record two different sequences of stopovers. The choice of the stopovers depends on elements that are not always easy to comprehend (e.g. the purpose of the travel) but it does not mean that an alternative sequence of stopovers was impossible. Several alternative paths could have existed at the same time to go from Damascus to Khan Yunus, on the Egyptian border. As a result, we considered the sequence of the stopovers registered in the historic networks as guidelines and not as defining an immutable road. The historic networks allowed us to demarcate a corridor or passage that was used to go from point A (e.g. Damascus) to point B (Khan Yunus) and to attribute a caravanserai to a corridor. Our purpose was to evaluate the overall consistency of the caravanserais' distribution pattern over a route, and not the regularity of the sequence of stopovers reported by historical sources and which reflect specific travelling needs. Thus, the 1200 CE and 1450 CE networks do not represent physical roads on a territory but connecting edges between nodes for the purpose of distance analysis.

This research also aims at investigating whether the study of distances between caravanserais can provide useful information to locate those caravanserais whose position is unknown. At the same time, the reasonable measure of a one-day's walk span as a maximum distance between structures seems a necessity-driven plausible criterion for the analysis of caravanserais' distribution. Medical studies show that a human being in normal physical condition and not trained can walk at 4.8 km/hour (Tate 2007; Silverstein 2007). Animals can move faster than 4.8 km/hour but the analysis of the historical sources appears to reveal that the majority of the travellers went on foot and, in any case, the load the caravan animals carried — merchandise or travellers' baggage — slowed down their pace (e.g. Phelps-Grant 2010). In the Middle East, travellers often assembled in caravans whose logistics appear to be well organized and who could march up to twelve hours without stopping, thus being able to cover approximately 50 km per stage (Ibn Ǧubayr 2003). In some cases, caravans could cover 70 km in 24 hours by stopping for 3–4 hours after 15–20 km and resuming the march to the following stopover (Ibn Ǧubayr 2003). Depending on the needs of the travellers and on factors

Tab. 1. Time matrix of caravanserais according to their construction date (blue rows represents uncertain structures, to be excluded from the process) and their life period (asterisks), assuming (in case of unknown life periods) an average life of 100 years for Ayyubid ones and a long-lasting existence well into the Ottoman era for Mamluk ones. 1200 CE and 1450 CE appear as the most significant phases for the inquiry (green columns) (Data processing: A. Palombini, C. Tavernari).

	AYYUBID		MAMLUK					OTTOMAN
	1200-1250	1250-1300	1300-1350	1350-1400	1400-1450	1450-1500	1500-1550	1550-1600
Abu Ghosh				*	*	*	*	*
Aqabat al-Rumman				*	*	*	*	*
Araq al-Manshiyya				*	*	*	*	*
Atni	*	*						
Bab (al-)	*	*						
Baydha (al-)	*	*						
Bayt Daras				*	*	*		
Bayt Jibrin/Bethgibelin	*	*						
Cane								
Enane								
Fandaqumiyya								
Dhra al-Khan		*	*	*	*	*	*	*
Ghabaghib					*	*		
Jabala				*	*	*	*	*
Jaljuliya			*	*	*	*	*	*
Jinin			*	*	*	*	*	*
Julaijil	*	*						
Khan ‘Abde/Orthosie							*	*
Khan al-Ahmar/Baysan			*	*	*	*	*	*
Khan al-Aqabah						*	*	*
Khan Aqabat Fiq	*	*						
Khan Arnabah								
Khan ‘Arus	*	*	*	*	*	*		
Khan Asal			*	*	*	*	*	*
Khan Ayyash		*	*	*	*	*	*	*
Khan Barur	*	*						
Khan Burj al-’Atash		*	*	*	*	*	*	*
Khan Dannun				*	*	*	*	*
Khan Jisr Banat Yaqub					*	*	*	*
Khan Jisr Majami			*	*	*	*	*	*
Khan Jubb Yusuf						*	*	*
Khan Jukhadar								
Khan Hathrura/Khan al-Ahmar					*	*	*	*
Khan Kamar al-Din								
Khan Khattab								
Khan Husein								
Khan Izdud								
Khan Lajjun			*	*	*	*	*	*
Khan Lubban					*	*	*	*
Khan Maysalun			*	*	*	*	*	*
Khan Minya					*	*	*	*
Khan Sabil				*	*	*	*	*
Khan Shaykhun						*	*	*
Khan Shih								
Khan Tujjar					*	*	*	*
Khan Tuman						*	*	*
Khan Turkman								
Khan Yunus				*	*	*	*	*
Hasya						*	*	*
Hawd al-’Azariya				*	*	*		
Khisfin								
Muzayrib			*	*	*	*	*	*

Qal'at Najm	*	*						
Qaqun			*	*	*	*	*	*
Qara	*	*	*	*	*	*	*	*
Qinnasrin	*	*						
Qtayfa	*	*						
Qunaytra						*	*	*
Qusayr	*	*						
Ruhin	*	*						
Sa'la	*	*						
Sanamayn	*	*						
Shaqhab			*	*	*	*	*	*
Saraqeb						*	*	*
Sa'sa						*	*	*
Suq al-Khan/Wadi al-Taym						*	*	*
Tamna								
Tall sultan	*	*						
Tira			*	*	*	*	*	*
Tizin								
Wadihi/Udehi								
Zur'a/Izra	*	*						
TOT	18	21	16	25	31	40	37	37

such as the weather conditions or unexpected casualties, the schedule could vary, the same distance being covered in seven days, ten days, or even more according to different sources (Ibn Ğubayr 2003; De Varthema 1885; Ibn Ği'ān 1922). Finally, it is important to note that carts pulled by animals were not used in the Middle East during the period under consideration.

4 Analysis and results

4.1 The 1200 CE phase

The majority of the caravanserais built in the 1200 CE phase are concentrated in the region between Damascus and the present Syrian-Turkish border. As stated above, we chose to compute distances between nodes constituted by both the caravanserai and urban area networks and to limit the analysis to the most eminent area of the region, the Damascus-Aleppo segment (Fig. 5). The result is a stage sequence average of 24.56 km ±12.8 km (Tab. 2), which shows that distances, if not usually substantial, were nonetheless fairly irregular. The longest stage is Hama-Ma'arrat al-Nu'man, which is 54 km. From the travels of Ibn Ğubayr (2003) and a recent study (Tate 2007) we know that this remarkable distance could nonetheless represent a one-day stage (4.8 km/hour × 12 hours = 57.6 km), albeit a demanding one. At any rate, the analysis shows that such vast distances were uncommon on an important road such as the Damascus-Aleppo road, one of the north–south backbone axes of the Syrian region. To break the unusually large distance between Hama and Ma'arrat al-Nu'man, the Mamluks then built a caravanserai at Khan Shaykhun (Fig. 5), approximately halfway between the two cities. The existence of a Mamluk caravanserai at Khan Sahykhun might suggest that a similar structure also existed before the Mamluk period or rather that, if a caravanserai was to exist before the Mameluks it would have probably been built at this location. Unfortunately, it is not possible to confirm or deny such a hypothesis because we lack any historical or archaeological data on the presence of a caravanserai at Khan Shaykhun before the Mamluk period. The comparison between our network of structures and urban areas and the Damascus-Aleppo road as described in sources also highlights some differences (Fig. 6). It is thus possible to confirm that the caravanserai of 'Atni does not represent a stopover of the Damascus-Aleppo road, but of the Damascus-Palmyra road. The caravanserai of 'Atni is then excluded from the list of structures catering to the Damascus-Aleppo road and a new computation of distances is carried out on the basis of the new list. The results, however, are very similar to the previous ones — the average stage sequence is 24.6 km and the standard deviation ± 13.2 km.

4.2 The 1450 CE phase

For the 1450 CE phase, we chose to consider the Damascus-Khan Yunus segment. This segment was selected both because the majority of caravanserais belonging to this phase were built in the historical Palestinian region and it is one of the best-documented routes of the Mamluk period. The computation of distances used the same criteria of the 1200 CE phase (i.e. caravanserais and urban areas) and the results were then compared to the historic networks recorded by Qalqašandī (Fig. 7) and Qaytbay (Fig. 8).

Notwithstanding the construction of numerous caravanserais during the Mamluk period, the stage sequence average for the 1450 CE phase along the Damascus-Khan Yunus segment presents similar results to the previous case, the main difference being a shorter average distance (20.8 km) while the standard deviation remains quite high (± 12.1 km). Only one stage shows a remarkably high distance that significantly distinguishes it from the others and that recalls the situation along the Damascus-Aleppo segment during the 1200 CE phase. The Muzayrib-Ghabaghib stage peaks at 56 km, nearly

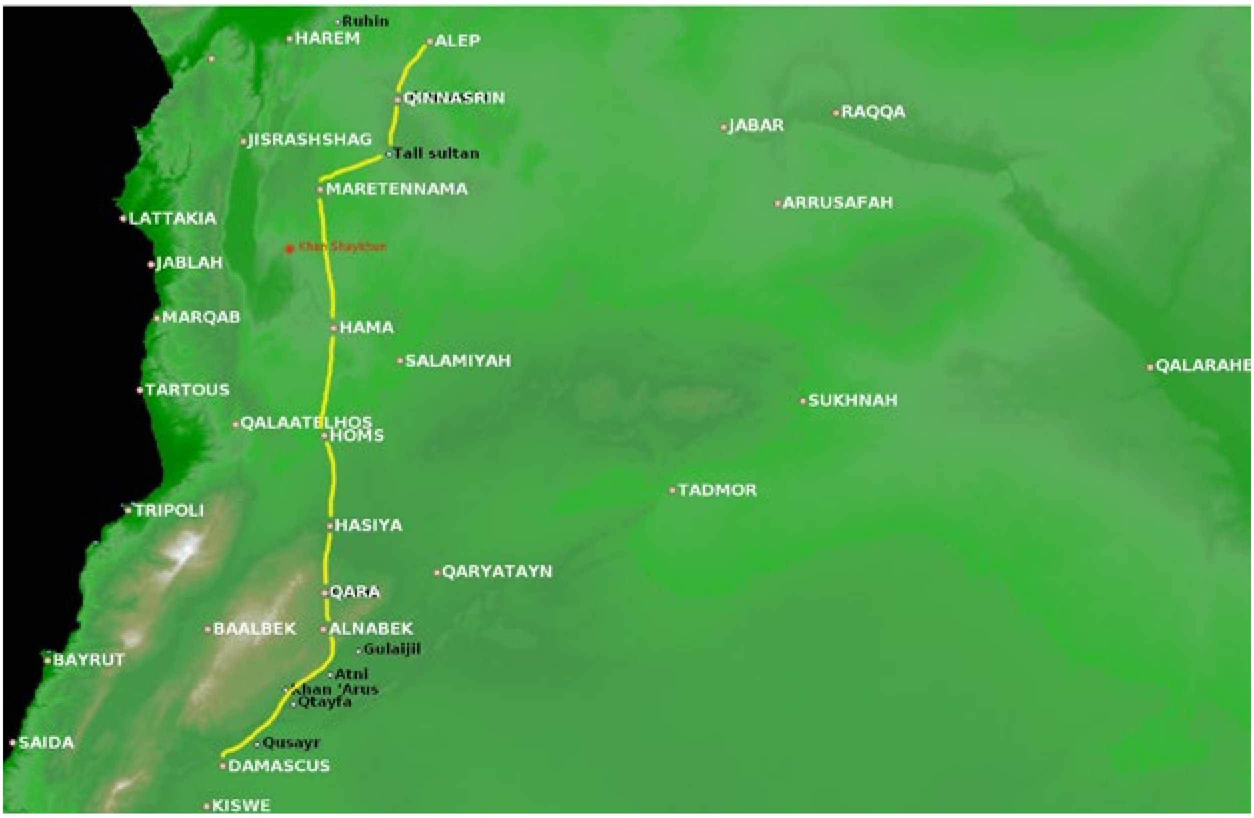

Fig. 5. The wayside caravanserais of the Ayyubid period along the Damascus-Aleppo segment and the caravanserai of Khan Shaykhun built during the Mamluk period (Map: A. Palombini).

Tab. 2. The Damascus-Aleppo segment during the Ayyubid period. Distances are calculated on the basis of the network of caravanserais and urban areas (upper-case letters) (data processing: A. Palombini, C. Tavernari).

AYYUBID PERIOD			
route (from-to)	**Km.**		
DAMASCUS-Qusayr	11	average	24,569
Qusayr-Qtayfe	21	st dev	12,811
Qtayfe-Khan al-'Arus	7		
Khan al-'Arus-'Atni	20		
Atni-AL-NABK	19		
AL-NABK-QARA	15		
QARA-HASIYA	17,4		
HASIYA-HOMS	36		
HOMS-HAMA	40		
HAMA-MA'ARRAT AL-NU'MAN	54		
MA'ARRAT AL-NU'MAN-Tall Sultan	30		
Tall Sultan-Qinnasrin	23		
Qinnasrin-ALEPPO	26		

Tab. 3. The Damascus-Khan Yunus segment during the Mamluk period. Distances are calculated on the basis of the network of caravanserais and urban areas (upper-case letters) (data processing: A. Palombini, C. Tavernari).

MAMLUK PERIOD			
route (from-to): DAMASCUS-KHAN YUNUS	**Km**		
Khan yunus-GAZA	27	average	20,888
GAZA-ASCALON	16	st dev	12,113
ASCALON-Khan Izdud	18		
Khan Izdud-RAMLA	26		
RAMLA-Jaljulya	27		
Jaljulya-Tira	9,4		
Tira-Qaqun	15,4		
Qaqun-Jinin	31,2		
Jinin-Khan Jukhadar	31		
Khan Jukhadar- Jisr al-Majami	8,6		
Jisr al-Majami-Dhra al-Khan	5		
Dhra al-Khan-IRBID	22		
IRBID-Muzayrib	23		
Muzayrb-Ghabaghib	56		
Ghabaghib-Shaqhab	12		
Shaqhab-KISWA	10,5		
KISWA-DAMASCUS	17		

the one-day limit distance and 25 km more than the second longest stage of the Damascus-Gaza segment (i.e. Qaqun-Jinin). Several structures that, due to their characteristics, have not been considered in our first computation could actually have broken the long path between Muzayrib and Ghabaghib. To the west of Muzayrib, the undated caravanserai of Khan Arnabah does not represent the best candidate, as the two sites are 53 km away from each other. The two structures of Sanamayn and ‘Izra that were used during the Ayyubid period seem to be better candidates, especially Sanamayn which, if not halfway between Muzayrib and Ghabaghib, lies on a seemingly direct north–south axis between the two sites. We know that the caravanserai of Sanamayn was in use in 1217 CE (Régnier-Bohler 1997) but we had considered it decayed by 1450 CE because historical sources appear to indicate that Ayyubid caravanserais had a shorter life than their Mamluks counterparts, whose use well into the Ottoman period is often documented. The comparison to the stopovers mentioned in historical sources indicates that Sanamayn was indeed a stopover of the postal route recorded by Qalqašandī in the 15th century and, although the presence of a caravanserai is not mentioned, it is possible that the Ayyubid building was still in use (Tab. 3).

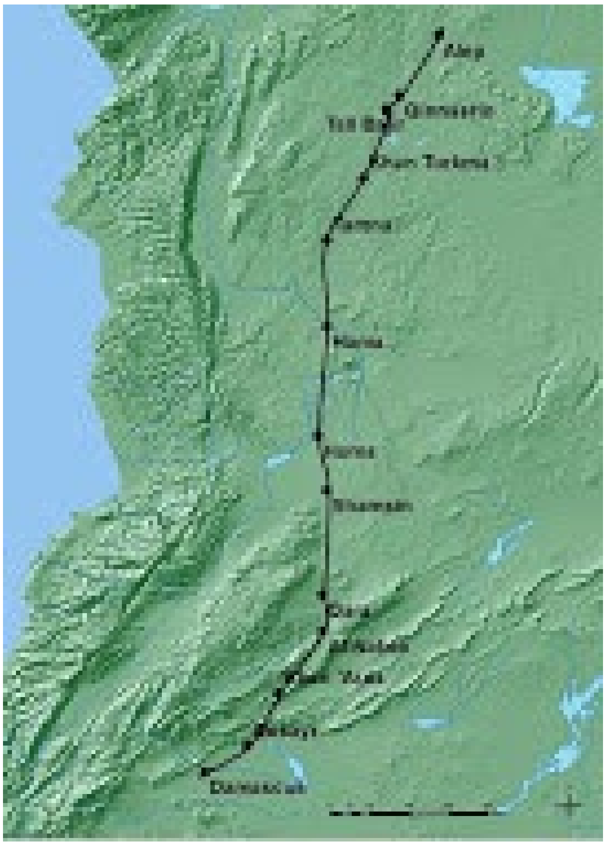

Fig. 6. The Damascus-Aleppo road followed by Ibn Ğubayr at the end of the 12th century (Map: C. Tavernari).

5 Conclusions and perspectives

The main result that emerges from the two case studies under examination is that they yield similar results in relation to both the average stage distance and the standard deviation, notwithstanding the differences in time and place. It thus appears that caravanserais and urban areas did not represent a regularly spaced network. Also noteworthy is the fact that the distance that separates most stages is significantly lower than the distance that can be covered if we calculate a speed distance

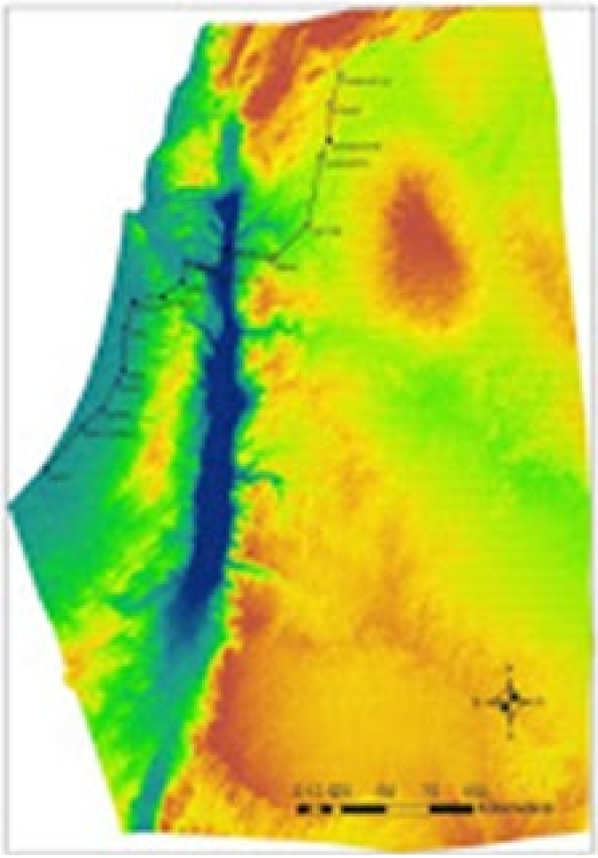

Fig. 7. The Damascus-Gaza road described by Qalqašandī in the 15th century (Map: C. Tavernari).

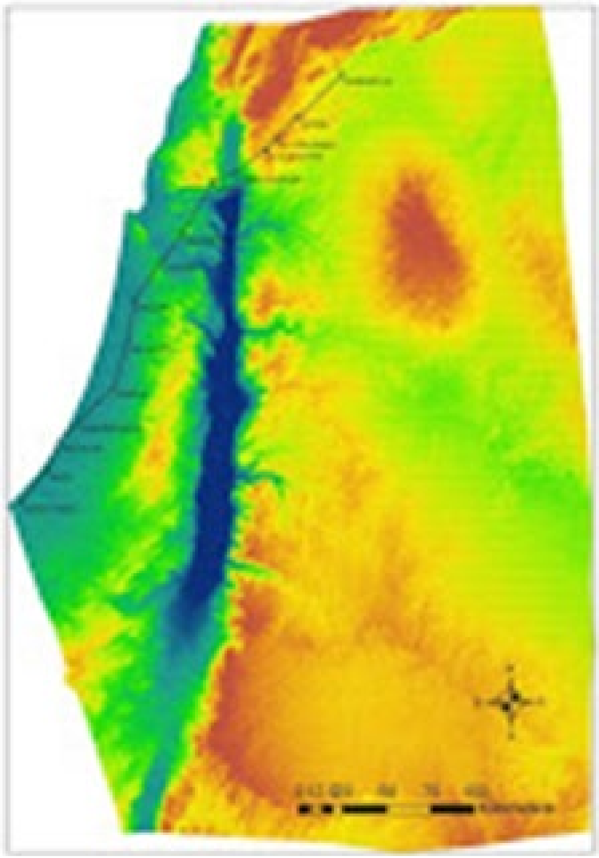

Fig. 8. The road followed by the Mamluk sultan Qaytbay during his travels to northern Syria (Map: C. Tavernari).

of 4.8 km × 12 hours. While we know that in some cases large distances should be covered every day due to the characteristics of the travel and the condition of the terrain — such as in the case of a pilgrimage to Mecca which should follow a precise schedule stipulated by religious imperatives and the harsh geographical and climatic conditions (e.g. the scarcity of water) — it is possible to imagine that many travellers adopted a slower pace. The proposed figure of 4.8 km × 12 hours should be considered as a culminating point when travelling in ideal climatic and geographical conditions or when following a demanding schedule that could be dictated by religious or commercial imperatives (e.g. the caravan with whom Ibn Ǧubayr was travelling managed to cover approximately 70 km in 24 hours; cf. Tavernari 2011).

Such a study may be seen as a methodology useful in different ways. It can be used to argue a possible non-documented path, on the basis of recurrent distances between structures along the same direction, and it can be fundamental in verifying the position of those caravanserais whose location has not yet been firmly established, as well as their building and decaying dates. Because of the destruction of several edifices and the changes in the toponymy of the region, the precise location of some wayside caravanserais is still hypothetical (e.g. Khan al-Turkman at Baqidin, cf. Ibn Ǧubayr 2003). The study of the distances between the caravanserais is thus essential to verify the soundness of our hypothesis and may represent a research tool suitable for similar route-based problems in other historical contexts.

Acknowledgements

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Bibliography

Constable, O. R. 2003. *Housing the stranger in the Mediterranean world. Lodging, trade and travel in Late Antiquity and the Middle Ages*. Cambridge, Cambridge University Press.

Cytryn-Silverman, K. 2010. The Road Inns (Khāns) in Bilād al-Shām. Oxford, Archaeopress.

De Varthema, L. 1885. *Itinerario di Ludovico Varthema*. Bologna, Regia Tipografia.

Erdmann, K. 1961. *Das anatolische Kervansaray des 13. Jahrhunderts*. Berlin, Mann.

Ertepinar-Kaymakci, P. 2005. *Geoarchaeological investigation of Central Anatolian Caravanserais Using GIS*. Unpublished Master Thesis, Middle East Technical University, Ankara.

Hodder, I. and Orton, C. 1976. *Spatial Analysis in Archaeology*, New studies in Archaeology. Cambridge, Cambridge University Press.

Ibn Ǧi'Ān, A. 1922. Relation d'un voyage du sultan Qaytbay en Palestine et en Syrie (translated from Arabic by R.L. Devonshire). *Bulletin de l'IFAO*. 20: 1-40.

Ibn Ǧubayr, M. 2003. *Riḥla Ibn Ǧubayr*. Beyrouth, Dār al-Kutūb al-ʻIlmiyya.

Kleiss, W. and Kiani M. Y. 1995. *Iranian Caravanserais*. Tehran, Iranian Cultural Heritage Organization.

Phelps-Grant, C. 2010. *The great Syrian desert. Caravans, travel and exploration*. London-New York, Routledge.

Qalqašandī, A. 1963. *Ṣubḥ al-aʻšā fī ṣināʻat al-inšā'*. Cairo, Al-Mu'assasa al-Miṣriyya al-ʿĀmma li-l-Taʾlīf wa al-Tarǧama wa al-Našr.

Regnier-Bohler, D. 1997. *Croisades et Pèlerinages*, Paris, Laffont.

Silverstein, A. J. 2007. *Postal Systems in the Pre-Modern Islamic World*. Cambridge, Cambridge University Press.

Tate, R. R. 2009. *The Seljuk Caravanserais of Anatolia. A GIScience and Landscape Archaeology Study*. Unpublished dissertation proposal, University of Chicago.

Tavernari, C. 2011. *Caravansérails et réseaux routiers du Bilād al-Šām (fin XII siècle - début XVI siècle)*. Unpublished PhD thesis. Paris, Université Sorbonne – Paris IV.

Van Leusen, M. 1999. Viewshed and Cost Surface Analysis Using GIS (Cartographic Modelling in a Cell-Based GIS II). In J.A. Barceló, I. Briz, A. Vila (eds.), *New Techniques for Old Times. CAA98. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 26th Conference, Barcelona, March 1998*, British Archaeological Reporst International Series 757. Oxford, Archaeopress.

Modelling Regional Landscape Through the Predictive and Postdictive Exploration of Settlement Choices: a Theoretical Framework

Emeri Farinetti
emerif@tin.it
THALIS programme researcher, Aristotle University of Thessaloniki, Greece

Abstract: The paper illustrates the theoretical approaches to the regional landscape, which can interact, aiming at the modelling and exploration of past landscape dynamics, in particular the settlement chamber model, the community area theory, and further implications, as well as the taskscape approach. The main goal is to set up a meaningful framework for both predictive modelling and postdictive analysis of the available datasets, aiming at the long-term investigation of location choices and physical and cultural characteristics of landscape zones and settlement chambers. The settlement dynamic approach applied for the definition of settlement chambers over the ancient Greek Boeotian landscape will be used for illustration purposes. It allows the detection of different areas with settlement potential in the long term, mainly by analysing the presence and location of known settlements in different periods.

Keywords: Regional landscape, micro-regions, settlement history, predictive modelling, cultural variables

Introduction

One of the challenges of regional landscape researches is to make the best use of the archaeological datasets available in different areas, setting up an environment within which heterogeneous legacy data, often incoherent and incomplete, could be integrated in a meaningful way, aiming at the modelling and the exploration of past landscape dynamics. The main goal is to set up a meaningful framework for both predictive modelling and postdictive analysis of the available datasets, aiming at the long-term investigation of location choices and physical and cultural characteristics of landscape zones and settlement chambers.

In this paper, I will illustrate the theoretical approaches to the regional landscape, which can interact. The *settlement dynamic approach* applied for the definition of settlement chambers over the ancient Greek Boeotian landscape, at the 1st and 2nd level in the settlement hierarchy, will be used for illustration purposes. It allows the detection of different areas with settlement potential in the long term, mainly by analysing the presence and location of known settlements in different periods. The methodology can be meaningful at the micro-regional level, provided a critical assessment of the archaeological record is available, as well as in the comparative analysis to detect settlement trends and landscape choices in different parts of a region with specific environmental and cultural landscape characteristics.

1 Theoretical framework

Historical geography and the *Landeskunde* tradition were concerned with *settlement chambers* because of their interest in the main settlements and their territories (von Thünen 1826; Jahnkuhn 1955; Lehmann 1939; Philippson 1950/9).[1] Later, the *Community Area* school, as proposed by Neustupny and the Czech group in the early 1990s (Kuna 1991; Venclova 1995), also showed interest in settlement chambers, but this time because of interest in the distribution of activities in the landscape in the long term.

A *community area* is a space where the activities of one community took place. Communities performed many different activities, which in turn structured the space in which the communities lived. Each of the activities could have occupied a different spatial unit, a different ‘activity area’: habitation, storage, burial, ritual, as well as production areas, fields, pastures, woodland, quarries, and mines. Thus, the community area approach focuses on the individuation of settlements exploiting a particular micro-landscape, therefore giving attention to small landscapes within which the main settlement, and consequently other activities, might show either continuity or shift in location.

Not only environmental factors (availability of fertile land, location of agricultural land, presence of water sources) are used to individuate settlement chambers, but social and historical variables are also involved in the definition of community areas active in more or less spatially well-defined settlement chambers.

A region could often be divided into micro-regions, whose boundaries are marked both by historical and cultural characters. Within the micro-regions, we can localise micro-landscapes. Some of these can be considered to possess long-term potential, with regard to the presence of a nucleated settlement site or an area of residential activities of some kind.

Although in this paper focus is given to the 1st and 2nd settlement level, in the definition of settlement chambers the

[1] In archaeological research, interest in micro-regions, and consequently in micro-landscapes, seems to have been strong during the final decades of the 19th century (and in the first half of the 20th), within the framework of the German *Landeskunde* tradition. This probably occurred because past societies, the objects of archaeological studies, were based on rural economies as well as on southern European society in the 19th and the beginning of the 20th century. Rural communities still lived then according to micro-regional settlement organizations, and therefore archaeologists naturally tended to focus their research on past societies around micro-landscapes. Within this framework and social context the concept of *Siedlungskammern*, settlement chambers, originated, which was then borrowed by geographical studies.

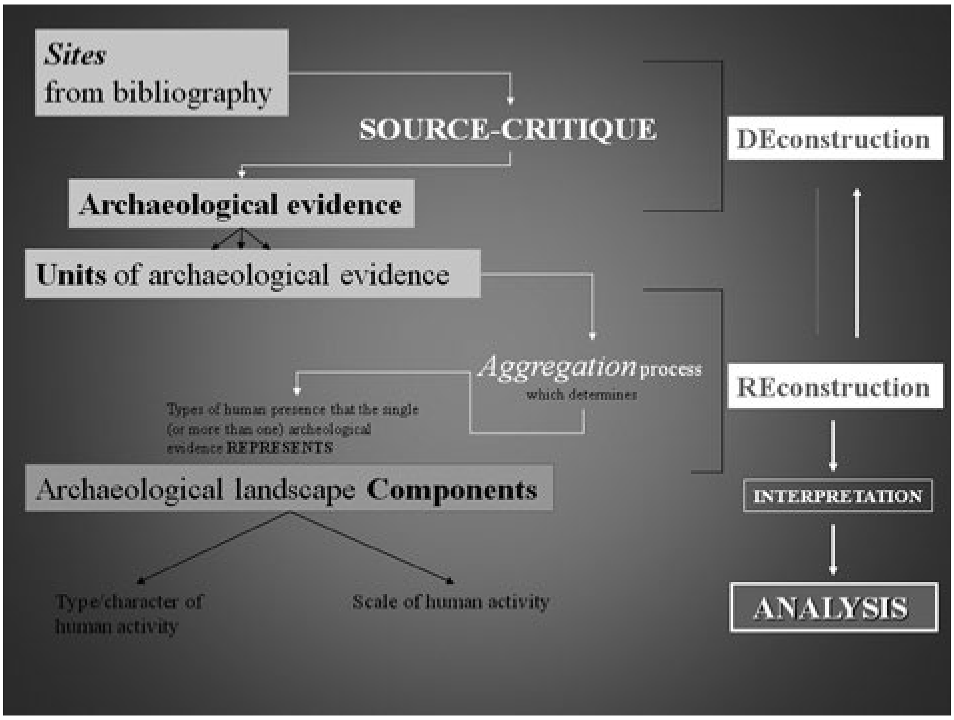


Fig. 1. Model of deconstruction and reassessing of the archaeological record (Farinetti 2011).

whole range of known archaeological information is used, from excavated buildings to movable items accidentally discovered, representing diverse past archaeological entities: rural sites, cult places, burial sites, communication routes, etc. Taking into account the dishomogeneity, non-linearity, and incoherence of the datasets, mainly constituted by legacy data, the first step is to deconstruct the available archaeological record, through a process of strong source-critique, and reconstruct it in terms of meaningful units of social activities in the landscape, extracting the meaning from each individual component to assess in the best way the huge quantity and variety of archaeological information available (Fig. 1). In order to achieve this, most of the work is done during the construction of the database and the critical assessment of metadata (Gillings and Wheatley 2002; Van Leusen 2002; Verhagen *et al.* 2010; Farinetti 2011).

Returning to the theoretical framework, Ingold's 'dwelling perspective' is given a spatial dimension through his image of *taskscape*, which is seen as an array of related activities spread across the physical landscape (Ingold 1993). Taskscape approach may also concern settlement chambers, as it considers the different areas of activities in the landscape, calling them all 'dwelling' (in the Heideggerian sense), and therefore also includes the actual activity of inhabiting as well as all the other human activities.

Settlement chambers, *community/settlement areas*, and *taskscapes* can all be considered concepts belonging to the same reasoning on landscape history and narratives, having as a basis the landscape as a social space, although expressed in different ways and with slightly different implications, and generated within different disciplines (archaeology with a strong influence from geography on the one hand, anthropology reasoning on archaeological and material culture issues — space and time — on the other).

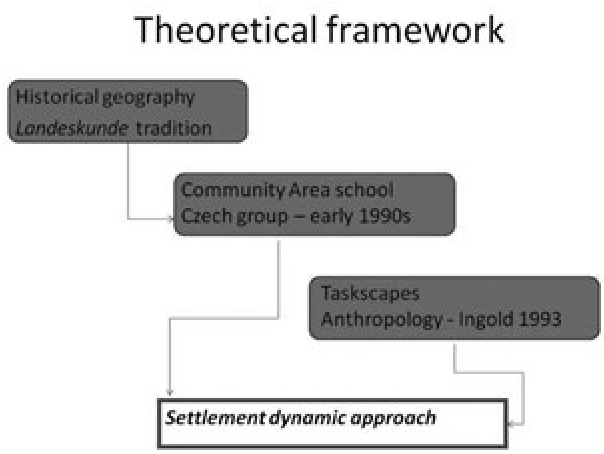


Fig. 2. The theoretical framework.

The resulting *settlement dynamic approach* gives focus to the micro-region, enlightening the role of landscape character, as a result of the association, transforming through time between landscape zones and activities within a wider region; it reproposes the settlement chamber approach born within the *Landeskunde* tradition, renewed and revisited with demanded modifications through the community area and taskscape approaches described earlier (Fig. 2).

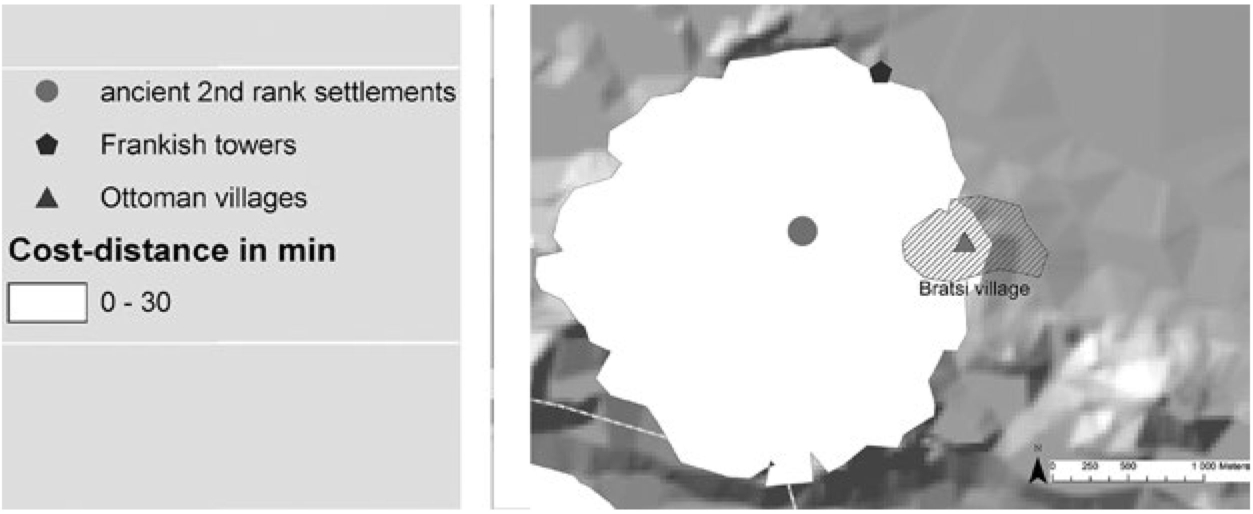


Fig. 3. Shifting of the main settlement in a micro-landscape.

2 A Case Study

In the study of the ancient Greek Boeotian landscape, a *settlement dynamic approach* has been applied for the definition of settlement chambers, at the 1st and 2nd settlement level, in order to detect different areas with settlement potential in the long term, by analysing the presence and location of known settlements in different periods (Farinetti 2011).

Within a community area, continuity of occupation of particular locations in the landscape does not automatically mean that the permanent settlements remain at the very same locus for centuries or millennia, but could correspond to a continuous oscillation of residential areas around some focal points in the landscape, which could explain striking long-term continuity. The examination of the continuity or shift of main settlement and other activities within a small landscape through time, would allow us to 'narrate' the story of the small 'chamber', without taking for granted stability of landscape conditions or of economic or social factors, and without 'idealising' continuity with the attempted emphasis on the role of memory, but rather focusing on recurrent natural and cultural factors.

In some micro-landscapes a settlement can always be detected in the different chronological periods, even if a shift in location sometimes occurs. For instance, in the Late Helladic/Mycenaean period settlements were located mainly on prominent hills, and in the Early Helladic they were located on lower hills, while in the Greco-Roman period settlement/habitation areas became to a large extent nucleated into larger centres, but in fact, even if the settlements and other activity foci moved within the area, people living in it exploited and used the same land, the same territory, and experienced the same landscape.[2] Therefore, one should examine archaeological settlement 'continuities' or 'shifts' on a particular micro-landscape rather than on a particular location (Fig. 3).

Through the comparison between Prehistoric, Greco-Roman, and medieval and post-medieval data, and the modern settlement network, we can investigate the complexities of matching archaeological settlement 'continuities' or 'shifts' with population and ethnic continuity (in terms of postdictive analysis). This allows us to identify clear empty spaces in the ancient Greco-Roman landscape, due to the lack of knowledge or absence of archaeological records for the Greco-Roman period, which could correspond to potential settlement chambers (in terms of predictive analysis).

The distribution of the modern villages can be examined, as well as the boundaries of modern administrative divisions, in an attempt to progress from the actual situation (the 'known') to the archaeological reconstruction (the 'unknown'). The map (Fig. 4) shows that modern *koinotites* (areas administratively belonging to a village) in the Boeotia region, for instance, include different landscape zones, such as different geomorphological and agricultural zones, parts of plains, as well as valleys, foothills, and the inner areas of mountains. Figure 5 shows the hypothesised ancient *chorai* border lines, reconstructed mainly according to three variables: the presence of physical boundaries (such as streams or hillcrests), modern *koinotites* boundaries, and details mentioned in historical sources. By examining the hypothesised boundaries of the micro-regions/*chorai*, gravitating around a historical centre at the polis level, in the Boeotian regional panorama, one can easily see how some of them are more clearly defined through physical landscape characteristics (either by physical boundaries — rivers, watersheds — or by the presence of outstanding environmental features — a lake, marsh, or basin), while others are less easily definable, and socio-political/historical variables play the most crucial role.

In the Copais basin, communities gravitating around it would today divide the farming land available after drainage (according to administrative partitions) (Fig. 5). By contrast, in ancient times, when the lake existed and water covered most of the land, boundaries would have worked in a somewhat different way and the lake itself would have played a role in defining boundaries. The line of these boundaries would have greatly fluctuated according to the level of the lake water and

2 Techniques used to measure and model the continuity of the cultural landscape where developed in the framework of the Archaeomedes EU research programme (see Favory *et al.* 2003). For an application, see for instance Tourneux *et al.* 2006. For an improvement of the model with the inclusion of socio-cultural variables see Verhagen *et al.* 2013.

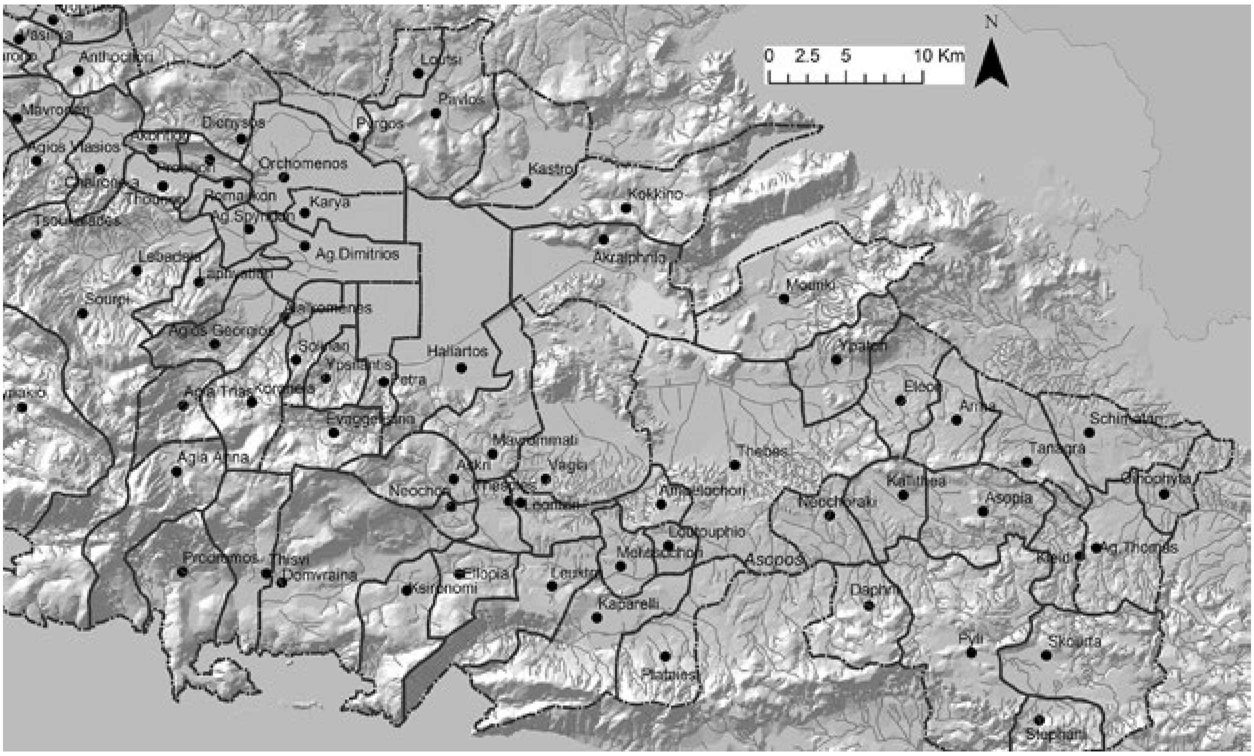


Fig. 4. *Koinotites* (administrative divisions) and *choria* (villages) of modern Boeotia, based on the 1960 map updated in 1983 (Hellenic Statistical Service).

the land actually covered by water, as well as the presence of marshy areas. The slide shows a reconstructed digital model (Farinetti 2008) (Fig. 6).

Of the ancient settlement network, in Greece the polis level is the best known, both from historical and archaeological sources. A comparison between the hypothesised extension of the *chorai* and the supposed extension of the corresponding city sites can give us an idea of the actual impact of some poleis on the territorial behaviour of the 'districts', which sometimes seems not to take into account the actual land available but is instead dictated by other socio-political factors (as in the case of Thebes, the major city which clearly dominates the landscape of the region) (Fig. 7).

Another issue to be examined is the location of the major settlement (polis) within its *chora*. The distance from the geographical centre of the *chora* is greater in eastern Boeotia, as one can appreciate in the map (Fig. 5), where the geometric centre of the *chora* polygon is compared with the actual location of the polis.

In western Boeotia the poleis are very close to the geometric centre of their *chorai*, since factors such as suitable topographical location (hilltops for the acropolis, dry land, strategic position), proximity to water, and proximity to the contact point between two land zones play a role in the choice. This means that the cities, being in the centre of their *chora*, enjoy optimum exploitation of the whole polis territory. This central position is also related to the small size of the *chorai* of western Boeotia, as well as to the strong topographical constraints that define their boundaries. On the other hand, in eastern Boeotia the deviation is larger. The lack of strong topographical constraints corresponds to larger fluctuations of the boundaries over time and therefore to a non-central position of the main settlement. The strength of Thebes acts as a cultural constraint for the location of neighbouring poleis and the formation of their mutual borders.

The location of the poleis within their *chora* certainly influences the location and distribution of the 2nd rank settlements, and stronger fragmentation is visible in the western area of the region, marked by both the presence of stronger topographical constraints (mountain ridges and the large marshy lake) and the absence of a strong political power such as the city of Thebes. Unlike the polis settlement level, the available record for the 2nd rank settlements, i.e. towns and large villages (*komai*), is certainly incomplete, as seen earlier.

In order to fill in the gaps in the picture of the village-based landscape, several variables should be weighted and included in the GIS analyses, including the presence of an earlier or a later settlement, when known, as well as the calculated agricultural potential of the area, in order to evaluate the gaps.

In an attempt to reconstruct, and consequently explore, the ancient settlement network of the region, we can explore:

- continuity of occupation within the settlement chamber
- agricultural land potential examined jointly with the geomorphological-physiographical classification and the reconstructed digital model of the Copais lake behaviour
- presence of human activities, other than dwelling

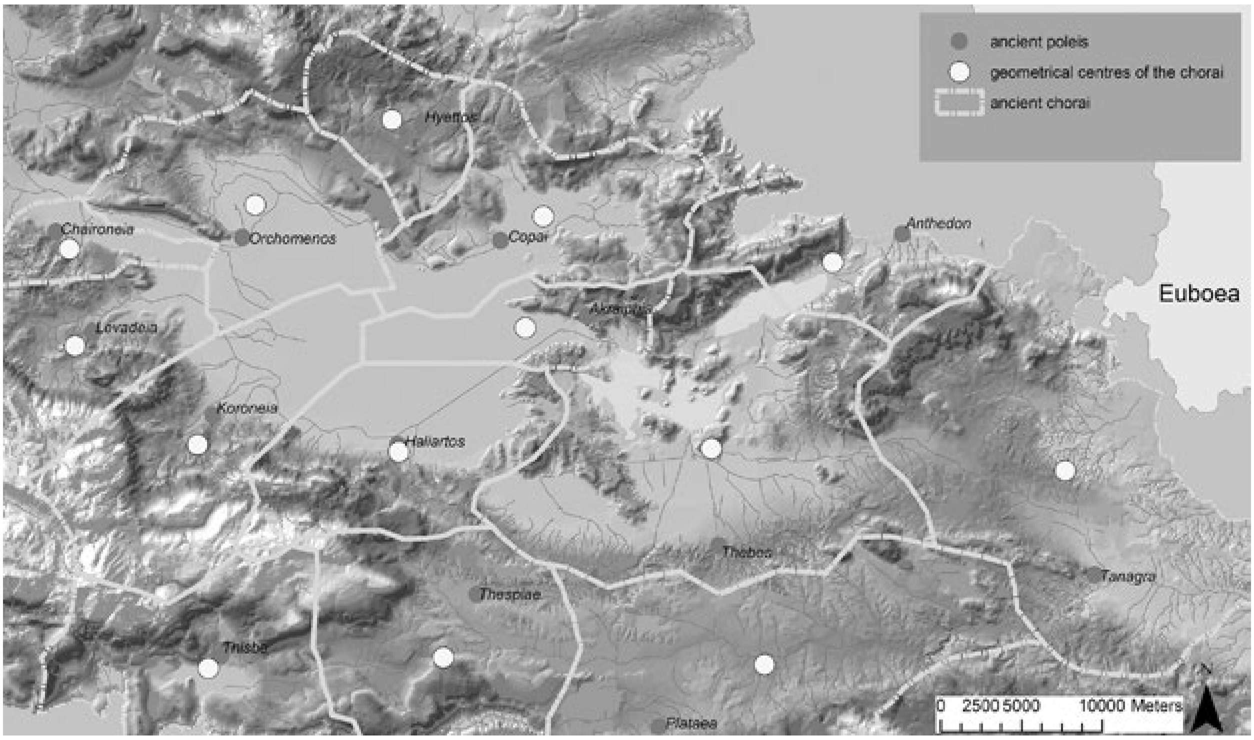


Fig. 5. Map showing the geometric centres of the *chorai* polygons compared to the location of the major Boeotian poleis.

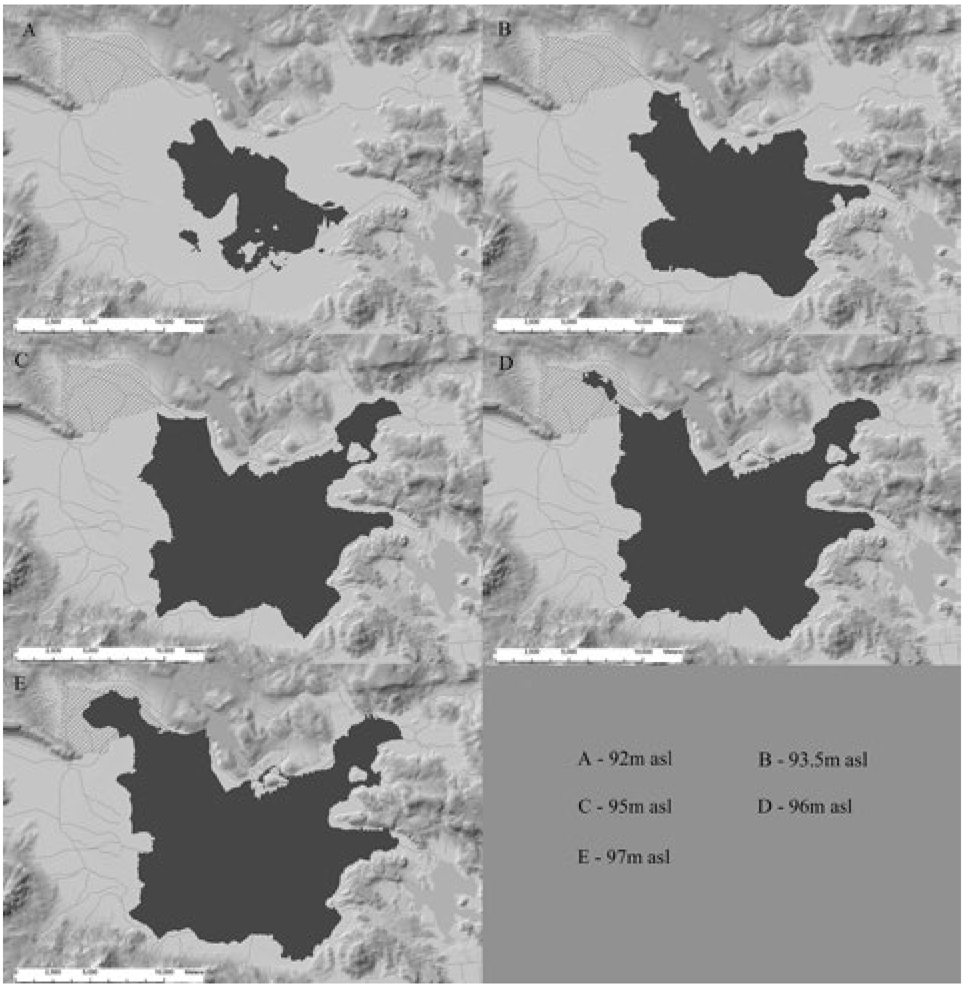


Fig. 6. A digital model of the water fluctuations of Copais Lake. Annual model (A: dry periods – D and E: wet periods and catastrophic years) – Seasonal model (B: summer C: winter) (Farinetti 2008).

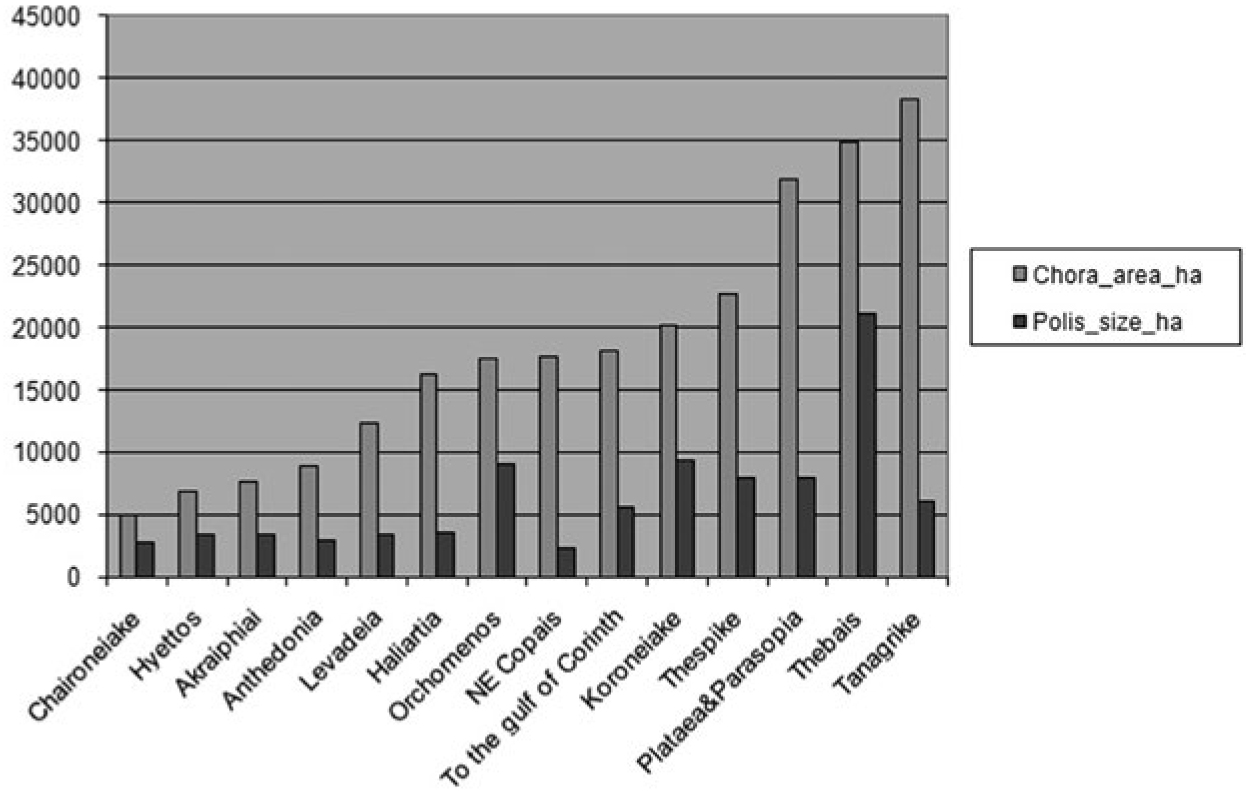


Fig. 7. Bar chart comparing *chorai* and poleis extensions in ancient Boeotia (polis areas in hectares are exaggerated by a factor of 500 in order for the values to be graphically comparable with the extension in hectares of the *chorai*; *chorai* extensions are in ascending order).

- boundaries: based on physical constraints or cultural factors

Afterwards, on the basis of topographical criteria (slope and presence of water), enhanced by the above-mentioned variables, in a study a cost-surface analysis was performed, which produced a map showing a cost-weighted distance from each ancient settlement (the dataset including the 'known' and the 'predicted' villages/2nd rank settlement) (Farinetti 2011) (Fig. 8).[3]

What stand out clearly in the map are the cases in which an actual boundary role is played by physical constraints, such as mountains or rivers. The map also clearly shows that the highest density of 2nd rank settlements can be observed in central and eastern Boeotia. Here we see large distances between the main poleis (Thebes, Plataea, Tanagra), and the intermediate areas are occupied by a ring of 2nd rank settlements around each of these poleis, creating a 'village-based landscape'.

On the other hand, in western Boeotia the density of poleis is higher and the number of 2nd rank villages smaller. Yet we should consider that a number of villages have not yet been identified, and they could correspond to the potential settlement chambers marked in the figure to the left.

The graphs in Figure 9 help us better to compare the two main areas of the Boeotian landscape, marked by different geographical and topographical characteristics. For each wide zone of Boeotia the graph shows the percentage of settlement chambers associated with strong, medium, or low/absent topographical constraints, thus evaluating to what extent topography and/or cultural factors influence the presence of settlement chambers. Considering the graphs in Figure 10, it seems that the majority of the settlements is associated with a large proportion of fertile and mid-fertile land in their territory (calculated on the basis of a land evaluation analysis; Farinetti 2011). Graph 1 shows the occurrence of fertile–mid-fertile and low-fertile land, and land unsuitable for agriculture in the immediate territory of the 1st and 2nd rank settlements. Graph 2 shows the occurrence of 1st and 2nd rank settlement territories with different percentages of F-MF land. The analysis shows a definite preference for settlement locations that offer fertile territories in the immediate surroundings.

Comparison of the settlement network in later periods with the pattern of known prehistoric activity foci supports the existence of the landscape units defined as settlement chambers. Comparative analyses are needed to investigate the issue of continuity over the Boeotian landscape, looking for the occurrence of settlement foci of different periods within a potential settlement chamber. The following periods are considered: prehistoric, Greco-Roman, Frankish, Ottoman, and

3 The cost-surface analysis was based on the slope of the terrain, according to the formula provided by Gorenflo and Gale 1990. As for the potential settlement chambers shown in Fig. 8, source points are assumed only, on the basis of the distance from surrounding settlement sites, suitable locations for settlement, and the qualitatively weighted presence of later occupation in the detected wider settlement chamber. Analyses were performed in ArcGIS 9.3.

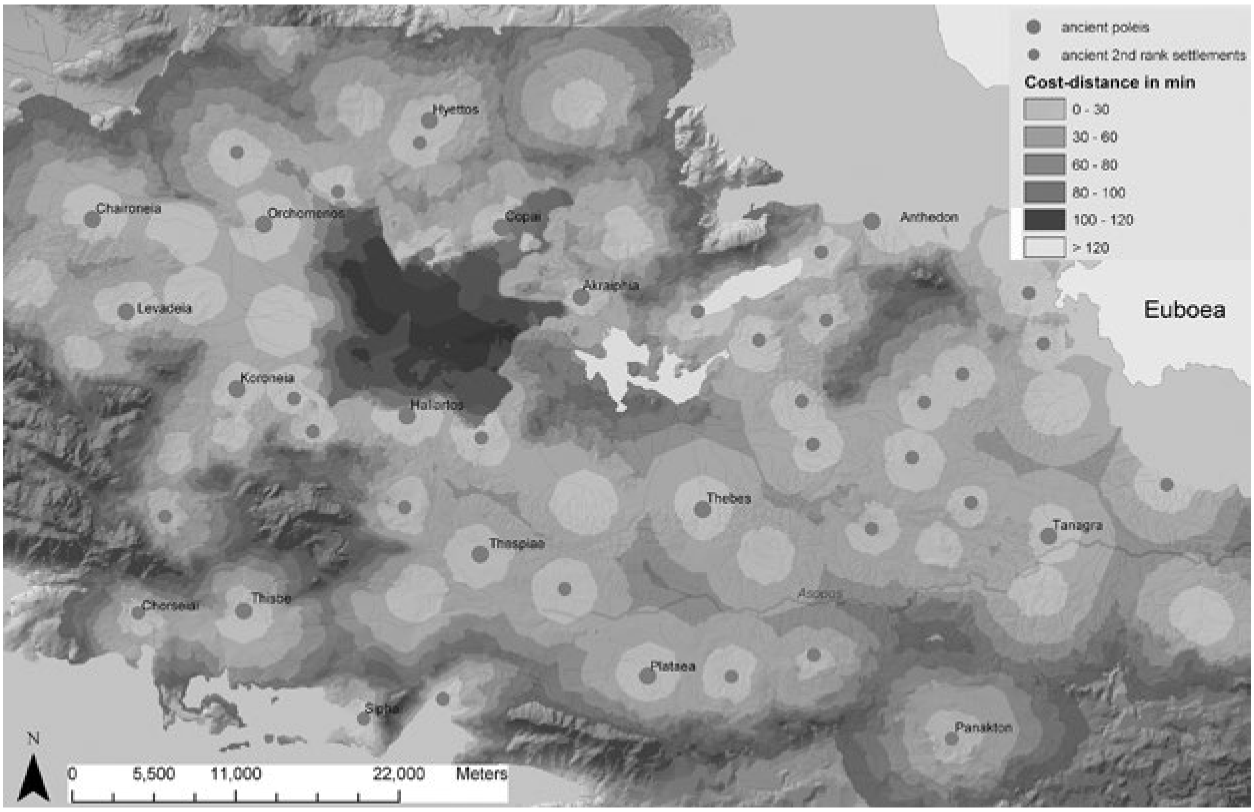


Fig. 8. Classified surface representing the cost-weighted distance (30 mins walking and further ranges) from recognised 1st and 2nd rank ancient settlements (represented by larger and smaller dots). Areas without dots indicate potential settlement chambers.

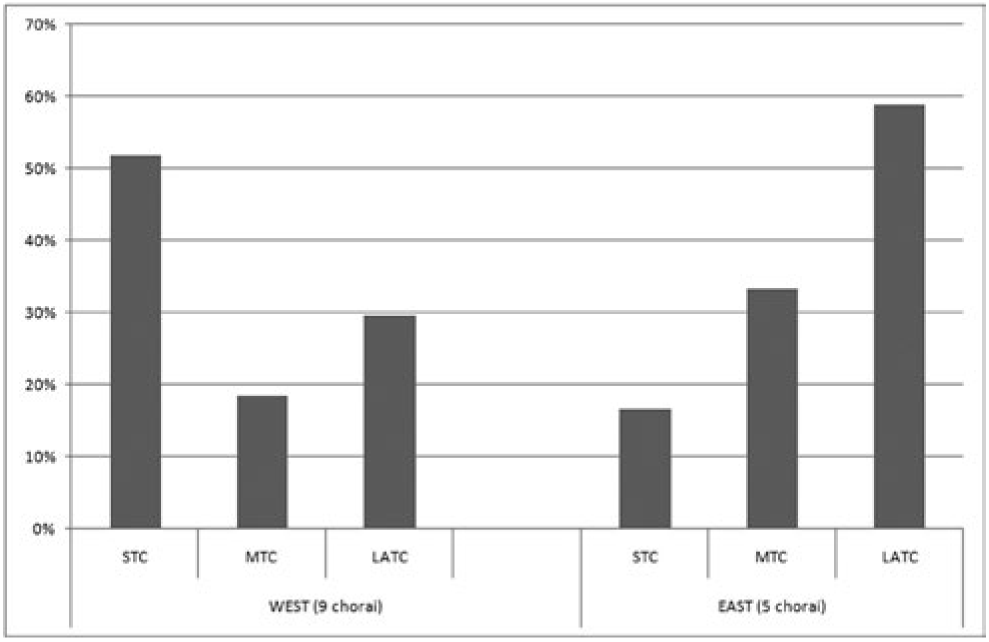
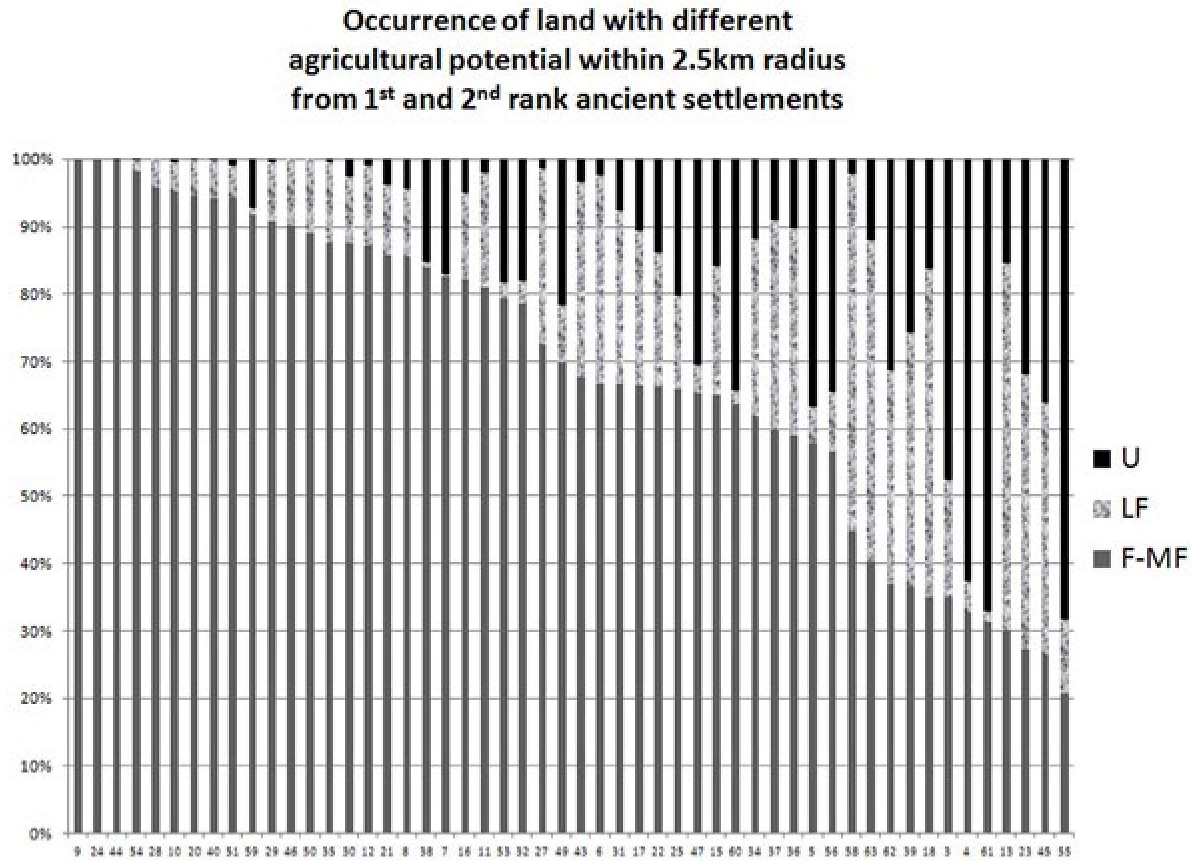
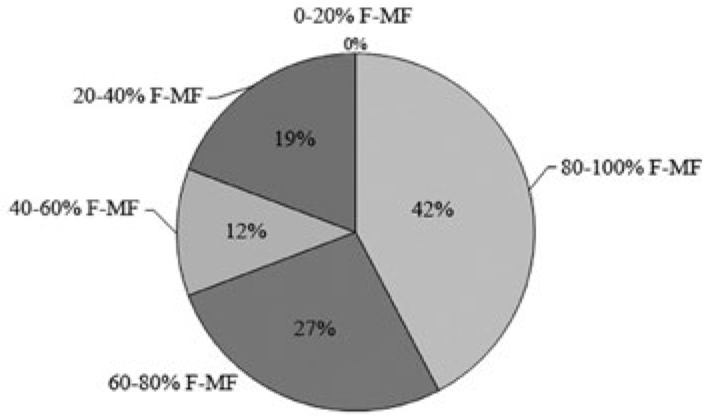


Fig. 9. Percentage of settlement chambers associated with strong (STC), medium (MTC), or low/ absent topographical constraints (LATC) in western and eastern Boeotia.



graph 1



graph 2

Fig. 10. Graph 1: occurrence of F-MF (fertile–mid-fertile), LF (low-fertile), and U (unsuitable for agriculture) land in the immediate territory (30 mins walking time) of the 1st and 2nd rank settlements. The interested areas (numbered on the x axis of the graph) are marked in the map in Fig. 10. Graph 2: occurrence of 1st and 2nd rank settlement territories with different percentages of F-MF land.

modern. Within a settlement chamber one can point out some recurrent occurrences of the main periods, as shown at the top of the graph. The majority of settlement chambers show the presence of settlements of all the main periods (Fig. 11 – top).

The location of the main settlement at the same spot in different periods may mean, in terms of history of landscape, memory in addition to continuity. Thus, in western Boeotia, for instance, which was less affected by population loss and subsequent Albanian colonisation in the late Frankish period, villages with Greek-speaking populations and registered in the Ottoman defters (tax registers) form large nucleated villages close to the ancient Greco-Roman centre, keeping their traditional location and land use (Mediterranean polyculture) – Farinetti-Sbonias 2004. The choice of settling on the same spot recurs especially in certain periods, as shown in the graph (Fig. 11 – bottom).

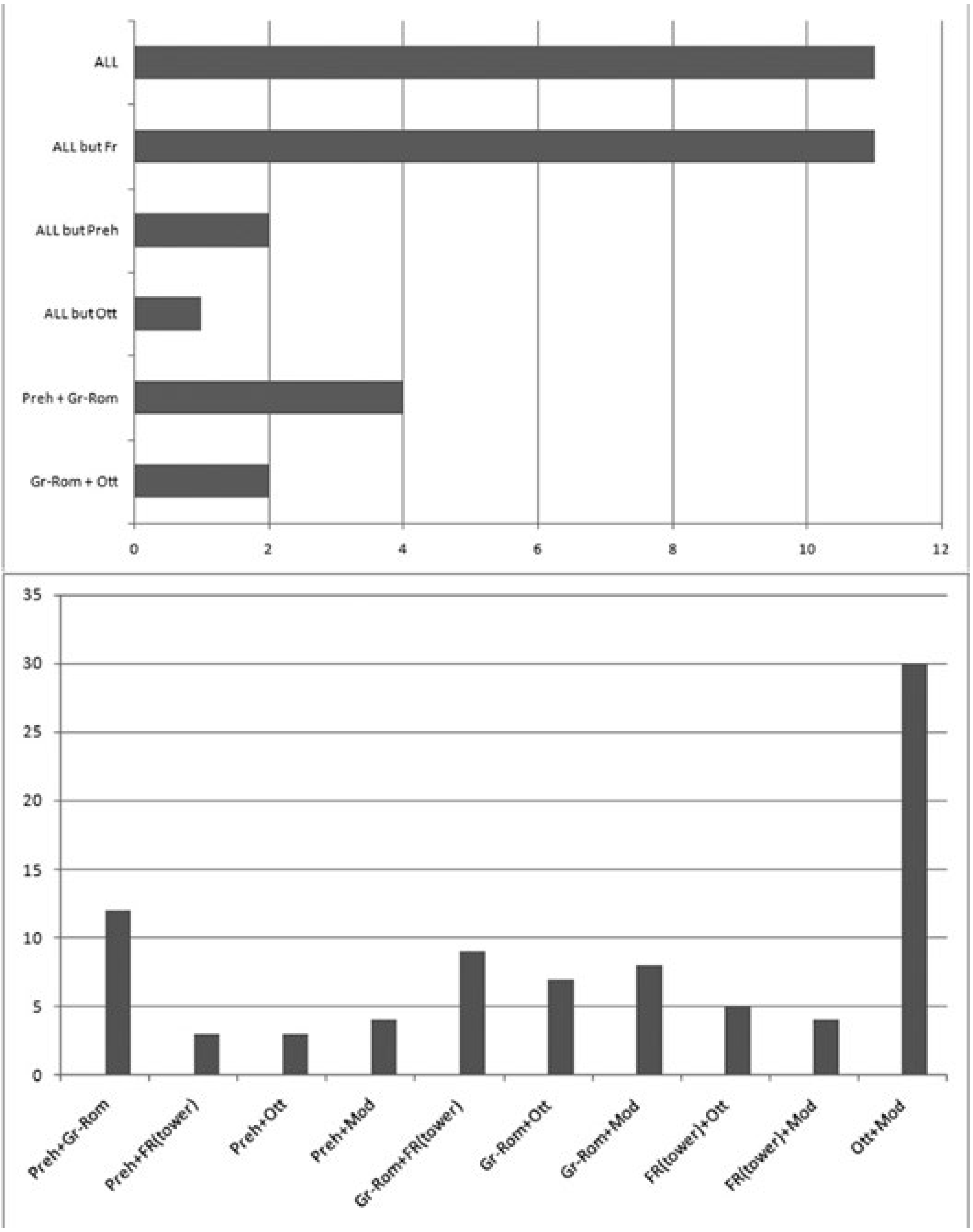


Fig. 11. Top: recurrent occurrences of settlement foci of the main periods considered (prehistoric, Greco-Roman, Frankish, Ottoman, modern) within recognised Boeotian settlement chambers. Bottom: recurrence of settlement foci in the same location in the main periods considered (prehistoric, Greco-Roman, Frankish, Ottoman, modern).

As for non-contiguous periods, the few examples of habitation on the same spot may reflect similar choices in the landscape.

3 Conclusions

To conclude, it can be stated that traditional theoretical approaches can still be meaningful in the construction of micro-regional models, provided the critical assessment of the archaeological record is available as well as the comparative analysis, in order to detect settlement trends in different parts of a region with specific environmental and cultural landscape characteristics (Fig. 12).

The aim of regional studies is to identify similarities and contrasts within a single landscape unit across time in order to analyse and interpret the history of the landscape. In order to do this, occasionally the datasets to be used are not complete and we need to populate them on the basis of previous knowledge or valued factors based on known situations. The selected variables (topographical settling, geomorphological

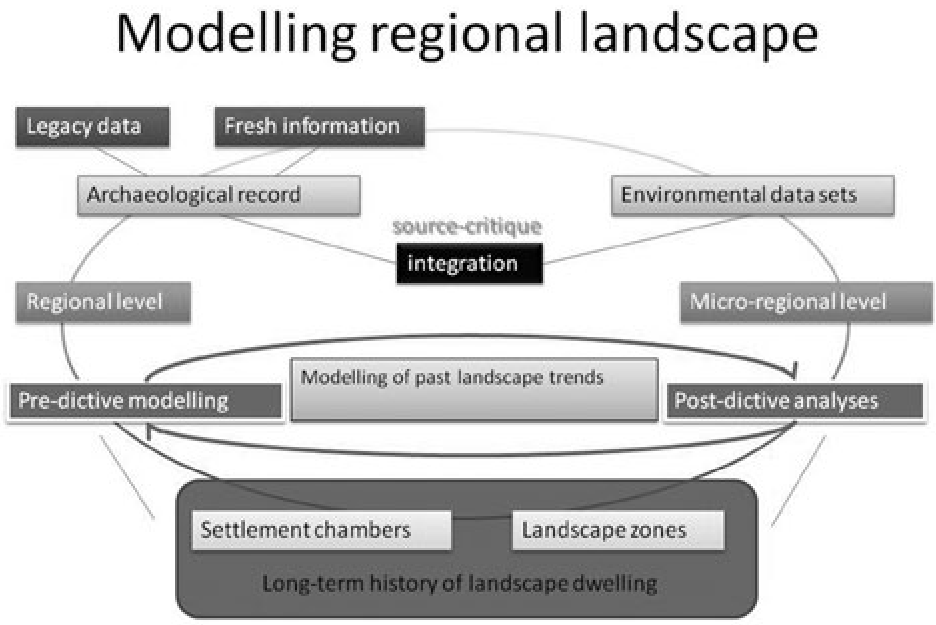


Fig. 12. Modelling the regional landscape: a conceptual model.

and physical characteristics as well as land potential for agriculture or economic activities, long-term history of landscape dwelling) are used to build up a model, using conventional GIS techniques based on cost distance analysis and the creation of friction surfaces. A further development of the *dynamic settlement approach* proposed in this paper might be the application of the selected variables in agent-based modelling or network analyses, in order better to appreciate the shifting of settlements over culturally meaningful foci. Generally speaking, we suggest that, while weighting the most useful variables to build up predictive models in order to detect potential settlement gaps, the perspective should be enlarged and attention should be addressed to wider areas, existing or potential settlement chambers, rather than to specific settlement locations. The latter can be performed only when the known landscape picture is thoroughly analysed and historically understood. In this way, postdictive analyses certainly provide a better basis to construct predictive models able to fill in gaps in lesser known areas. Thus, predictivity and postdictivity jointly contribute to the definition of micro-regional and regional landscape trends.

Bibliography

Farinetti, E. 2008. Fluctuating landscapes: the case of the Copais basin in ancient Boeotia. *ASAtene* LXXXVI: 115-38.

Farinetti, E. 2011. *Boeotian Landscapes: A GIS-Based Study for the Reconstruction and Interpretation of the Archaeological Datasets of Ancient Boeotia*. British Archaeological Reporst International Series 2195. Oxford, Archaeopress.

Farinetti, E., Sbonias, K. 2004. Fields of Wheat back to the Land. A GIS environment for the study of medieval village history in Central Greece. *Enter the Past CAA* 2003 – Wien. British Archaeological Reporst International Series 1227: 271-5.

Favory, F., Fiches, J.-L., Van Der Leeuw, S. 2003. *Archéologie et systèmes socio-environnementaux. Etudes multiscalaires sur la vallée du Rhône dans le programme Archaeomedes.* CRA-Monographies. Paris, CNRS Editions.

Gillings, M., Wheatley, D. 2002. *Spatial Tecnology and Archaeology. The Archaeological Applications of GIS.* London and New York, Taylor & Francis.

Ingold, T. 1993. The temporality of the landscape. *WorldArch* 25, 2: 152-74.

Jahnkuhn, H. 1955. Methoden und Probleme siedlungsarchaeologischer Forschung. *Archaelogica geographica* 4: 73-84.

Kuna, M. 1991. The structuring of prehistoric landscape. *Antiquity* 65: 332-47.

Lehmann, H. 1939. Die Siedlungsräume Ostkretas im Wandel der Zeiten. *Geographische Zeitschrift* 45, 6: 212-28.

Philippson, A. 1950/9. *Die Griechischen Landschaften. Eine Landeskunde*. Frankfurt am Main, Vittorio Klostermann.

Tourneaux, F. P., Nuninger, L., Ostir, K. 2006. ModeLTER: Modelling of landscapes and territories over the long term. International Conference of Territorial Intelligence of Alba Iulia 2006 (CAENTI) http://www.territorial-intelligence.eu

Van Leusen, M. 2002. *Pattern to Process. Methodological investigations into the formation and interpretation of spatial patterns in archaeological landscapes.* Unpublished PhD thesis, University of Groningen. Available at: http://www.rug.nl/research/portal/files/7002343/thesis.pdf).

Venclová, N. 1995. Settlement area, production area and industrial zone. In Kuna, M. – Venclová, N. (eds.), *Whither Archaeology?*, Paper in honour of Evžen Neustupný. Praha: 161-9. Praha, Institute of Archaeology.

Verhagen, P., Kamermans, H., Van Leusen, M., Deeben, J., Zoetbrood, P. 2010. First thoughts on the incorporation of cultural variables into predictive modelling. In Niccolucci, F., Sorin H. (eds.), *Beyond the artefact: digital interpretation of the past. Papers from the 32nd Annual Conference of Computer Applications and Quantitative*

Methods in Archaeology (CAA), Prato, 13-17 April 2004: 307-11. Budapest, Archaeolingua.

Verhagen, Ph., Nuninger, L., Tourneux, F.-P., Bertoncello, F., Jeneson, K. 2013. Introducing the Human Factor in Predictive Modelling: a Work in Progress. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I., Wheatley D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 379-88. Amsterdam, Amsterdam University Press.

Von Thunen, J. H. 1826. *The Isolated State*. Chicago, Loyola University Press.

Site Location Modelling and Prediction on Early Byzantine Crete: Methods Employed, Challenges Encountered

Kayt Armstrong[(1)]
k.l.armstrong@ims.forth.gr

Christina Tsigonaki[(2)]
tsigonaki@uoc.gr

Apostolos Sarris[(1)]
asaris@ret.forthnet.gr

Nadia Coutsinas[(1)]
nadia.coutsinas@gmail.com

[1] Laboratory of Geophysical, Satellite Remote Sensing & Archaeoenvironment,
Institute for Mediterranean Studies, Foundation for Research and Technology, Rethymno, Greece
[2] University of Crete and Institute for Mediterranean Studies,
Foundation for Research and Technology, Rethymno, Greece

Abstract: This paper explores the pre- and post-dictive models of the locations of Early Byzantine Sites on Crete employed in the DynByzCrete project, which aims to examine changes in the inter- and intra-site record during the Early Byzantine period. This project is carried out under the framework of the Operational Programme 'EDUCATION AND LIFELONG LEARNING' (NSRF 2007-2013) and specifically the action 'ARISTEIA II', co-funded by the EU (European Social Fund) and national resources.

The models examine the landscape factors involved in determining the survival of sites beyond the Roman period. Location models examining geology, farming suitability, and access to communication networks discussed groups of characteristics used to define settlement classes. Furthermore, the site location models could be used predictively, suggesting locations for sites known from (and locationally constrained by) historical evidence.

Keywords: Post-dictive models, Site location models, Landscape archaeology, Historical archaeology

Introduction: aims and research context of the DynByzCrete Project

The DynByzCrete project sets out to highlight the changes in Cretan settlements during the Early Byzantine period (from the 4th century to the early 9th century), combining a careful reading of historical and archaeological evidence with the spatial analysis offered by the application of new technologies in archaeological research.

We have key questions about the crisis of the 7th–9th century: specifically, why some formerly prosperous sites disappear from the record, while other persist, even after the Arab occupation. Scholars have to date largely focused on the historical context of this crisis rather than taking a physio-geographical approach. Questions regarding settlements from the so-called 'Dark Ages' of Byzantium (mid-7th century until the early 9th century) were formulated for the first time by A. Kazhdan and G. Ostrogorsky in the 1960s and they have been revived with great intensity during the last decade. Until recently, however, research into this period has been limited to a discussion of the eventual 'decline' of the cities of late antiquity and the resulting 'collapse' — or, as many scholars prefer to define, the 'transformation' — of the ancient world (cf. Saradi 2006: 13–43, for a review of the bibliography). A more systematic study of the period between the 7th and 9th centuries has long been prevented by a bipolar interpretative scheme, seeking only for evidence of either prosperity or decline. This scheme has generally been used to prove either the continuity or discontinuity of late antique culture. The collapse of ancient public buildings, the encroachment of former public spaces, and the degradation of building activities have been considered as obvious evidence of decline as early as the 4th century, when cities gradually shrank or, in some cases, even disappeared. This paper discusses the early stages of building post-dictive models of landscape factors that may have played a role in this period of crisis, and the methodological and theoretical issues encountered.

Crete emerged from late antiquity as one of the most urbanized regions of the Byzantine Empire and fully integrated in the maritime military and trade routes in the unified Mediterranean Sea. The Peutinger map (Levi and Levi 1967: fig. 2) shows a number of key ports, settlements, and roads on the island. The fragmented character of the landscape, with dominant mountain ranges isolating several areas, probably determined the organization of Cretan populations into several autonomous cities in antiquity, which were unified in the Roman period into one administration with the capital at Gortyna. Thanks to a combination of historical documents and field research, we are aware of 83 higher-order settlements of the Early Byzantine period (Fig. 1), about half of which can be securely identified with their historical name. A large team has gathered all of the available data about Early Byzantine Crete, from the published

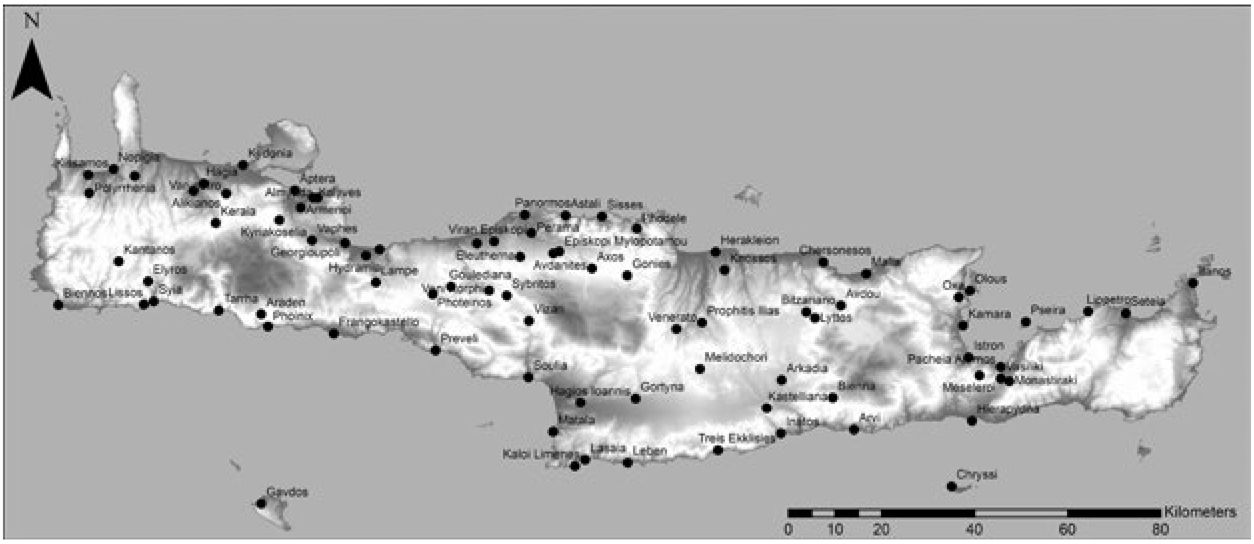


Fig. 1. Crete and the 83 Early Byzantine sites considered in this analysis

record and new topographical fieldwork, which comes together in a series of databases, linked to a GIS which, as well as acting as a repository and dissemination tool, allows us to explore the structured spaces of Early Byzantine life on Crete.

1 Site location models: methodological and theoretical approaches

Location models allow us to examine different geographical factors, and crucially, to see if they differ between the sites that survive to the end of this crisis period, and those that do not. Thus, our post-dictive site location model aims to identify not only the locational characteristics of the Cretan settlements, but also to see if there are any groupings within these that could be used to classify the sites, and whether those classes match with historically established classes of survival and abandonment. Given that we are halfway through a year-long project, we are still at this first exploratory stage of the analysis, as the research team continues to refine and expand their knowledge of the sites. We intend to examine any groupings that emerge from the location models, to see if they correspond to the pattern of surviving vs. failing settlements. If they do, the location models could be used to suggest explanatory factors in the failure of settlements during a period of crisis. We intend, ultimately, for the site location model to be used also as a predictive model, to suggest landscape locations for as yet unidentified Early Byzantine settlements.

The location model is based on point-data for the sites (rather than polygonal representations of the area the site covers) and on other factors, such as area data for the landscape within a one-hour walking radius of the site. A number of decisions about which sites to include are discussed here. Crete is a relatively large region for this sort of study, thus only 'higher-order' sites were selected from the full range of sites where there is evidence of settlement during this period. Sites were included in the analysis based on the following criteria:

- The site has been strongly identified (by historical data or archaeological data) as a site known from the historical record as a polis/city (a political status) in the preceding period, or is mentioned as such in records from the period in question

- Where no historical data is available (i.e. the ancient identification of the site is uncertain), then the site has been included on the basis of the presence of either fortifications dated to the period, or the presence of substantial infrastructure, public or religious buildings *in association* with settlement evidence

- Or a combination of these categories: for example a well-identified settlement such as Sougia/Syia, which is not mentioned as having city-status, but which had walls and several substantial churches

A programme of fieldwork is underway to visit sites where the exact topographic location is uncertain (to allow better landscape modelling), and to examine upstanding architectural remains such as basilicas, walls, towers, and cisterns. For two key sites, detailed published excavation records are available, Gortyna (Di Vita 2010) and Eleutherna (Tsigonaki 2007). Details about specific buildings and the 'places' they occur are stored in the relational database being built by the project team, with links to coins, seals, and inscriptions found there or mentioning the place. From the published material the team have recorded 113 inscriptions, 836 coins, and 95 seals. Alongside these, a large number of coins and seals stored in Cretan museums remain unpublished. The historical records catalogued in the database are also linked to the places they mention. These monuments and places are also recorded in the project GIS, where known (allowing the recording of information about towns, the geographical location of which is uncertain), recorded as two separate point datasets, one for the settlements and one for the specific monuments. The level of certainty and the source of the point (e.g. modern settlement, GPS from fieldwork visit, identification in Google Earth) are recorded. These datasets are linked back to the relational database, allowing tables generated by database queries to be appended to the site/monument records for spatial querying.

Furthermore, where field visits have taken place, or we have access to georeferenced excavation plans, separate geospatial layers exist for a specific settlement, with the data recorded about walls, buildings, excavations, and known find-spots.

Smaller rural sites known from field-walking surveys, and classed as villas, farmsteads, hamlets, and villages have perforce been excluded from the island-wide analysis. This is because the entire landscape has not been examined at this level of detail, and therefore including sites that generally only become known during intensive landscape investigations would seriously bias the dataset, implying absence of occupation in areas where what has really occurred is an absence of research. Moreover, the field-walking surveys themselves employ different methodologies, levels of intensity, and different periodization of the materials found. Furthermore, they might have a specific focus on a much earlier period, and record material from historical periods only in very broad categories, if it is recorded at all.

1.1 Theoretical considerations: environmental determinism, tautological models.

Site location models have generally been employed to understand the initial decision to found a settlement, usually, though not exclusively, for prehistoric societies (Stancic and Kvamme 1999; Posluschny 2010 to give two examples). The idea is to examine the possible landscape factors involved in the decision to settle in a particular location, often with a view to developing a predictive model that allows the suggestion of other possible settlement locations. This, coupled with the ease of modelling physio-geographical factors (and the difficulty of incorporating social and cultural factors) in GIS models has led to a criticism of such models, and of predictive models based upon them as being overly environmentally deterministic (Gaffney and van Leusen 1995; Wheatley 1996; Verhagen *et al*. 1995; Wheatley and Gillings 2002: Ch. 8 and references therein; but see Verhagen and Whitley 2011 for counter-arguments). That is, they assume that people in the past behave as rational components in an ecosystem seeking to maximize economic/subsistence benefits while minimizing effort. It suggests that people in the past can be reduced to units within a system who have no say in their own fate and exist at the mercy of climate, resource availability, and other systems beyond their control or influence. Critics of such models argue that using them to explore causality in the past denies humans their agency and ignores a large spectrum of human behaviour: any examination of how people behave arrives at the rapid realization that they are not at all rational when they make important decisions, and that they are governed by culture, personal relationships, religion, emotional attachments, and many more intangibles when decisions are made.

We argue here that although site location models can fall into environmentally deterministic traps, they are a useful method to employ in this specific case. While it would be wrong to assume the environment as the sole driver of past human behaviour, it would be equally wrong to exclude it entirely from an analysis of settlement patterns. Furthermore, the question of the physical landscape and its role in society has generally not been considered for the Early Byzantine period. The landscape archaeology of this period is only now coming into focus as a discipline, which has previously relied on art-historical approaches and a concern with standing monumental architecture. Finally, our GIS model seeks to incorporate, where possible, social and economic factors, such as communication and trade.

As mentioned above, because predictive models are either a priori generated from landscape factors or are based on location models of known sites, they have fallen under the same criticisms. They have also been criticized on the grounds that they are inherently tautological, and that the nature of the archaeological record is not well suited to the statistical methods frequently used (Wheatley and Gillings 2002: see Ch. 8 for a detailed discussion). Because a model is ultimately derived from known sites (whether directly, or in the process of forming assumptions in a priori models), they can only tell us more of what we already know. If there are biases in the original dataset (for example surveying only sites on ploughed land), these will be perpetuated in the final model: you cannot model your unknown-unknowns. Furthermore, since so much of the archaeological record is fragmentary, you also have to consider deposition and preservation biases, as well as discovery biases. Even if you could identify every remaining piece of archaeology in a given landscape and use that for your model, biases would remain. This criticism has been strongly levelled at predictive models used in the CRM process to help make planning decisions about the level of archaeological intervention required, and the issues raised are indeed serious. In this instance, however, we are not seeking an archaeological 'risk map' but help in identifying possible landscape locations (that may have modern towns on them, preventing archaeological identifications) of sites known in the historical record. We can use the historical evidence to constrain the landscape models, and vice-versa, producing a useful investigative tool.

Finally, our location models do not seek to explain *choice of settlement location*: all of our sites were already in existence at the start of the period in question, some of them since the Bronze Age, with compelling histories and cultural narratives built up around them by their inhabitants. What we seek to explore is the phenomena of the abandonment of these sites: what led people to determine that they were no longer appropriate places to live? In other words, our model is post-dictive, and attempts to describe and understand the landscape factors in play at each location, with a view to identifying trends and dissimilarities.

2 The site location model

Although we are following an Exploratory Data Analysis (Tukey 1977; Wheatley and Gillings 2002: 142–146) approach, the main factors to be considered in the site location model were set at the project planning stage. They are:

- Natural 'fortifications' (topographical setting)
- Cultivable land
- Access to raw materials
- Access to water
- Access to the sea
- Visibility/intervisibility

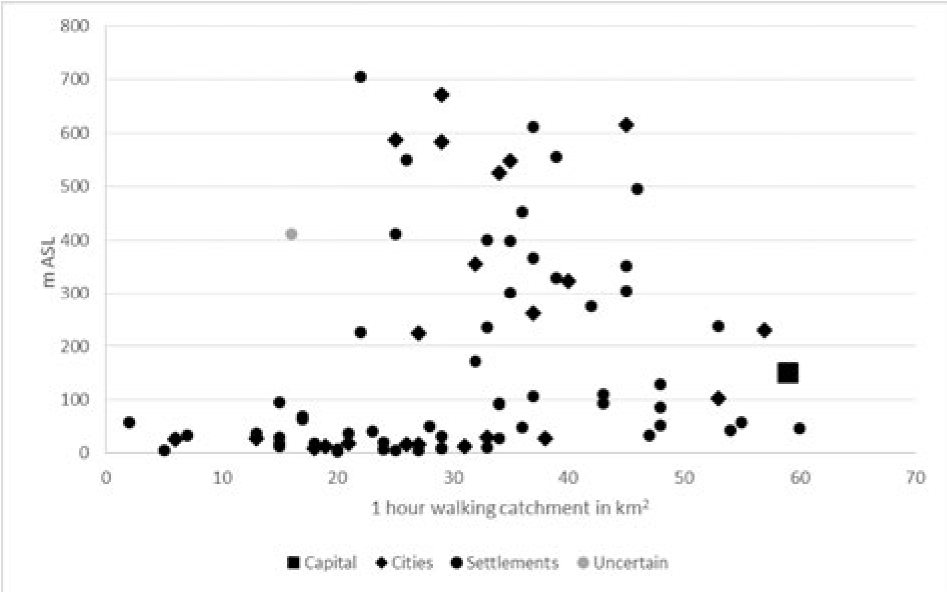


Fig. 2. Plot of site elevation vs. site catchment area (see section 3.2)

- Communication and trade networks (combined with Least Cost Path models that take into account coastal routes)

The present paper will discuss the first five of these factors and what the analysis has revealed to date. The final two factors have not yet been fully investigated, as the network analysis is a complex step that requires a much clearer picture of the phasing of the sites and maritime links than we have at present, and the visibility analysis requires fieldwork to establish exact locations of fortifications such as towers, which drastically affect the outcome of GIS-based viewshed analysis.

2.1 Topographical setting: are some of the sites in 'naturally fortified' locations?

To begin investigating the topographical setting of the sites, we examined the elevations of the sites. As can be seen in Figure 2, no sites occur much above 700 m ASL. A Kolmogorov-Smirnov test (Shennan 1988: 55–58), taking the cumulative distribution of sites vs. elevation, in comparison to the cumulative count of DEM cells in each elevation bracket and calculated for both the whole elevation range (and repeated, but cut off at 1000 m to remove uninhabited mountain areas), showed that the site elevations significantly differ from the general distribution of elevations on the island. Patterns within the elevations of the sites are hard to extract, but fortified sites (i.e. sites where defence was clearly a factor for the population) are either below100 m ASL (and are coastal towns), or lie generally between 300 and 500 m ASL. The exception to this is the capital of the island, Gortyna.

The elevation itself, however, is a poor indicator of the local topography surrounding a site. Slope models can allow an instinctive reading of the roughness of the terrain in the immediate landscape, and future models examining the local relief, using neighbourhood- rather than point-based methods, are planned following feedback on this paper given during the conference. Work on this dataset has continued since the conference, and geomorphological models of the site locations have been created and studied using several different approaches. This work was undertaken by Dr Nasos Argyriou at the GeoSatReSeArch Laboratory and will be published at a later date, along with any changes this produces in our results and conclusions.

2.2 Site catchments: access to farmland, natural resources and tradeable goods

Although the project design specified 'access to natural resources' as a factor to consider, records directly pertaining to the Early Byzantine period are lacking. There are good records for the late Roman period, and we can assume some continuation of these practices into the period of our study. There are a few mineral resources on Crete that were known to be exploited during the period in question, although during the Roman period Leben and Lasaia enjoyed prosperity based on mineral resources on Mt Kofinas (Tsougarakis 1988: 139), and there was a source for whetstones at Olous that was being exploited until the 19th century (Sanders 1982: 33). We know from historical documents that the exports of Crete during the Roman period were mainly agricultural products like olive oil, wine, timber, herbs, and honey, but also seaweed, sponges, and perfume ingredients (Harrison 1993: 109-18; Tsigonaki 2007: 264). Crete participated in an extensive Mediterranean maritime trade network, and evidence from Gortyna suggests this trade continued until the 8th century (Portale 2011; 2014). After the middle of the 7th century, that maritime trade was destabilized by the Arab-Byzantine war. A large proportion of coastal sites, particularly on the mountainous south coast rely on sea travel, even today, for access to the rest of the island. If those sites, with their steep and mountainous catchments, lost access to regular maritime trade, could they perhaps cease to be viable? As well as exports, the subsistence needs of the local population need to be taken into account.

In order to examine access to arable land and natural resources, one-hour walking distance polygons were generated for each site. This was achieved using the path distance tool in ArcGIS 10.2 (ESRI Inc. 2013), using modifications for the % slope, using Tobler's hiking formula over a 20 m resolution DEM (created from stereo SPOT panchromatic images). These polygons could then be intersected with other datasets

Tab. 1. Chi Squared test of whole landscape geology vs. geology at site locations, demonstrating a preference for Quaternary Alluvium.

Geology	Count of Raster Cells	Percent of Crete	Expected site Count	Observed Site Count	χ 2
Carbonate	5600352700	67.19	55.77	44	2.48
Flysch	710786000	8.53	7.08	4	1.34
Igneous	94223200	1.13	0.94	1	0.004
Metamorphic	1013100000	12.16	10.1	8	0.432
Quaternary Alluvium	915616000	10.99	9.12	26	31.26
Grand Total	8334643562	100	83	83	**35.51**
Critical χ 2 (p 0.001)					**18.47**

to examine what was available to the settlement inhabitants within a one-hour range. This one-hour range was selected based on the finding that late classical and antique city dwellers preferred to cultivate fields within one hour of their home base (Chisholm 1962; Bintliff 1999; 2002). We are aware that this is a very simple approach to human movement in landscapes and that there is extensive literature on this topic. As our questions did not involve discovering or creating networks of paths between settlements, but rather a 'sensible estimate' of the size of the one-hour walking catchment, we elected not to pursue more complex models of movement. The results from the ArcGIS path-distance tool were compared with the GRASS 7.0 r. walk tool for the location of Gortyna, and were found to be reasonably equivalent, but because the primary GIS was implemented in ArcGIS we decided to keep all of the workflows within that same software environment.

A key factor in agricultural viability is the character of the soil, which in turn is dependent on the geology, climate, and relief. The parent geology is also important for other reasons; it dictates the landforms and can provide raw materials for building. The first analysis of the site catchments was to observe the makeup of their geology, in broad terms, and compare that to the geology of the island as a whole. As can be seen in Table 1 there is a significant preference for the sites to be located on quaternary alluvium, which on Crete consists of valley-floor fills and sediment fans at coastal exits of gorges. These form flatter environments in a landscape dominated by steep topography: it is possible, therefore, that it is not the soils present on these deposits but their flatness that is attractive to people for settlement building. Unravelling the 'flatness' component from the soil preference is very difficult, statistically, and ultimately we are not trying to understand why these sites were chosen in the first place, but why they might have been abandoned. Thus, the productivity of the catchment is of much greater interest.

To examine the agricultural potential of the site catchments, the landscape was classified by criteria developed by Goodchild (2007) to look at agricultural production and subsistence in the Tiber Valley. Her models went a great deal further than ours need to, as she was interested in modes of production and population reconstructions; here we need only a basic examination of the agricultural potential for two important crops, wheat and olives. The reason we selected Goodchild's model was because her work involved reading the ancient sources, to try to understand what would have been considered as suitable land by antique farmers. The factors in her models are thus derived from ancient farming texts. The criteria

Tab. 2. Scoring used in the wheat suitability model (after Goodchild 2007).

Factor	Class	Score
Slope	0-8%	255
	8-13%	191
	13-25%	127
	25-55%	63
	55% +	1
Aspect	N, NW, W, Flat	1
	NE, SW	127
	E, SE, S	255
Geology	Quaternary Alluvium, Igneous, Metamorphic	255
	Carbonate, Flysch, Neogenes	127
Elevation	< 1200m ASL	255
	> 1200m ASL	1
Water Access	Not Applicable	-

and ranking we have adapted for Crete for wheat and olive suitability are shown in Tables 2 and 3 respectively, and the resulting landscape classifications are shown in Figures 3 and 4 respectively.

The classifications shown are derived as follows: elevation is an absolute limiting factor; areas outside the cultivable ranges given in the tables produce a 'not suitable' result, as does a score of 1 across the remaining four criteria; a score more than 1 in one or more of the remaining four criteria leads to a 'partially suitable' result, and a score of 255 in all four criteria results in 'most suitable'. At present this is actually a Boolean classification based on number of criteria fulfilled (0, or fail on elevation, 1–4, 5). The numerical scoring system, however, remains in the underlying factor maps in preparation for the introductions of weightings, once these results have been verified against modern land-use data. When the percent distribution of each class in the one-hour catchment is considered, there is a link between wheat suitability and size of catchment; this is because both of them are influenced by 'flatness' as a positive factor. Even with this taken into account, however, three sites show higher than expected percentages of the 'best' quality land, Hierapydna, Phaistos/Hagios Ionannis,

Tab. 3. Scoring used in the olive suitability model (after Goodchild 2007).

Factor	Class	Score
Slope	2-25%	255
	25-55%	127
	0-2 %, 55% +	1
Aspect	NE, E, SE, Flat	1
	N, S	127
	SW, W, NW	255
Geology	Quaternary Alluvium	1
	Igneous, Metamorphic, Carbonate, Flysch, Neogenes,	255
Elevation	< 700m ASL	255
	> 700m ASL	1
Water Access	Not Applicable	-

and Gortyna. The first two were important autonomous cities in preceding periods, and Gortyna was the capital of Crete during the period in question. Could ready access to prime agricultural hinterlands have played a role in the historical pre-eminence of these settlements and helped them weather the crisis?

2.3 Access to water (rivers): irrigation

Modelling access to water for the sites proved to be difficult. There is no complete and accurate record of the springs on the island that were producing water during the Early Byzantine period. Furthermore, we know that some ancient water sources, like the one that fed the aqueduct and massive cisterns of the Roman period at Eleutherna went dry sometime after the late 7th or early 8th century. Therefore surveys of known cisterns and water-based infrastructure are not helpful, as we do not have dates for when they dried up or otherwise went out of use. The very strong earthquake of AD 365 potentially had an effect on spring lines, certainly in western Crete (Stiros 2001). Written sources and archaeological evidence provide information for other important seismic events throughout this period (Tsougarakis 1988: 20–22 and 27)

There is also no complete survey of currently flowing springs on Crete; all we have to go on are the rivers digitized within the CORINE 2000 project (European Environment Agency 2011); and for these, crucially, we do not know which are active year-round. Simply put, on current evidence it is impossible to reconstruct the water resources available to the Early Byzantine settlements. We did examine the distance (in walking time) to the modern rivers and streams (which do not include seasonality data) and discovered that nowhere was more than an hour's walk from a water body as defined by the CORINE 2000 dataset. Given that none of the rivers provide navigable communication routes inland, and that many ancient settlements have evidence for water storage and management, we conclude that direct water access was not a primary concern for the inhabitants. Given our incapacity to make accurate models of past water access, we have excluded this aspect from further analysis and will remove it from future agricultural models.

2.4 Access to the sea: trade and communication

Access to the sea is a factor that needs to be considered, this time in terms of access to maritime trade. We can treat access to harbours as a proxy for access to maritime trade. When we consider distance to the coastline, no particularly significant pattern emerges, but much of the coastline of Crete is not suitable for landing boats; we need to consider harbour sites and measure access to those. Modelling 'good' harbour locations is beyond the scope of this project as it depends on a large number of factors: prevailing winds, bathymetry, overland access to the harbour, fresh water for replenishing ships stores, seasonality, and draft of the ships in question. We do, however, have information about known harbours and places ships could safely come ashore for water, in the form of historical itineraries such as the *Stadiasmus Maris Magni*. Specialists date the compilation of this work from the 3rd to the 5th century

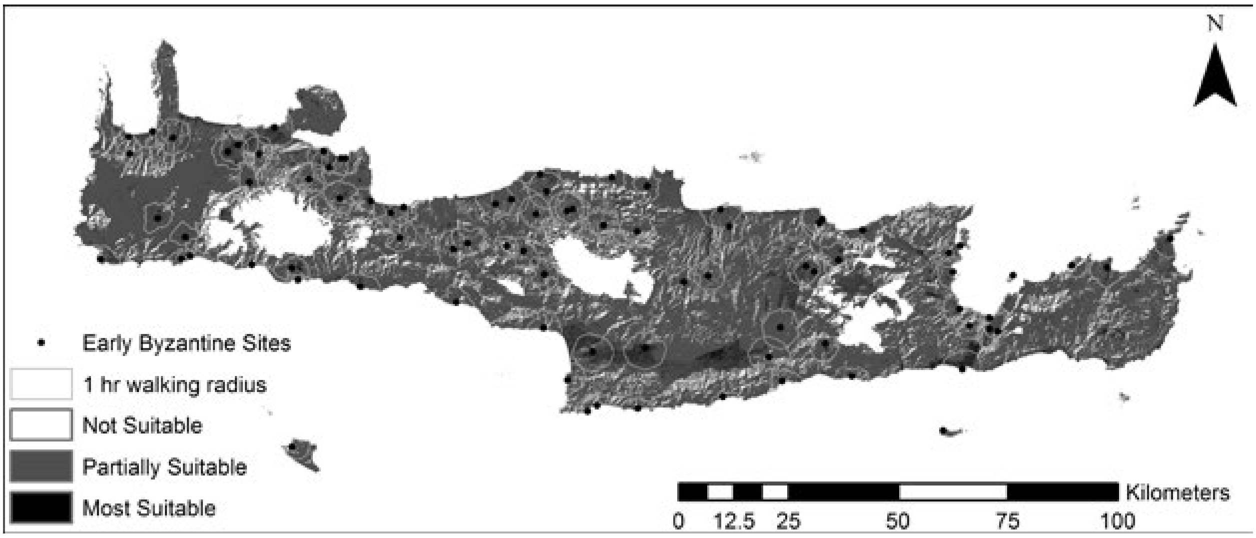


Fig. 3. Suitability for wheat farming (after Goodchild 2007) with site locations and catchments

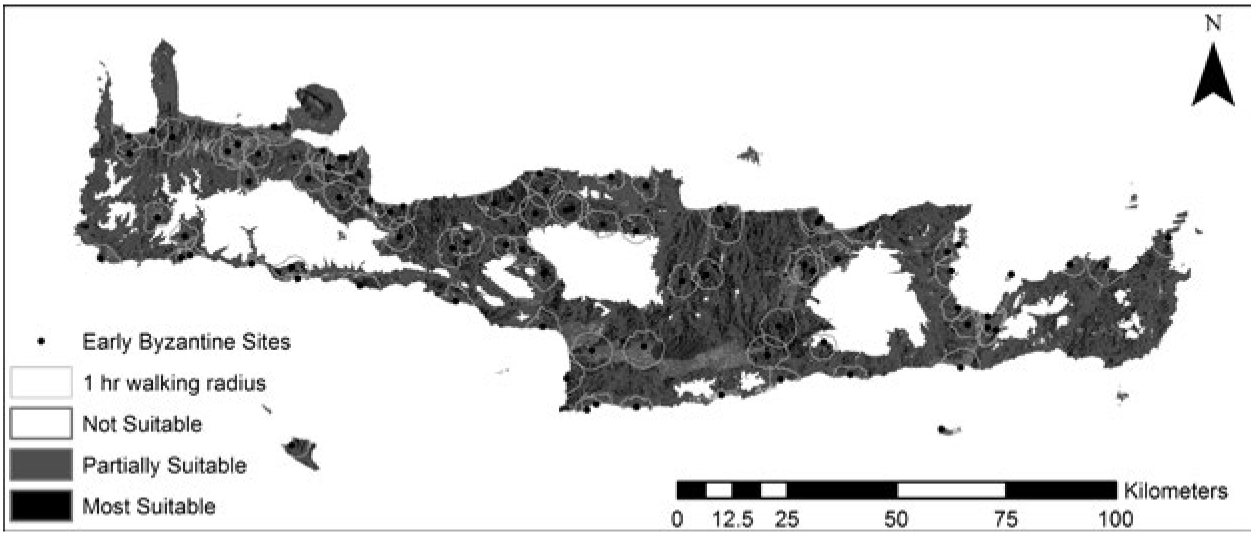


Fig. 4. Suitability for olive farming (after Goodchild 2007) with site locations and catchments

(Arnaud 2009: 166–170), which gives a useful starting point for the coastal sites in existence at the beginning of our period. When we look at all of the towns mentioned as ports or havens in that document, plus the other coastal sites as yet unidentified with their historical name, we end up with 39 known possible 'harbours' operating in the Early Byzantine period, and 44 known inland sites. When we look at the distances of the inland sites to the harbour towns, there is no significant difference (using a KS test of cumulative distribution, as above) between the inland sites and general access to harbour sites. In other words, the distance to a possible harbour does not appear to be a factor in the location of an inland site. In terms of our question about site survival, this is unsurprising, since many of the abandoned sites are small harbours on the south coast, rather than inland sites. Indeed, inland sites might well have become refuges for populations seeking shelter from coastal raids. In this case, relative *inaccessibility* from the coast may have been a favourable factor in site survival.

3 Conclusions to date

The EDA conducted to date has so far not yielded strict categories of sites, but some general rules about site location have been established: all sites are below 800 m, and there is a strong preference for location on flatter alluvial fans, with good access to carbonate geologies and soils in the site catchment. We can also see that when we sort the sites into classes using the Grouping Analysis tool in ArcGIS 10.2 (K means, without spatial constraints, using random seeds, and requesting five groups), and then plot them on the map, there is a clear patterning in terms of smaller sites on the coast in steep terrain being prevalent on the south coast, as seen in Figure 5. It is this region of the island that sees earlier and higher rates of abandonment during the Early Byzantine period. These small sites, in rough topography, with poor access to the rest of the island overland, seem to be most at risk from disruptions to maritime trade, and it is the seas to the south of the island that saw the biggest impact from raiding and piracy during this period. We can suggest that their smaller hinterlands and lack of strong overland links made these sites more vulnerable in times of stress, and if they could not be self-sufficient without maritime trade, that subsistence and economic factors may have made them unviable.

Moving the models forward to create predictive models, to help solve questions about the identification of known sites or the discovery of new ones is harder; the site location models have to date come up with little in the way of hard and fast rules or strong statistical patterns. There needs to be a key focus on methods for the identification of naturally fortified sites in a way compatible with the GIS. We can go out into the landscape and see likely candidates based on the topography (both immediate and in terms of the wider views afforded from the site), but to put those instincts into GIS terms is a challenge. We do not, however, need to create a comprehensive model of the landscape with verified percentage-based probabilities of site presence; we need to be able to make reasonable suggestions of 'best' candidates from possibilities provided from and constrained by the historical records. Even if hard rules and clear patterns do not emerge, this analysis has already made an impact on the study of Early Byzantine Crete by introducing the landscape dimension into discourse and analysis.

Acknowledgements

This project has benefited a great deal from the feedback from experts in the session, especially about the choice of path-distance algorithms and suggestions for better ways to handle the question of 'natural fortification'.

Bibliography

Arnaud, P. 2009. Notes sur le Stadiasme de la Grande Mer (1): la Lycie et la Carie. *Geographia Antiqua* 18: 165–94.

Bintliff, J. 1999. Settlement and Territory. In Barker, G (ed.), *Companion Encyclopedia of Archaeology* 1. London and New York, Routledge.

Bintliff, J. 2002. Going to Market in Antiquity. In Olshausen, E. and Sonnabend, H. (eds.), *Zu Wasser Und Zu Land. Verkehrswege in Der Antiken Welt*. Stuttgart Kolloquien Zur Historichen Geographie Des Altertums 7 (Geographica Historica 17): 209-50. Stuttgart, Franz Steiner Verlag GmbH.

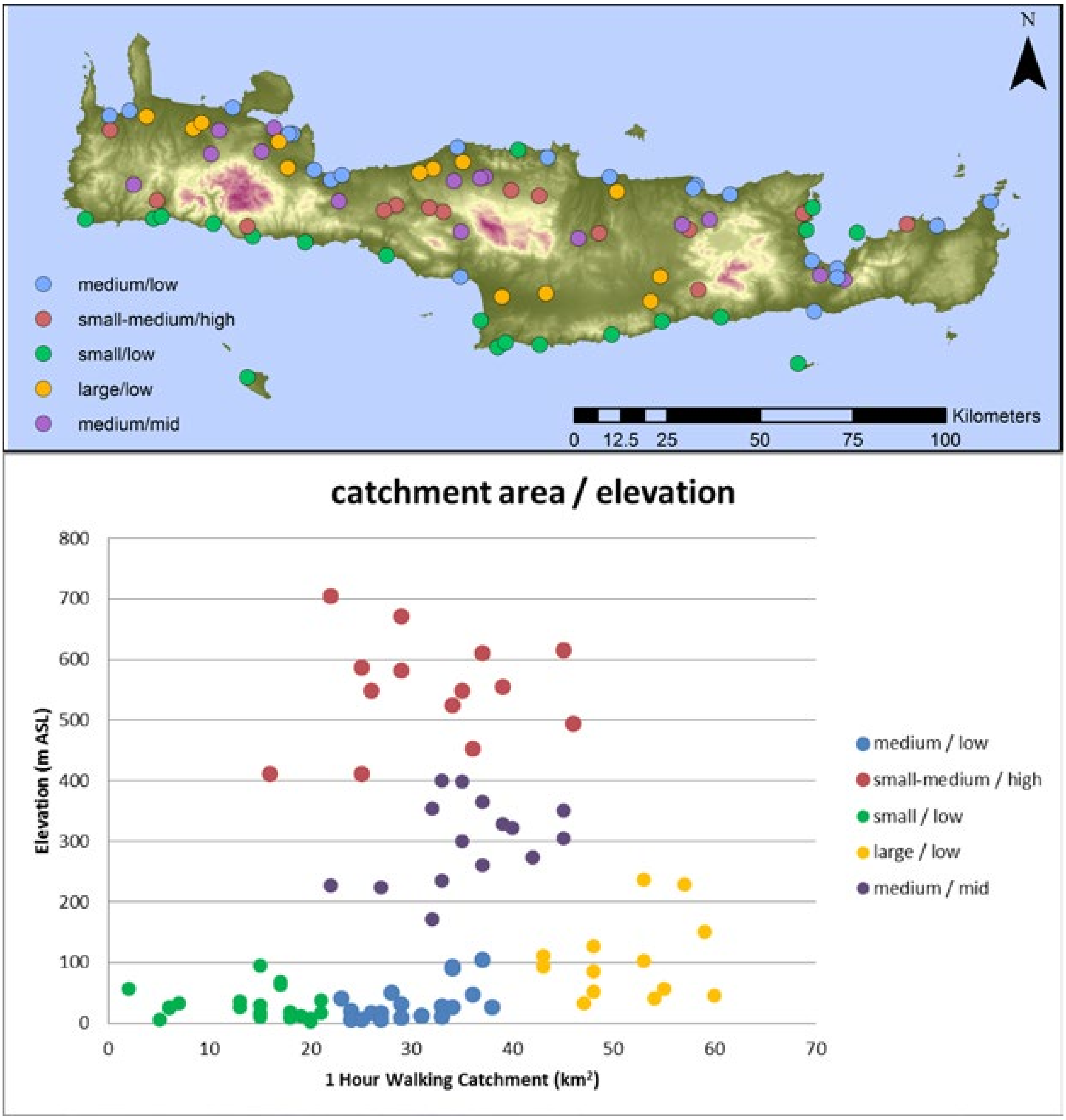


Fig. 5. Result of Grouping Analysis performed on elevation vs. catchment area (K means, without spatial constraint, using random seeds, and requesting five groups). Top: sites mapped by group; bottom: groups on elevation/catchment size plot.

Chisholm, M. 1962. *Rural Settlement and Land Use*. New Brunswick and London, Aldine Transaction.

Di Vita, A. 2010. *Gortina di Creta. Quindici Secoli di Vita Urbana*. Rome, L'Erma di Bretschneider.

European Environment Agency 2011. *CORINE 2000 Land Cover (raster & Vector Datasets)*. [Online] Available from: http://www.eea.europa.eu/data-and-maps/find/global#c12=CORINE+2000. [Accessed: 30 june 2015].

Gaffney, V., and Van Leusen, M. 1995. Postscript- GIS, Environmental Determinism and Archaeology: A Parallel Text. In Lock, G. R. and Stancic, G. (eds.) *Archaeology and Geographic Information Systems: A European Perspective*. London & Bristol, PA, CRC Press.

Goodchild, H. 2007. *Modelling Roman Agricultural Production in the Middle Tiber Valley, Central Italy*. Unpublished PhD Thesis, University of Birmingham.

Harrison, G. W. M. 1993. *The Romans and Crete*. Amsterdam, Adolf M. Hakkert.

Levi, A. and Levi, M. 1967. *Itineraria Picta, Contributo allo Studio della Tabula Peutingeriana*. Studi e Materiali del Museo dell'Imperio Romano 7. Rome, L'Erma di Bretschneider.

Portale, E. C. 2011. Contenitori da Trasporto. In Di Vita, A. and Rizzo, M. (eds.), *Gortina Agora- Scavi 1996-1997*. Studi di Archeologia Cretese, IX. Padua, Bottega d'Erasmo.

Portale, E. C. 2014. The Sunset of Gortyn: Amphorae in 7th-8th Centuries AD. In Poulou-Papadimitriou, N., Nodarou, E., Kilikoglou, V. (eds.), *LRCW 4 : Late Roman Coarse Wares, Cooking Wares and Amphorae in the Mediterranean : Archaeology and Archaeometry : The Mediterranean : A Market without Frontiers*. British Archaeological Reports International Series 2616 (I): 477-89. Oxford, Archaeopress.

Posluschny, A. 2010. Over the Hills and Far Away? Cost Surface Based Models of Prehistoric Settlement Hinterlands. In Frischer, B., Webb Crawford, J., Koller, D. (eds.), *Making History Interactive: Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, 22-26 march 2009*. British Archaeological Reports International Series 2079: 313-9. Oxford, Archaeopress.

Sanders, I. F. 1982. *Roman Crete: An Archaeological Survey and Gazetteer of Late Hellenistic, Roman and Early Byzantine Crete.* Warminster, Aris & Phillips Ltd.

Saradi, H. 2006. *The Byzantine City in the Sixth Century: Literary Images and Historical Reality*. Athens, Society of Messenian Archaeological Studies.

Shennan, S. 1988. *Quantifying Archaeology*. Edinburgh, Edinburgh University Press.

Stancic, Z. and Kvamme, K. 1999. Settlement Pattern Modelling through Boolean Overlays of Social and Environmental Variables. In Barcelo, J.A., Briz, I. and Vila, A. (eds.), *New Techniques for Old Times. CAA98. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 26th Conference, Barcelona, March 1998*. British Archaeological Reports International Series 757: 231-7. Oxford, Archaeopress.

Tsigonaki, C. 2007. Les villes crétoises aux VIIe et VIIIe siècles: L'apport des recherches archéologiques à Pyrgi d'Eleutherna. *Annuario Della Scuola Archeologica Italiana Di Atene* LXXXV, 1: 263-97.

Tsougarakis, D. 1988. *Byzantine Crete from the 5th Century to the Venetian Conquest*. Historical Monographs 4. Athens, S.D. Basilopoulos Historical Publications.

Tukey, J. W. 1977. *Exploratory Data Analysis*. Addison, Wesley Publishing Company.

Verhagen, P., Mcglade, J., Gili, S., Risch, R. 1995. Some Criteria for Modelling Socio- Economic Activities in the Bronze Age of South-East Spain. In Lock, G. R. and Z. Stančič (eds), *Archaeology And Geographic Information Systems: A European Perspective*: 187-210. New York: Taylor & Francis.

Verhagen, P, and Whitley, T. G. 2011. Integrating Archaeological Theory and Predictive Modelling: A Live Report from the Scene. *Journal of Archaeological Method and Theory* 19, 1: 49–100.

Wheatley, D. 1996. Spatial Technology and Archaeological Theory Revisited. In Lockyear, K., Sly, T. J. T. and Mihăilescu-Bîrliba, V. (eds.), *CAA96. Computer Applications and Quantitative Methods in Archaeology*. British Archaeological Reports International Series 845: 123-132. Oxford, Archaeopress.

Wheatley, D. and Gillings, M. 2002. *Spatial Technology and Archaeology: The Archaeological Applications of GIS*. London, Taylor and Francis.

Potential Paths and the Historical Road Network between Italy and Egypt: from the Predictive to the Postdictive Approach.

Andrea Patacchini
patacchiniandrea@gmail.com

Giulia Nicatore
giulianicatore@hotmail.com

University of Siena, Italy

Abstract: In this paper we aim to present the preliminary result of two case studies focused on the predictive and postdictive approach to historical routes. We developed and tested the procedure in two different geographical areas, northern Lazio and the valley of the Kings in Egypt. Our work is based on three stages. The first is predictive. We evaluated the movement in a given geographical context and period. In this phase we produced several potential paths between two known settlements by changing the weight of the environmental and cultural factors. In the second stage we verified the prediction directly on the field. The last step is postdictive. We change the question and asked, why did they use those precise paths? We modelled several cumulative cost surfaces to produce a simulation that overlaps as much as possible the historical paths. In this way, we can understand and evaluate the key factors that constrained the route network.

Keywords: Predictive and postdictive method, least-cost path, mobility in archaeology, historical roads

Introduction

Recently, predictive models in archaeology have been critically debated (Verhagen, Whitley 2011; Casarotto, Kamermans 2013; Verhagen 2013). It has become increasingly apparent that we are not able to reconstruct the palaeo-environment precisely in a given period but, especially because of the difficulty of processing cultural aspects, this may lead to the avoidance of GIS tools. We think, however, that we are not obliged to choose between enthusiastic acceptance and paralyzing scepticism. We can use these tools as simple tools, among many. In addition, they constitute a prediction, although they do not deal with site location. Indeed, the forecast of potential paths in a given geographical space and historic period is itself a prediction. The approach we propose is based on the idea of joining predictivity with postdictivity. It gives us a flexible tool

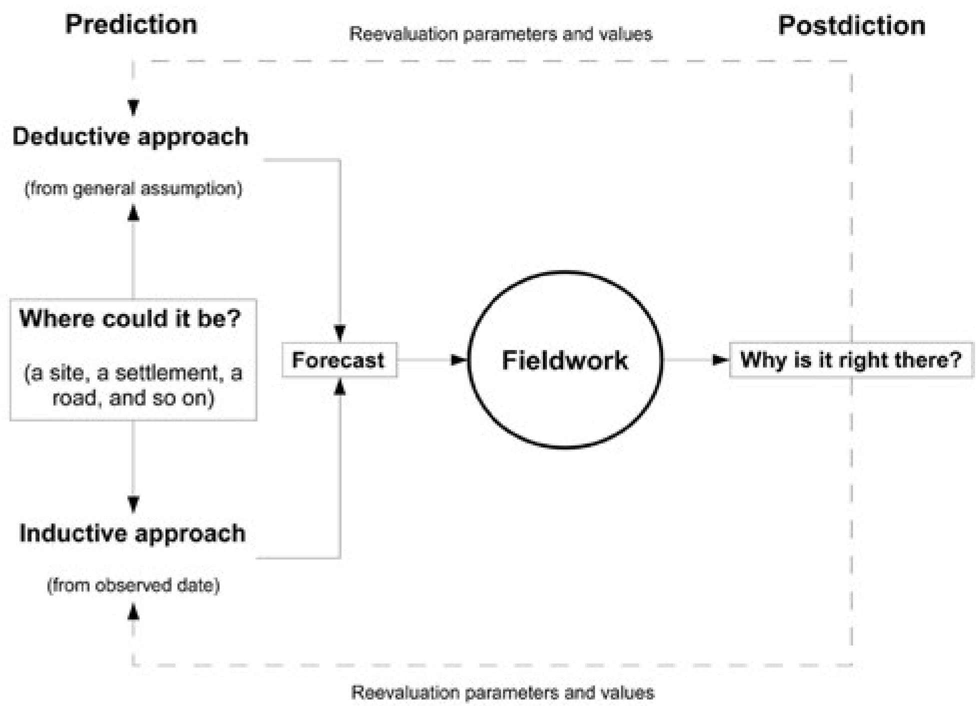
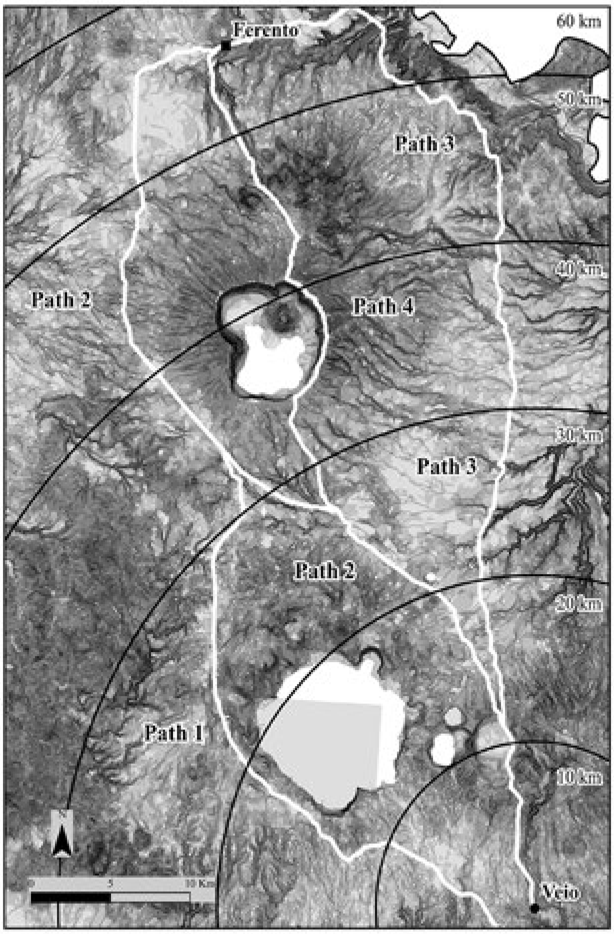
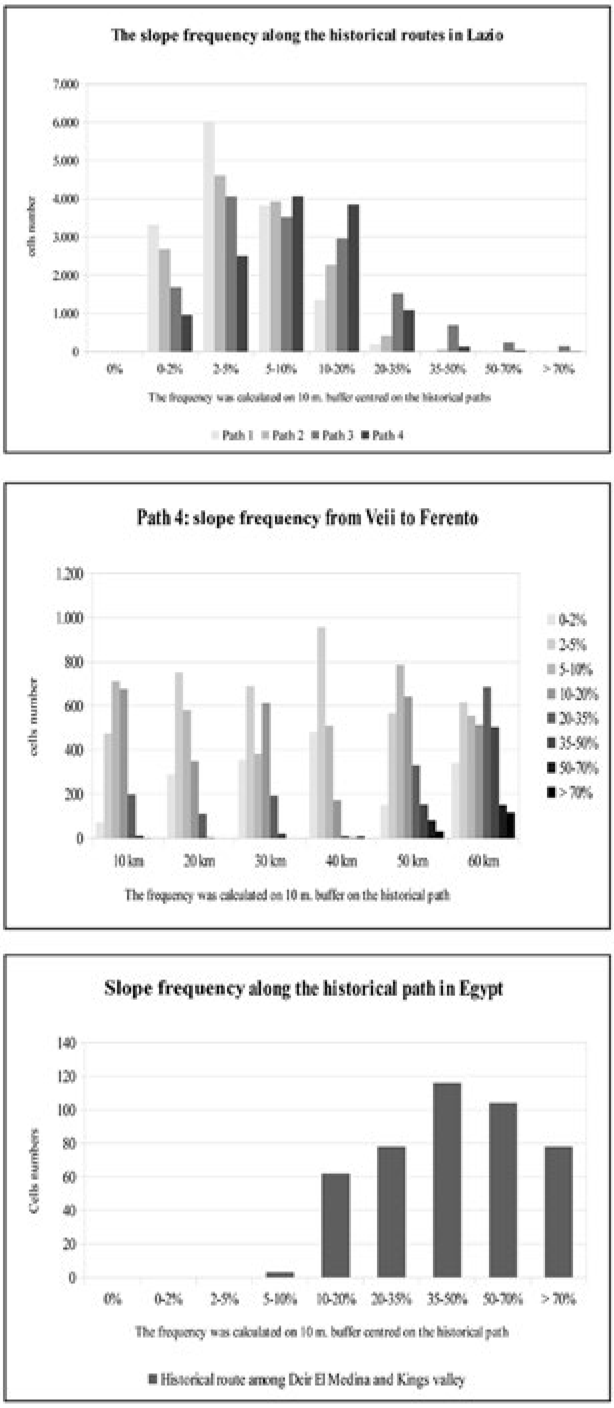


Fig. 1. The predictive and postdictive workflow.





	Slopes' weighted Lazio				Slopes' weighted Egypt
Slope classes	Path 1	Path 2	Path 3	Path 4	Postdictive path D
0%	3	3	3	4	5
0-2%	2	2	2	2	3
2-5%	1	1	1	1	3
5-10%	5	1	1	1	3
10-20%	10	10	5	3	1
20-35%	20	20	20	20	2
35-50%	50	50	50	50	1
50-70%	75	75	75	75	4
> 70%	100	100	100	100	100

Fig. 2. The slope frequency and the slopes' weights after the frequency calculation.

and an alternative from the inductive-deductive method (for a first consideration see Citter, Arnoldus-Huyzendveld 2014). Our procedure is based on three stages. The first is predictive. In this case the questions are all related to a forecast. Was there a connection between points A and B in that context and period? Was there only one possible connection? The latter raises a further question. Was it the result of a single action or a long-lasting process? In the second stage we verified the forecast directly on the field. Fieldwork is a crucial step to obtain the necessary information to establish the reliability of the processed simulations. The last stage is postdictive. In this phase we reversed the process and also changed the questions. Why did they move along those precise paths? What were the factors that attracted the movement in that area? Were they environmental or cultural factors? The two theoretical phases take into account a circular interaction between deductive and inductive approaches, in a potentially endless cycle (Fig. 1).

Of course, although our procedure uses numbers (which are not the answer but a helpful tool), we can imagine that the outputs are driven by the archaeologist. He works on the algorithm or, as in our case, on the cost surface and changes values and variables until he gets the result he wants. This criticism is correct if the values and the parameters are not explicit and if we limit our work to the predictive phase (for more details see Citter, Patacchini, in press). The first test developed with this approach produced encouraging results (Patacchini, Moretti, in press; Citter, Patacchini, in press). In these case studies we went a step further and evaluated the slope frequency along the historical routes we are dealing with. This estimation allows us to improve and calibrate the slopes' weight by creating more accurate raster maps (Fig. 2). Here a brief note on the least-cost path algorithm is essential. All the GIS packages, no matter what the operator's skills (Gietl *et al.* 2008; Herzog, Posluschny 2011), force the computer to choose the cells that have a lower cost within a neighbourhood of the given cell, regardless of how much lower it is. This detail is crucial when we work on a postdictive level, because humans, unlike the algorithm, do not feel small value changes and prefer to walk as much as possible along a straight line. To avoid this, we chose to evaluate the overlay between the known historical route and the predicted one within a 100 m buffer. We also tried a slightly larger buffer (125 m) to incorporate errors generated by the least-cost path algorithm.

1 Northern Lazio (A.P.)

The starting point for both case studies (Fig. 3) was the reconstruction of the historical route network that joined the two settlements we chose for the evaluation. In northern Lazio we focused on the area between Veii and Ferento, where we reconstructed the main historical paths using traditional sources: itineraries (*Tabula Peutingeriana* and *Itinerarium provinciarum*), aerial photographs, historical maps, and archaeological data (Fig. 4).

This step is relevant during the postdictive phase, because it allows us to compare the expected route with the historical one. In addition, it enables the more accurate calibration of the weight of each parameter. All the potential paths generated by this procedure are based on environmental and cultural factors (Figs. 5 and 6). They can be considered as attractors (such as springs or central locations), detractors (lagoons or low-draining soils), facilitators (gentle slopes or water crossings), and obstacles (rivers, streams, or ravines). The first two act on the distance, the latter directly on the ground (Citter, Arnoldus-Huyzendveld, Maccani 2013).

The resulting cumulative cost surface is a raster map, whose cells express the degree of advantage or disadvantage to moving in that context. Using some of the parameters shown in Figures 5 and 6 we generated several balanced potential paths between Veii and Ferento. In this phase we weighted the slope (to create this raster we used a 10 m resolution DEM; see Tarquini *et al.* 2007 and 2012) as environmental factor and as parameter driven by human choice. For instance, a gentle slope is obviously easier to go up than a steep slope, but sometimes the natural choice can be overridden by a cultural consideration, such as the need for a shorter route. Everything was related to the needs of travellers and we therefore calibrated some of them to facilitate the movement on a gentle slope (0–5%), and the rest to favour the movement on a rather steeper slope, though still accessible (5–10%). As can be seen in Figure 7, the potential paths define four different strips that have the same direction as the historical routes. This is a significant result because it means that the predictive step already holds the main factors and their reciprocal weight.

The field survey can be considered the main part of this procedure. First, we focused on those areas where the evaluated path runs far from the historical one. The aim was to look for possible traces of ancient roads nearby. In the surveyed areas we did not obtain any positive feedback. Although caution is always important, we considered that this is not a bias but an actual lack of data. Later, we verified every critical point raised by the evaluation process. In this case we had the opportunity of examining the real morphology of the landscape (slope, hydrography, soil type, etc.) and, importantly, to evaluate the historical routes in relationship to the environment, in particular, when they run through geographical constraints (Fig. 8).

After the fieldwork we worked on the postdictive side of the procedure, by integrating all the available data, including survey. Thus, we calibrated the former forecast, asking what factors had more influence on the four main historic roads between Veii and Ferento. To answer these questions we modelled several cumulative cost surfaces to produce a simulation that overlaps as much as possible the historical paths (Fig. 9). As we can see in the chart (Fig. 10), the overlap of 50% in the first buffer is reached only by path 4. By contrast, almost all the potential paths reach this threshold if we extend to the second buffer. The low overlay within the 100 m buffer is caused by the algorithm, as mentioned above. The slope frequency calculation was almost worthless. It only increased the overlay between the two paths a little, confirming it is one of the key factors involved in this case study. To conclude, we would like to make a brief remark on path 4, which seems one of the most interesting. As can be seen in Figure 9, this simulation connects Veii to Ferento through a stretch of the Roman Cimina road, which in the Middle Ages was considered to be a variant of the Francigena (Corsi, De Minicis 2012: 75–81). The Bronze Age settlements uploaded into the formula as attractors allowed us to achieve a high-level overlay. According to this evaluation, therefore, this route seems to be the most ancient and stratified route in the area, not least because it is still used. This is only a hypothesis, however, and any proof may emerge only thanks to archaeological excavations of parts of the road.

2 The Valley of the Kings (Egypt) (G.N.)

From a morphological point of view, the Egyptian case shows remarkable differences compared to the Latial one. Incidentally, in Egypt we have also focused on the study of a historical path between two known points. The path we have chosen still exists today and in ancient times between 1450 and 1100 BC Egyptian workmen used it daily. They started from Deir el Medina towards the Valley of the Kings, where they took part in the construction of the royal tombs. The aim of our analysis was to evaluate the factors that may have influenced its shape, and to understand the reasons that led the workers to prefer this path. A brief introduction is essential. In Egypt, it is not always possible to undertake research using the accurate database available in Italy or in Europe. The dataset are always very scanty; satellite images, aerial photographs, detailed geological, soils, and topographic maps are rare too. From this point of view, there are still too few archaeological missions that use the most updated technological tools, mainly due to economic reasons. The few exceptions are the area of

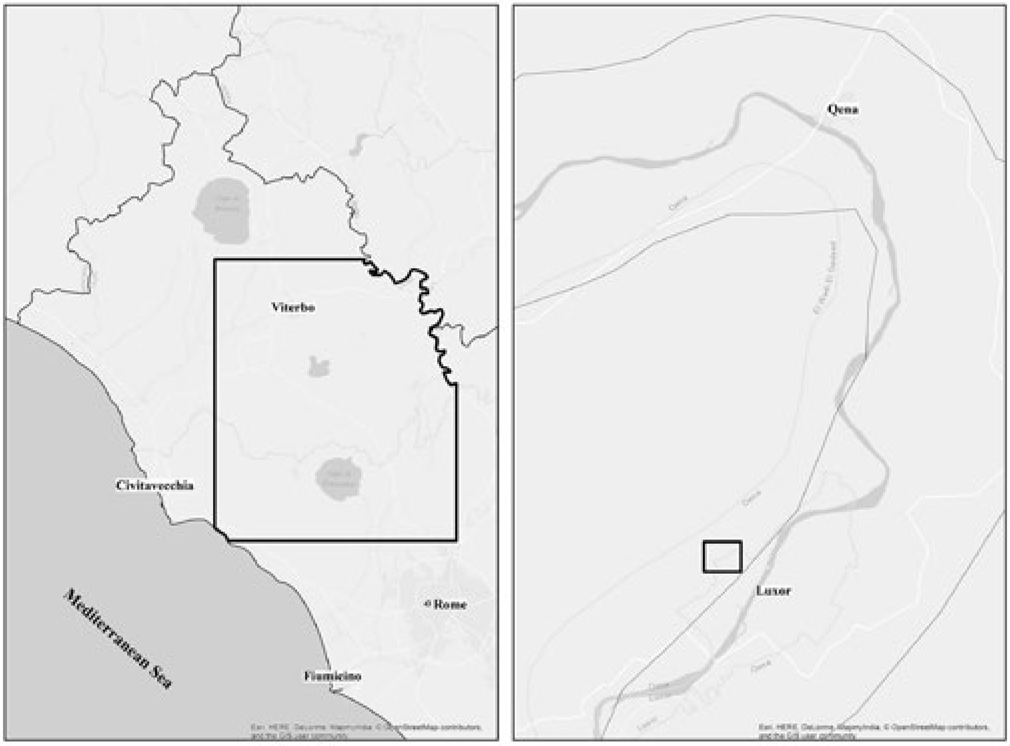


Fig. 3. Location of our study areas: northern Lazio on the left and the Valley of the Kings in Egypt on the right.

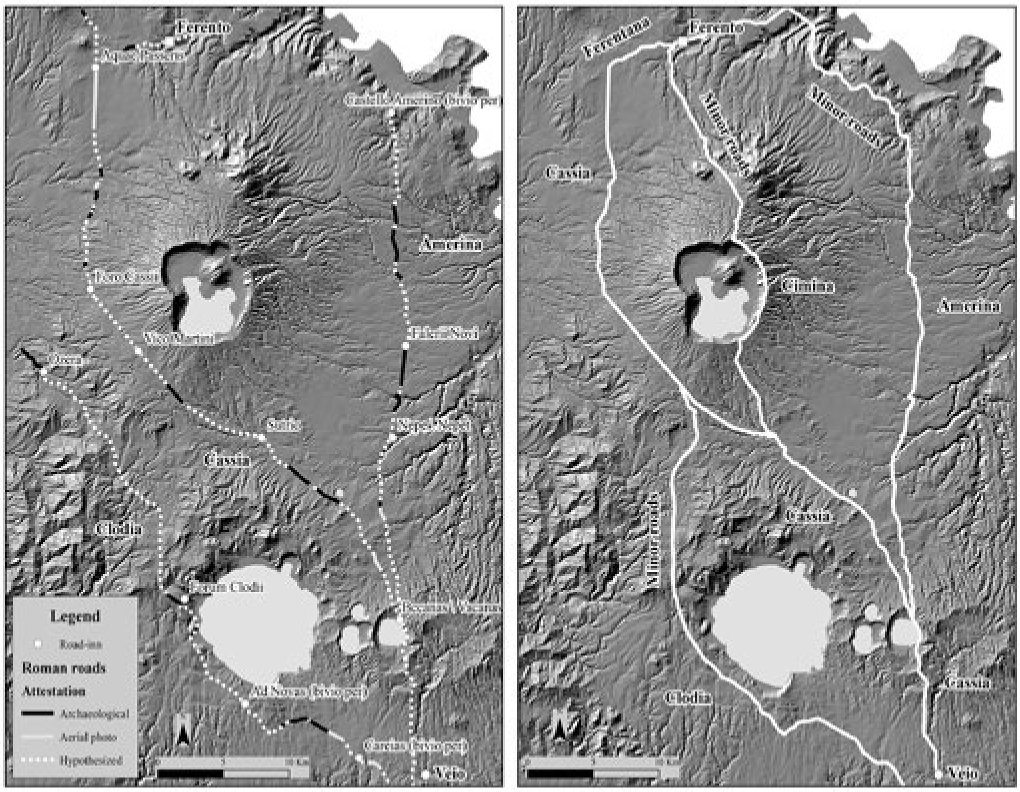


Fig. 4. Left: the main Roman roads — Clodia, Cassia, and Amerina (white dots = road-inn; black line = road stretch reconstructed with archaeological sources; light grey = road stretch reconstructed with aerial photos; and white dashed line = hypothesized stretch of road). Right: the historical road network that connected Veii to Ferento.

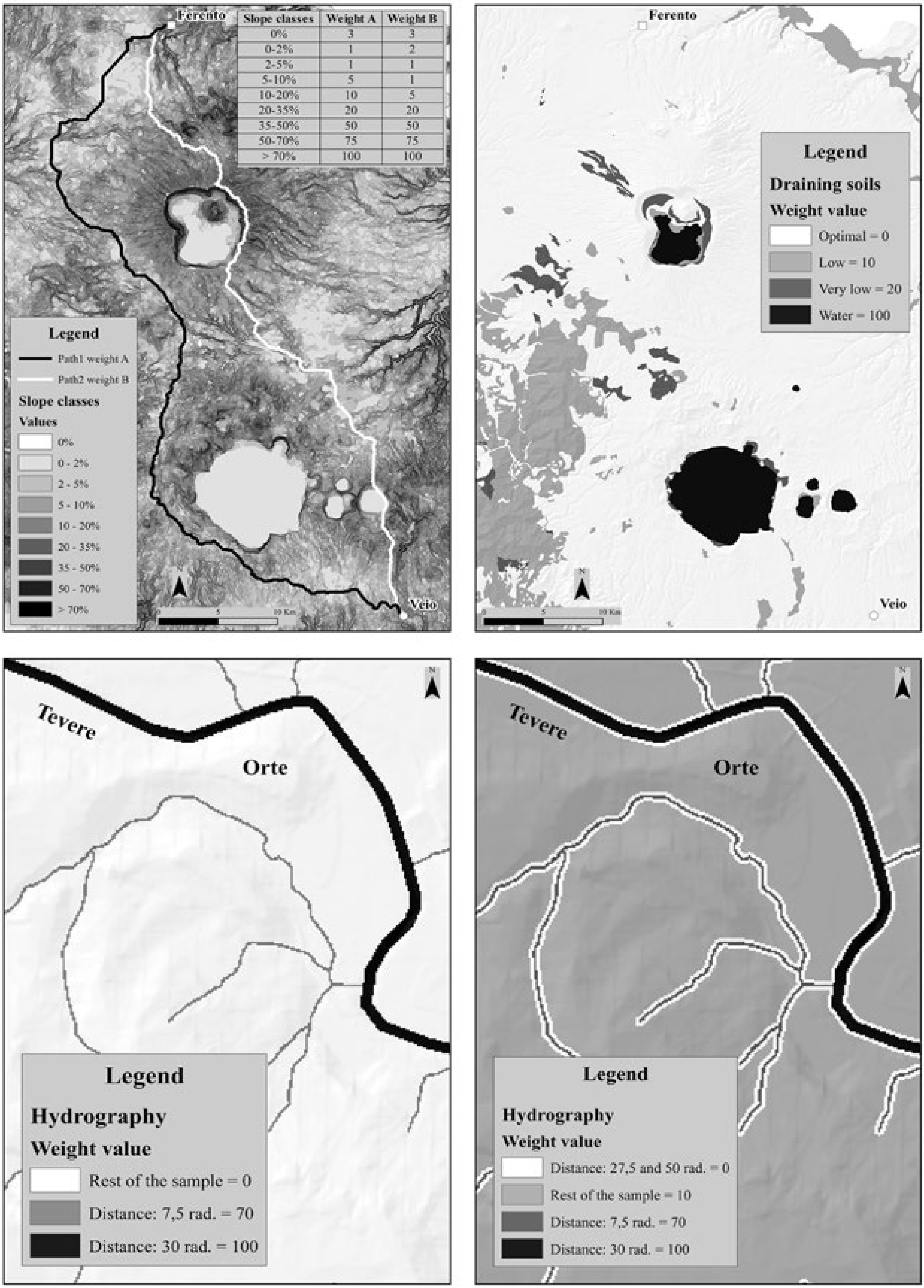


Fig. 5. The four images show some parameters and weighing taken into account during the operations. Top right: the slope; top left: soil drainage; bottom right: hydrography as obstacle; bottom left: hydrography as attractor.

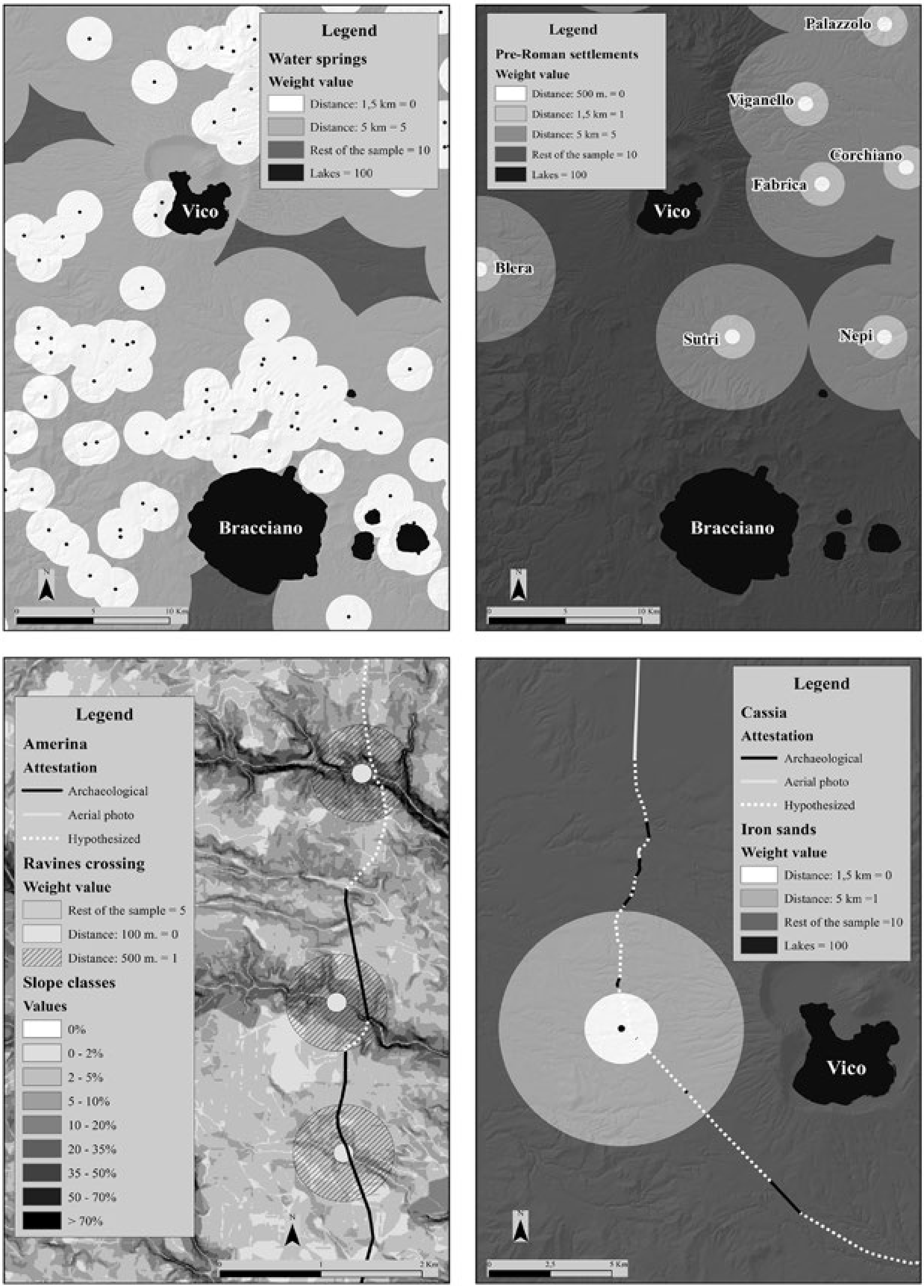
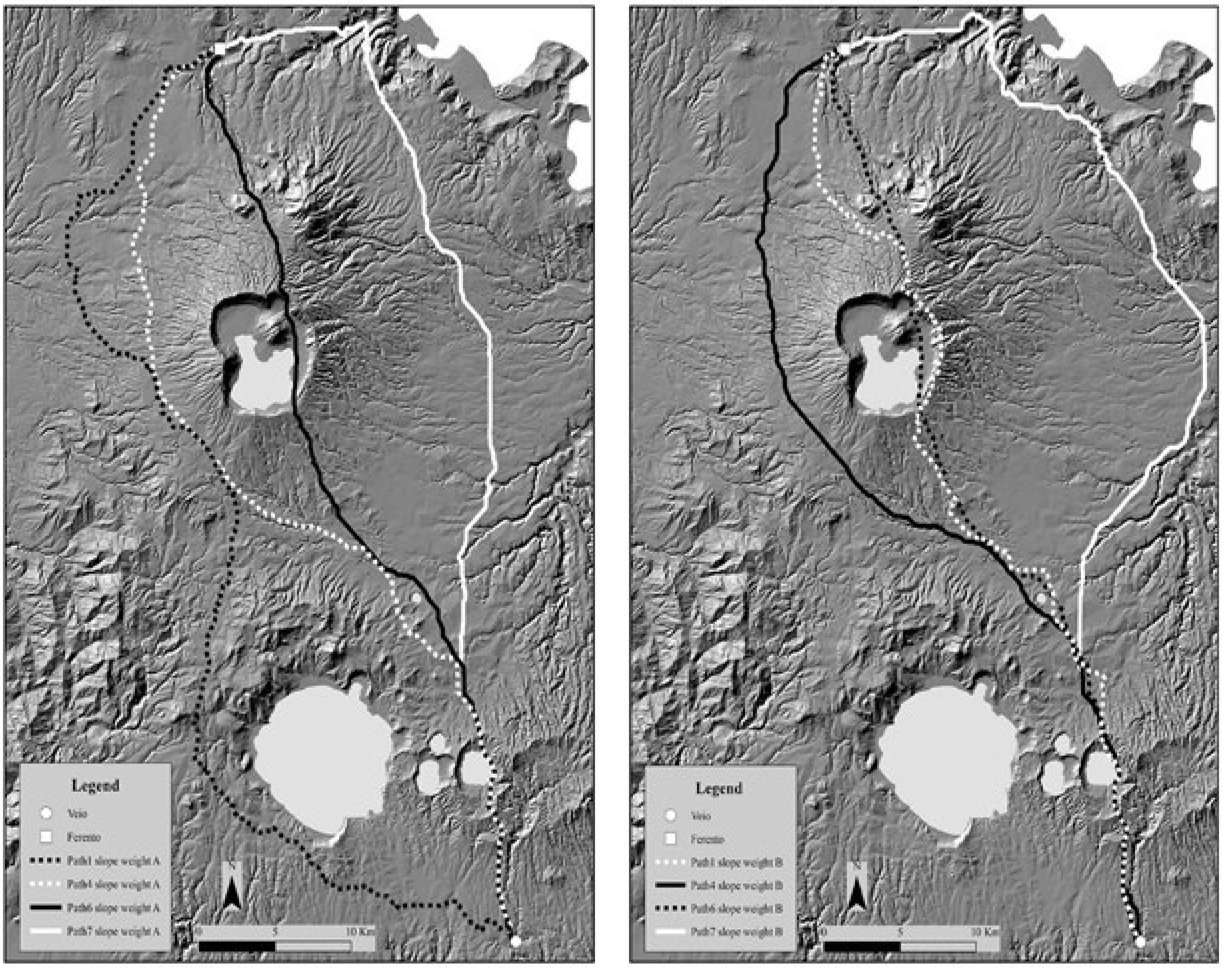


Fig. 6. Four other examples of parameters and weighing. Top right: water springs (attractors); top left: pre-Roman settlements (attractors); bottom left: the ravines crossing (facilitators); bottom right: the iron sands (attractor).



Paths	Formulas
1	Slope 50% - Hydrography 50%
2	Slope 50% - Hydrography (as attractors) 50%
3	Slope 35% - Hydrography 35% - Water springs 30%
4	Slope 25% - Hydrography 25% - Water springs 25% - Hot springs 25%
5	Slope 20% - Hydrography 20% - Water springs 20% - Hot springs 20% - Draining soils 20%
6	Slope 20% - Hydrography 20% - Water springs 20% - Hot springs 20% - Final Bronze age settlements 20%
7	Slope 25% - Hydrography 25% - Water springs 25% - Pre-Roman settlements 25%
8	Slope 25% - Hydrography 25% - Water springs 25% - Pre-Roman and roman settlements 25%
9	Slope 25% - Hydrography 25% - Water springs 25% - Main roman settlements 25%

Fig. 7. Both images show some predictive paths evaluated between Veii and Ferento. On the left the potential paths take into account, as a facilitator, a slope range from 0 to 5% (weight A). On the right, we can observe the same paths but in this case the simulations take into account, as a facilitator, a slope between 5 and 10% (weight B). In the table we have highlighted the formulas used for generating the potential paths displayed in the two pictures above.

the Delta and (fortunately) the Theban necropolis, thanks to the Theban Mapping Project (www.thebanmappingproject.com). In addition, we noted that the availability of updated and freely downloadable data is much less than that in any European country. This led us to improve the potential of our dataset, such as the DEM, downloaded from ASTER GDEM (http://gdem.ersdac.jspacesystems.or.jp/), with a cell size of 27 m, which has been refined through interpolation with contour lines (with a pace of 10 m) increasing the resolution up to 10 m. Obviously, this ‘new’ DEM does not actually have a cell size of 10, because we did not upload further elevations, therefore we can only consider an approximation to 10 m. This allows us, however, to draw a slightly more detailed slopes map (Fig. 11).

In order to study the potential paths that linked Deir el Medina to the Valley of the Kings during the so-called New Kingdom, therefore, it is necessary to start not only from the literature, but also from survey. As the available material on the subject

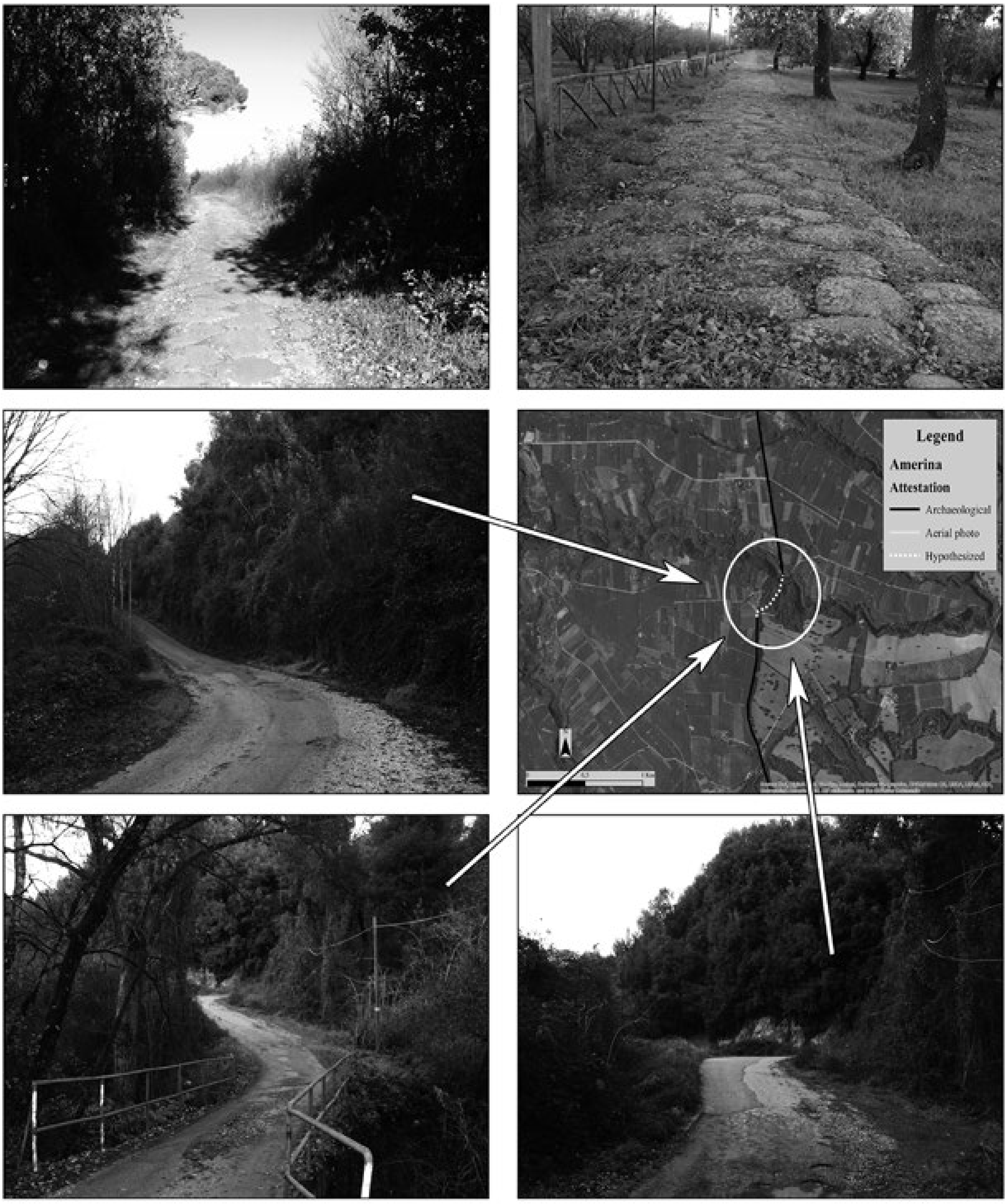


Fig. 8. Some photos taken during the field survey in Lazio. Top: the morphology along the Cassia and Amerina paths. In the four pictures below there is a kind of ravine crossing the Amerina path. We show how the modern road still passes through this area.

is virtually non-existent, the best way to get an idea of the area is to go *in situ* and walk the trails along which Egyptians and adventurous tourists can still travel. Moreover, the fieldwork allows us to understand not only the morphology but also the possible factors that most influenced ancient Egyptians, both to build the settlement and to connect it (Fig.12). We must recall that the village was built with the sole purpose of hosting the community of artisans involved in the construction of the royal tombs. The examined area, the Theban hills on the west bank of the Nile, has (and had) no vegetation, there are no sources of fresh water, and the temperature can go up to 45°C, making the desert and stony terrain unsuitable even for walking after 11 a.m.

Therefore, the knowledge of the landscape combined with the survey is crucial to evaluate the simulations of the predictive

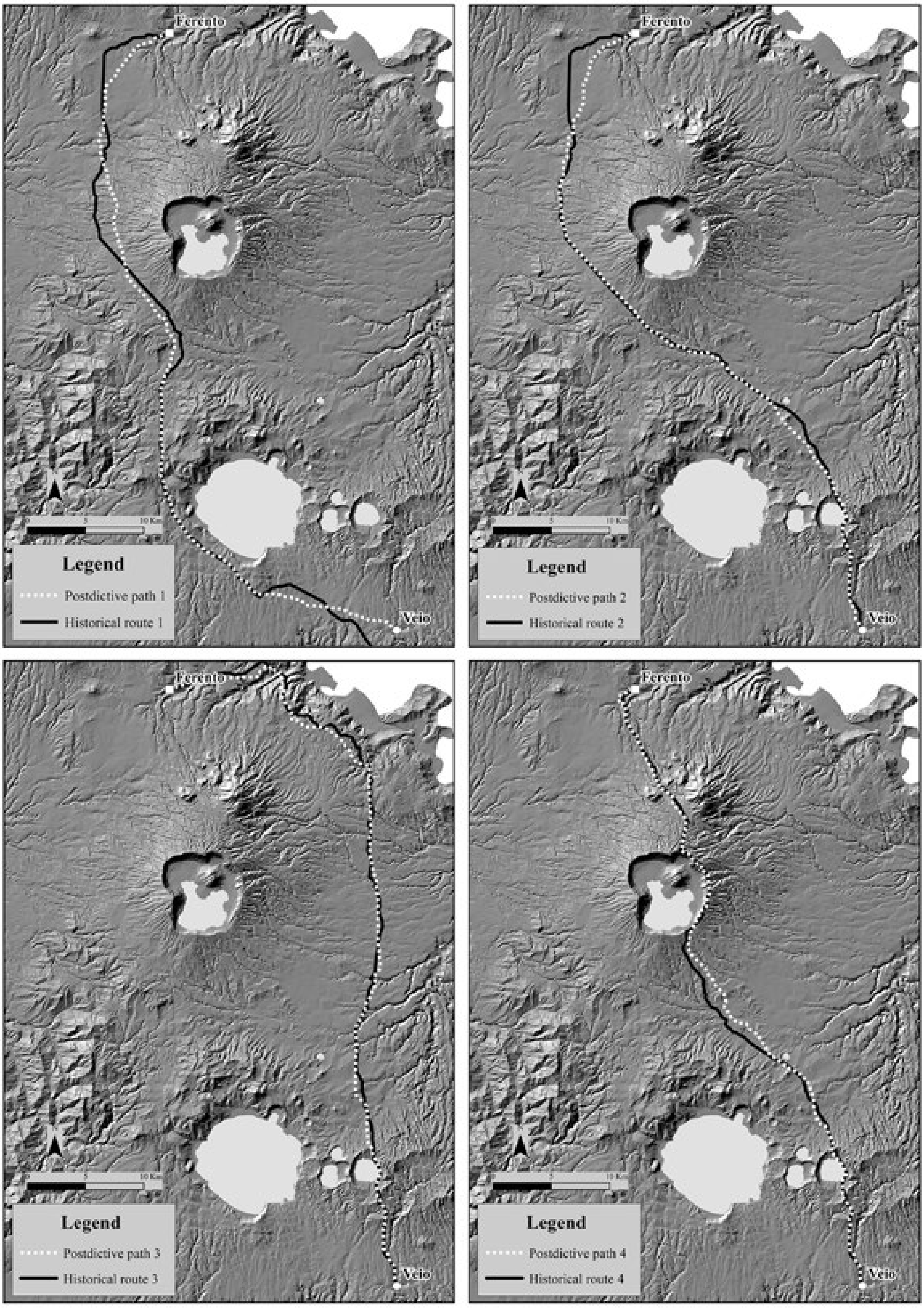


Fig. 9. The paths that connected Veii to Ferento in relation to our four postdictive simulations. The following explains the formulas used in each evaluation: Path 1: slopes' calibrated 35%, hydrography 35%, selected mines 20%, selected hot springs 10%. Path 2: slopes' calibrated 25%, hydrography 15%, water springs 20%, hot springs 20%, iron sands 20%. Path 3: slopes' calibrated 20%, hydrography 20%, water springs 20%, ravine crossing 10%, pre-Roman settlements 30%. Path 4: slopes' calibrated 35%, hydrography 30%, water springs 30%, final Bronze Age settlements 5%. The term 'selected' means a selection of the available data to attract the path in that zone; 'calibrated' means the weight given on the slope frequency calculated on each historical route.

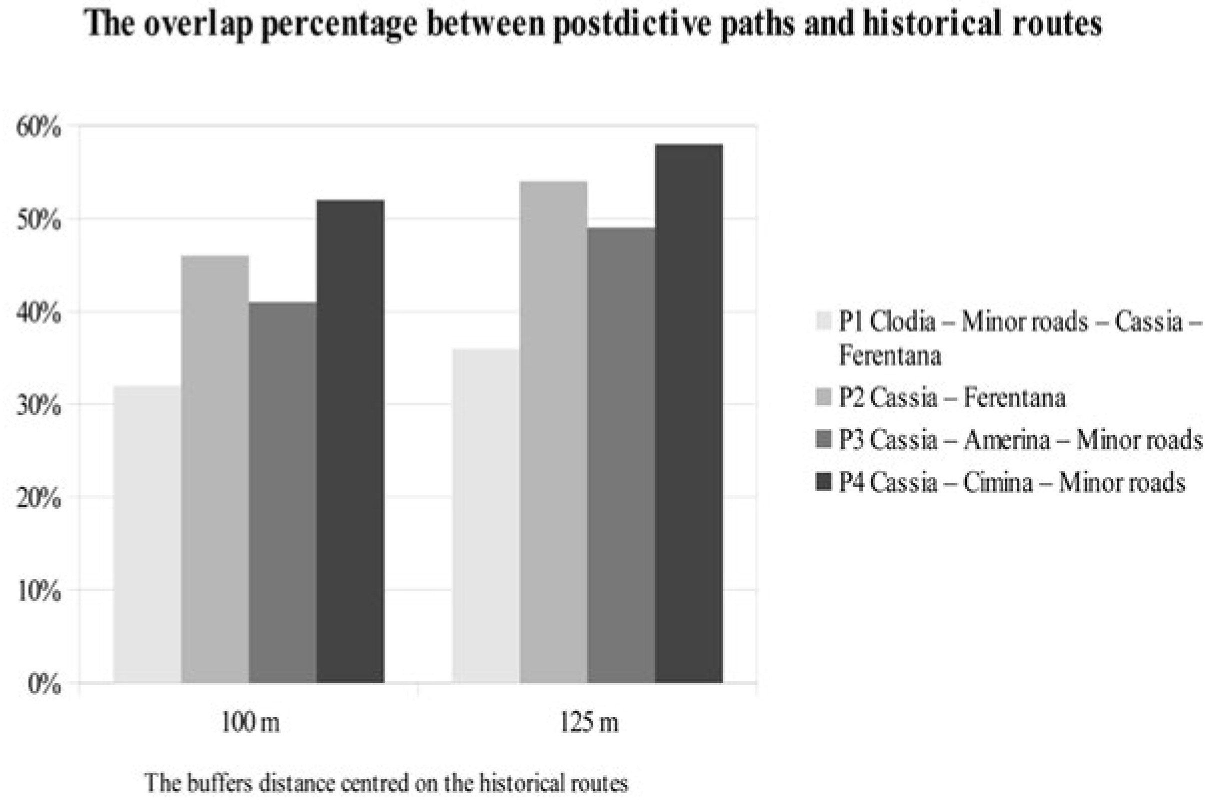


Fig. 10. The chart shows the overlap percentage among the postdictive paths and historical routes from Veii to Ferento.

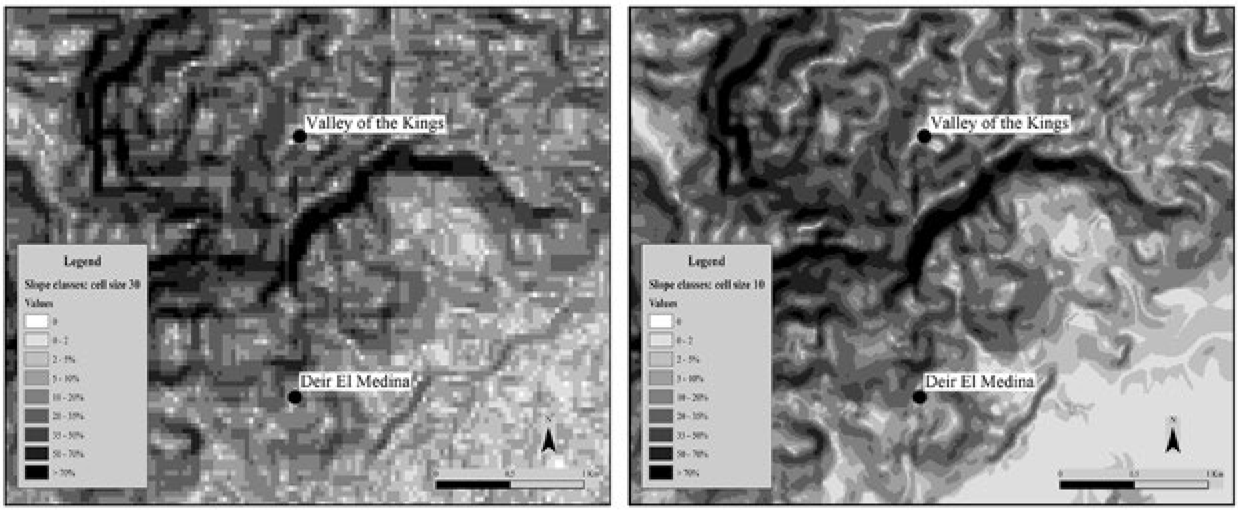
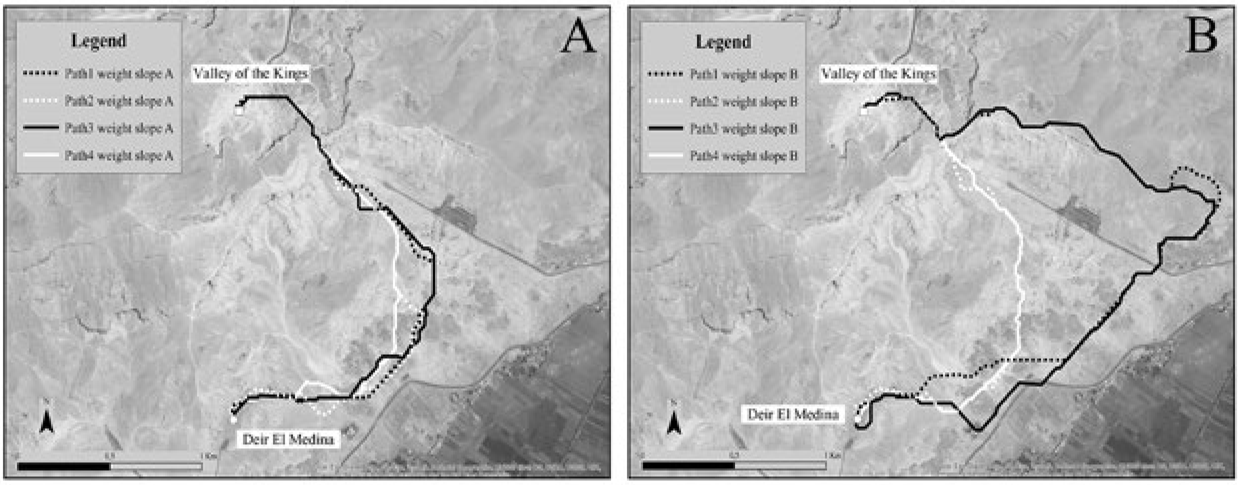


Fig. 11. The refined DEM, indicating the difference between the old slope raster (left) and the new one (right).

phase. As is shown in Figure 14, the predictive paths generated using slope, exposure, and potential hydrography (Fig. 13) are too long and do not coincide with the 'philosophy' of the historical route, which passes over the elevations to shorten the travel time. Please note that we consciously overlooked the geological map we obtained, because geology and soil composition, although interesting, did not seem to have any influence on the choice of a particular route. We can say the same for the temples, which we did not consider as attractors, because in this case the aim of the artisans was to reach the working site as quickly as possible.

The only potential paths that run close to the town are those shown at letter C: in this case we decided to consider the slopes

Fig. 12. The historical path survey; both images show the many slope changes along the road.



Path	Formulas
1	Slope 100%
2	Slope 50% - Aspect 50%
3	Slope 50% - Potential stream network 50%
4	Slope 35% - Potential stream network 30% - Aspect 35%

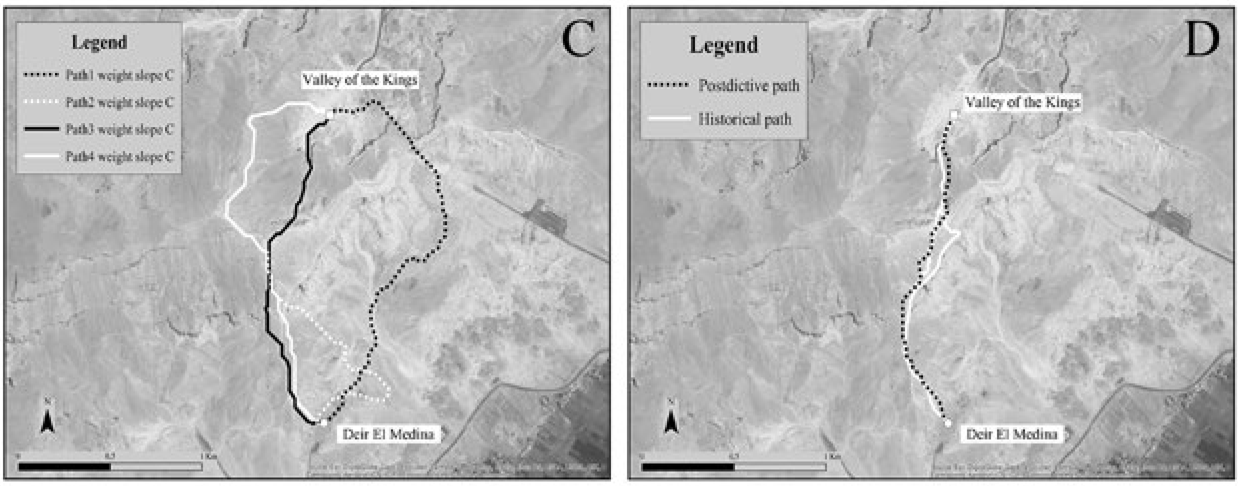
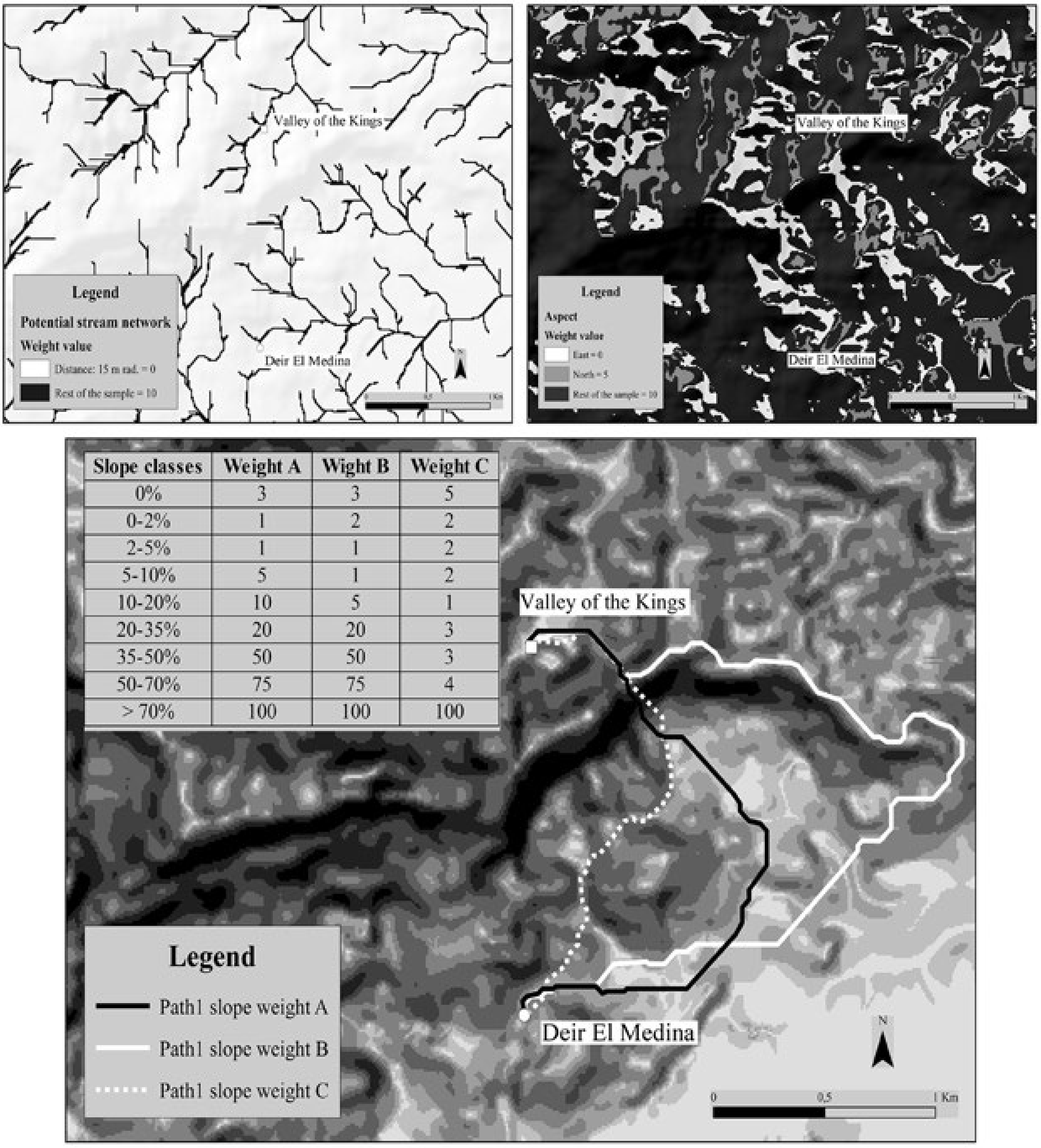


Fig. 13. All the parameters and weighing values used in Egypt. Top left: the potential stream network; top right: the aspect; below: the slope.



Slope classes	Weight A	Wight B	Weight C
0%	3	3	5
0-2%	1	2	2
2-5%	1	1	2
5-10%	5	1	2
10-20%	10	5	1
20-35%	20	20	3
35-50%	50	50	3
50-70%	75	75	4
> 70%	100	100	100

Fig. 14. Top and bottom left: the predictive paths (letters: A, B and C); bottom right: the postdictive path (letter D). To reach this overlap we worked on a slope values, giving a lesser weight on those slopes between 10 and 50%.

as if they were a cultural factor, assuming that the Egyptian artisans consciously chose the shortest, but harder, route. The result turned out to be interesting for another reason, precisely because path 1 reflects a current road visible from satellite and also mapped on IGN. Clearly, this has no link with any ancient route between the two points, but it tells us that the weighing choices to process the paths are in some way related to the reality. Direct knowledge of the area and the survey, however, led directly to the next, postdictive, stage. At this point, we digitized the aforementioned historical path, which runs through the village of Col, a small intermediate settlement sometimes used by the workers to rest. The data we have are almost definite as this is the only way a craftsman could walk through in the morning and in the evening (perhaps with tools and a load), wishing to make his trip quicker and easier. Indeed, this appears the only possible route, because other options to cross the heights in safety, avoiding steep slopes, are scarce. Once all available information was gathered (ASTER GDEM, a French IGN in scale 1:10,000, a topographical map, and a hydrographical map of the Valley of the Kings produced by the Theban Mapping Project and found at the TMP Library), we tested to see whether the slopes really influenced the performance of the historical path, as was already clear when we developed the predictive path 3 (letter C) shown in Figure 14. The calculation of the frequency of slopes spread over the historic route gave us valuable confirmation, indicating a preference for those slopes between 10 and 50%. These data, combined with those collected on the field, allowed us to reclassify the slope raster, assigning a lower weight (therefore more advantageous in terms of cost) to that particular range of values just mentioned, thus generating a postdictive path that reaches 100% overlap with the historical one, in a buffer of 100 m from the latter (Fig.14, letter D). In conclusion, we can state that the historical path was strongly influenced by slope, which in this part of Egypt seems to be predominant when we think in terms of ancient roads. Moreover, traces of ancient paths were often related to the morphology of the territory and to the stress on the traveller. This was not, of course, the only parameter considered when planning a path (hydrography, fords, springs, etc. were not undervalued at all), but it was certainly one of the most important.

Bibliography

Casarotto, A., Kamermans, H. 2013. Archaeological Predictive modelling: a proposal for the CRM of the Veneto region. In Gualandi, M. L. (eds.), *Opening the past 2013. Archaeology of the Future*: 10-1. Pisa.

Citter, C., Arnoldus-Huyzendveld, A., Maccani, C. 2013. Predicting site location through cost surfaces. A case study and a proposal. In Gualandi, M. L. (eds.), *Opening the past 2013. Archaeology of the Future*: 5-10. Pisa.

Citter, C., Arnoldus-Huyzendveld, A. 2014. Site location and resources exploitation: predictive models for the plain of Grosseto. In *Archeologia medievale* XLI: 65-78. Firenze.

Citter, C., Patacchini, A. (in press). Postdittività e viabilità: il caso della direttrice tirrenica. In Citter, C., Nardi Combescure, S., Stasolla, F. R. (eds.), *Tra la terra e il mare. La via Aurelia e il litorale tra il Lazio e la Toscana, Parigi, 6-7 june 2014*.

Corsi, C., De Minicis, E. 2012. *In viaggio verso sud. La via Francigena da Acquapendente a Roma*, DAIDALOS 14, Viterbo.

Gietl, R., Doneus, M., Fera, M. 2008. Cost Distance Analysis in an Alpine Environment: Comparison of Different Cost Surface Modules. In Posluschny, A., Lambers, K. and Herzog, I (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, April 2–6, 2007* (Kolloquien zur Vor- und Frühgeschichte, Vol. 10): 336-41. Bonn, Dr. Rudolf Habelt GmbH.

Herzog, I., Posluschny, A. 2011. Tilt - Slope - Dependent Least Cost Path Calculations Revisited. In Jerem, E., Redő, F., Szeverényi, V (eds.), *On the Road to Reconstructing the Past. Proceedings of the 36th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Budapest, 2-6 April 2008*: 212-8. Budapest, Archeaeolingua.

Patacchini, A., Moretti, S (in press). Studio dei potenziali percorsi storici attraverso le superfici di costo cumulative: la zona compresa tra Roselle e Saturnia. In Citter, C., Nardi Combescure, S., Stasolla, F.R (eds), *Tra la terra e il mare. La via Aurelia e il litorale tra il Lazio e la Toscana*, Parigi, 6-7 June 2014.

Tarquini, S., Isola, I., Favalli, M., Mazzarini, F., Bisson, M., Pareschi, M. T., Boschi, E. 2007. TINITALY/01: a new Triangular Irregular Network of Italy. *Annals of Geophysics* 50: 407-25.

Tarquini, S., Vinci, S., Favalli, M., Doumaz, F., Fornaciai, A., Nannipieri, L. 2012. Release of a 10-m-resolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web. *Computers & Geosciences* 38: 168-170. Available at: doi:10.1016/j.cageo.2011.04.018.

Verhagen, P., Witley, T. G. 2011. Integrating Archaeological Theory and Predictive Modeling: a Live Report from the Scene. *Journal of Archaeological Method and Theory*.

Verhagen, P. 2013. On the Road to Nowhere? Least Cost Paths, Accessibility and the Predictive Modelling Perspective. In Contreras F., Farjas, M. and Melero, F. J. (eds.), *Fusion of cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada 2010*. *British Archaeological Reports Series* 2494. Oxford, Archaeopress.

CHAPTER 9
Spatial Analysis: Occupation Floors and Palaeosurfaces in the Digital Era

Ritual use of Romito Cave During the Late Upper Palaeolithic: an Integrated Approach for Spatial Reconstruction

Michele De Silva[(1)]
michele.desilva@unifi.it

Giovanna Pizziolo[(2)]
giovanna.pizziolo@unisi.it

Paolo Machetti[(3)]
info@tecsette.com

Domenico Lo Vetro[(1)]
domenico.lovetro@unifi.it

Enrico F. Ortisi[(1)]
ortisienrico@hotmail.com

Vincenzo De Troia[(3)]
v.detroia@tecsette.com

Fabio Martini[(1)]
fabio.martini@unifi.it

[1] Dipartimento di Storia, Archeologia, Geografia, Arte, Spettacolo (SAGAS), Università degli Studi di Firenze, Italy
[2] Dipartimento di Scienze Storiche e dei Beni Culturali, Università degli Studi di Siena, Italy
[3] Tecsette srl, Firenze, Italy

Abstract: Grotta del Romito is one of the most significant Upper Palaeolithic sites on the Italian peninsula. The site comprises a rock shelter and a cave which would have been connected during the Palaeolithic to form a large living space. The imposing figure of an urus (Bos primigenius) and numerous linear signs are featured on two large boulders located under the rock shelter. To date, nine burials have been recovered from stratigraphic layers dating from ca. 18,000 to 11,000 BP, the majority of them refer to the Late Upper Palaeolithic. The site has a long history of excavation and therefore different types of documentation have been used in this cave context spanning from traditional distribution maps to laser scanner data acquisition.

This contribution presents an overview of the technologies used to collect data and discusses the integration of them in a GIS environment. The project focuses on the spatial use of the cave as a ritual context aiming to integrate and explore in a unique analytical environment the rock art and burial evidences.

Keywords: Upper Palaeolithic, 3D modelling, virtual reconstruction, GIS, Laser scanner

Introduction

This paper illustrates the ongoing project focused on developing an integrated approach to deal with spatial reconstruction of Palaeolithic evidence from the Grotta del Romito (Northern Calabria, Italy). The site, with its rare examples of rock art and several burials constitutes an exceptional context to attempt a visual analysis of a ritual space.

After a synthetic presentation of the geographical settings and archaeological context the paper is focused on the different kinds of archaeological documentation recorded during the excavations. This contribution presents an overview of the technologies used to collect data during both excavations and lab processing phases and discusses the integration of several approaches (CAD, QTVR, 3D-modelling, laser scanner). Within a GIS framework data have been integrated and a 3D environment has been built up. This contribution intends to present methodological issues and first considerations related to the reconstruction of Palaeolithic settings and to the spatial connection of features related to the same phase. In particular, attention has been paid to illustrate the potentialities of an holistic approach aiming to integrate in a unique analytical environment the rock art and burial evidence distributed inside the cave and in the shelter area in order to perceive this space as a whole.

1 Romito cave: the archaeological context

Grotta del Romito is one of the most significant Palaeolithic archaeological sites on the Italian peninsula (Graziosi 1962; Martini *et al.* 2007; Martini and Lo Vetro 2011; 2014; Martini *et al.* 2012). The cave was occupied during the Upper Palaeolithic from ca. 24,000 to 10,000 BP, until the Early Mesolithic (9000 BP ca.) through a period of considerable climate change that had marked impacts on the local environment. A further frequentation of the cave is evidenced by a limited number of remains, which refer to the Neolithic.

2 The site and its setting

The site (39° 54'N, 15° 55'E) is located in Southern Italy, 275m above sea level, and ca. 25km away from the Tyrrhenian coast of Calabria, in the Lao Valley (Fig. 1). The region has a rugged, high-relief topography with mountain peaks over 2000m high descending steeply towards the coast. The cave is situated at the foot of a rocky cliff on the right side of a narrow creek tributary of the Lao River, which itself is less than 500m away.

The cave, accessible through a narrow and short entrance, is dry, up to 4m high and 25-30m long, trending E-W. East of the entrance, along the cliff, below a rock shelter, a wide area extends. Boulders that lie on the slope in front of the rock

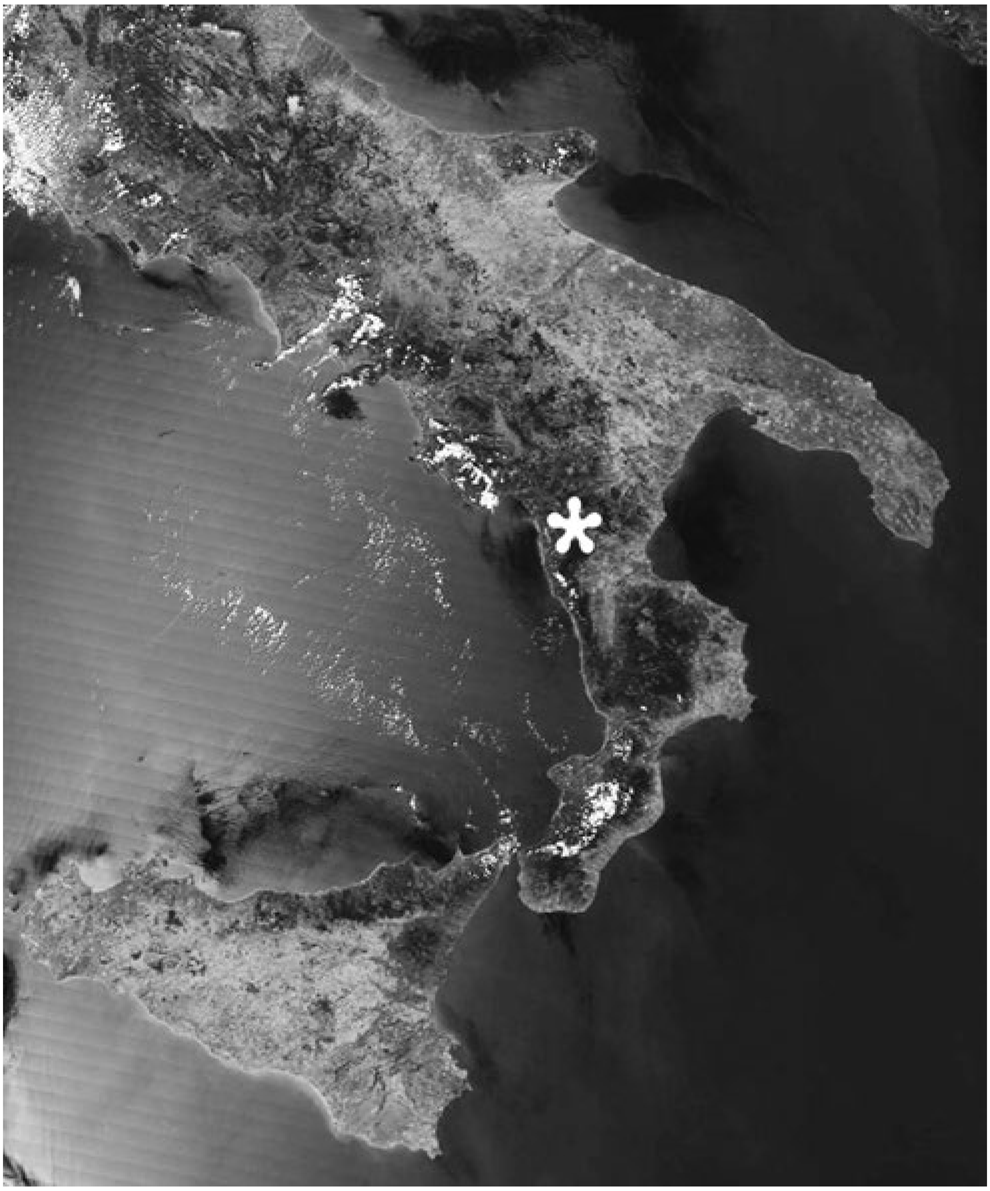


Fig. 1. Location of the Romito Cave in southern Italy.

shelter are the collapsed remains of an overhang of the rocky wall. The cave and the rock shelter (Fig. 2) appear today as two distinct areas separated by the rocky wall of the cliff behind which the cave lies, however this distinction is the result of the millennial growing of the archaeological deposit that partially filled the cave and had largely obstructed the original cave entrance.

During the Palaeolithic period, when the cave floor was at its lowest level, the rock shelter was connected to the main cave to form a large living space. The cave-fill deposits near the entrance are about 8m thick. Palaeolithic deposits, up 7m thick, underlie Holocene layers.

2.1 Archaeological setting

The site has a long history of excavation. It was first excavated in the 1960s by Paolo Graziosi (Boscato *et al.* 1996; Graziosi 1962; 1965; 1966; 1972), who opened some archaeological trenches both in the cave and under the rock shelter. In 2000 a new project of archaeological excavations was begun, enlarging Graziosi's trench and yielding well-preserved Palaeolithic deposits.

This systematic excavation in the cave exposed a long sequence of archaeological units bearing several archaeological layers (often palaeosurfaces) formed during episodes of intensive human occupation (Ghinassi *et al.* 2009). The succession ranges from the middle and late Gravettian to the Late Epigravettian. These units have been dated with a high resolution to ca. 24-11 ka BP. The recent excavations inside have provided large faunal and lithic assemblages. In the rock shelter, not so far from the present-day cave entrance, new excavations were started in 2011 along Graziosi's trench. The deposit in this part of the site contains late Epigravettian, Mesolithic and Neolithic layers. The Mesolithic layers revealed by the recent research

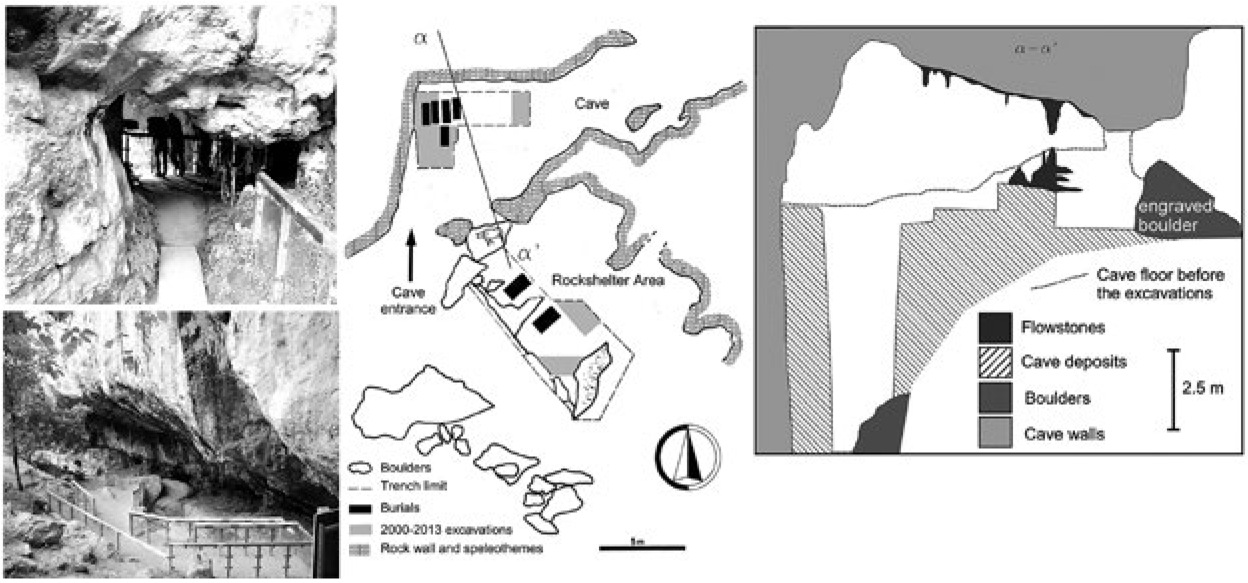


Fig. 2. Romito Cave, views of the rock shelter and cave entrance. General plan and cross-section of the site.

(2011-2014 excavations) represent the oldest evidence of this period in Calabria and are referred to Sauveterrian facies (dated to 10-9,000 uncal. BP) (López-García *et al*. 2014; Martini *et al.* in press).

2.2 The engraved boulders

Dominating the space of the rock shelter are two large engraved boulders (Graziosi 1962; 1971; Martini *et al*. 2007; Martini and Lo Vetro 2011). On the boulder located on the western side of the shelter, the imposing figure of an urus (*Bos primigenius*) is featured (Fig. 3).

On the eastern side of the shelter, at the extreme opposite end to the rock with the incised bull, stand the second boulder, thickly covered with numerous linear signs. This large rock seems to signify a kind of threshold to the living/domestic area. Based on the technical and stylistic characteristics, and compared to other figurative Palaeolithic Italian evidence, both the engraved boulders are dated to the late Upper Palaeolithic (about 14-12,000 uncal. BP)

2.3 The burials

In total, nine adult humans were recovered from the Palaeolithic deposits at Grotta del Romito (Craig *et al.* 2010; Graziosi 1965; 1966; Fabbri *et al*. 1989; Mallegni and Fabbri 1995; Martini 2006; Martini and Lo Vetro 2011; 2014). Two double burials (Romito 1-2 and Romito 5-6), excavated by Graziosi in the rock shelter, are related to a human presence at the site between 11,000 and 10,000 uncal. BP ca. These burials (Fig. 3), parallel and facing the same way (head oriented N-E), are placed between the two engraved large boulders. Five single burials (Romito 3, 4, 7, 8 and 9) were found in the cave, two of these during the 1960s (Romito 3 and 4) and three (Romito 7, 8 and 9) during the recent excavations. Romito 3, 4, 7, 8, were found in distinct but adjacent narrow and deep pits, parallel to the western cave wall, arranged side by side with the same orientation (heads oriented towards N). These burials, dated 12-11,000 uncal. BP ca., refer to the end of the Late Epigravettian. Romito 8, the nearest to the cave wall, is the oldest (12,000 BP ca.), Romito 4 is the last individual buried (11,000 uncal. BP ca.) among the single burials. Romito 9 is the oldest among the burials found at the site: it was dated to 17,000 uncal. BP ca. (Evolved Epigravettian) and is linked to a lower position in the stratigraphic sequence located circa 2m below the other burials.

3 Methodological approach and sources

The synthetic description of the archaeological excavations reveals that the cave and shelter area have been investigated through different field campaigns, spanning from 1962 to the present day, which obviously have adopted different methods, survey instruments and techniques. These conditions produced different types of archaeological documentation. As mentioned before one of the goals of this project is to build up a comprehensive framework to investigate the Palaeolithic use of the cave, consequently we need to manage these data in a single environment in order to contextualise all the available archaeological records. For this reason it is necessary to systematize our data in layers referred to chronological phases and produce features related to synchronic occupation of the site. Ideally we need to relate all the single palaeosurfaces which refer to the same phase in order to investigate in a spatially dynamic way the large palimpsest that testifies the sequence of actions occurring during the Palaeolithic. In particular we focus on the latest phases of the Late Epigravettian in which both the funereal graves (the four single burials in the cave and the two double ones in the shelter) and the engraved boulders refer, linking the information to the other features.

The challenge is to virtually explore the Upper Palaeolithic evidence attempting to reconstruct the Late Epigravettian living space. Today this wide area is not perceivable because the millennial growth of the archaeological deposit had partially filled the cave; during the Neolithic the top of the deposit had reached a long rocky ridge descending by the roof of the cave

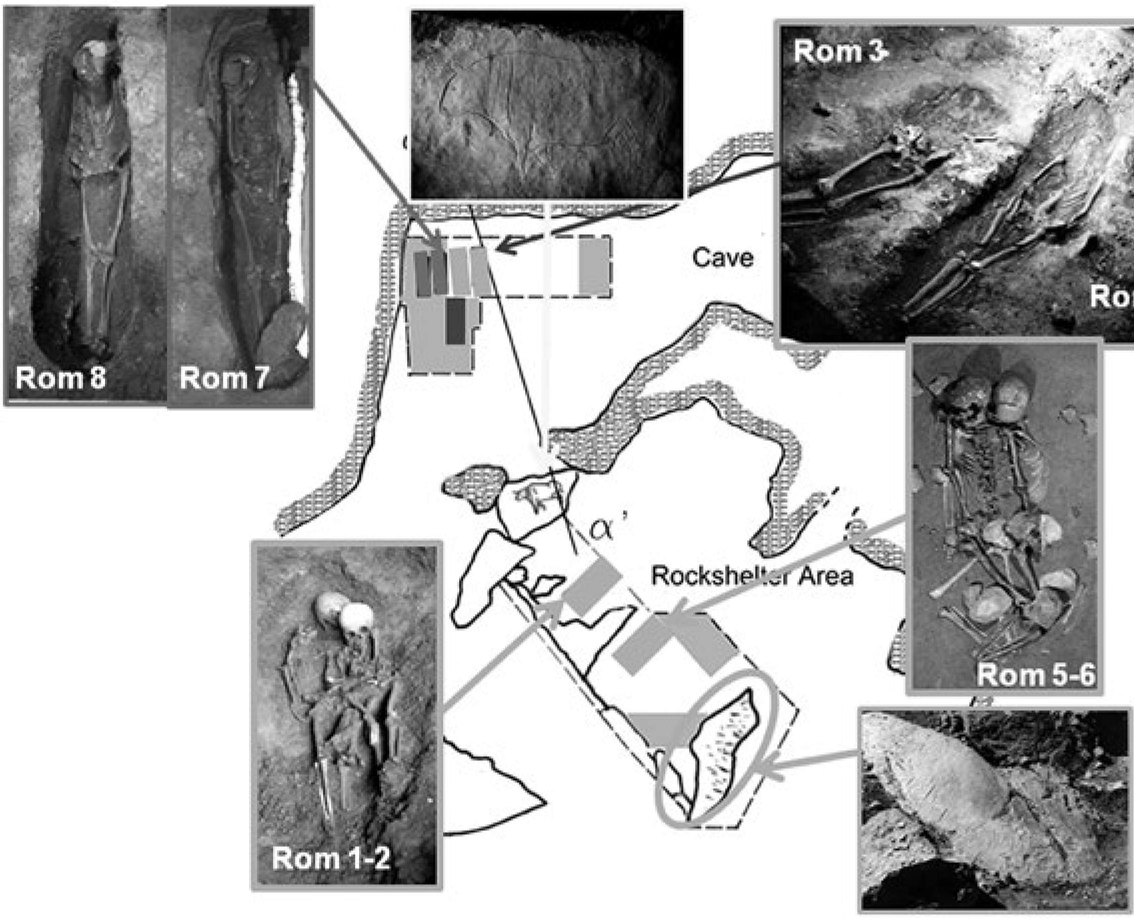


Fig. 3. Schema of funerary and ritual contexts of the cave and the shelter area.

largely modifying the unique room of the cave which now consists of two distinct areas: the inner part and the rock shelter (see above).

From a methodological point of view we have to process the archaeological information in a 3D system including features that are placed below or above our synchronic surfaces. It is clear that our settings are characterised by different accuracy in terms of spatial and chronological information, nevertheless we believe that it is worth attempting their exploration in a GIS environment.

Due to the great variety of types and formats of information, often not related one with the other, actually the aim of this study is to collect and organise in a single framework all the data previously acquired. This dataset will provide an homogeneous environment for updating and collecting new data for future research. For this reason a GIS project has been built up in order to relate those elements together referring to the same grid system.

Following a contextual approach, our goals are focused on the reconstruction of the late Palaeolithic setting of the site in synchronic and diachronic perspectives. Thus, on one hand the system allows us to perceive coeval elements as part of synchronic sets, and on the other hand to highlight continuity and changes in the human occupation of the site over time.

The heterogeneity of data characterises also the different strategy for digital acquisition carried on in the last decade. Since the first phases of the new field campaign at Romito Cave some attempts of data acquisition began in 2004 exploring different types of digital restitutions. Some traditional maps on paper have been acquired in a vector format within a CAD environment. A second step was focused on 3D acquisition using QTVR application (Rambelli and Nider 2004) in order to evaluate the efficacy of this survey method applied to funerary context in a cave environment. Other applications have been developed with the aim of reconstructing an interactive virtual model (Viti 2006) based on the interactions of vector features in a 3D environment.

Beyond the different digital acquisitions a series of laser scanning have been carried out since 2007 in order to provide a 3D documentation of some excavation phases and of some plaster casts of funerary burials excavated by Paolo Graziosi during the 1960s.

To sum up, the project focuses on the spatial use of the cave as a complex ritual context aiming to integrate in a unique analytical setting the rock art and burial evidences which are distributed inside the cave and the shelter in order to perceive this space as a whole.

In the next paragraphs we describe some phases of this research process and illustrate our 3D sources.

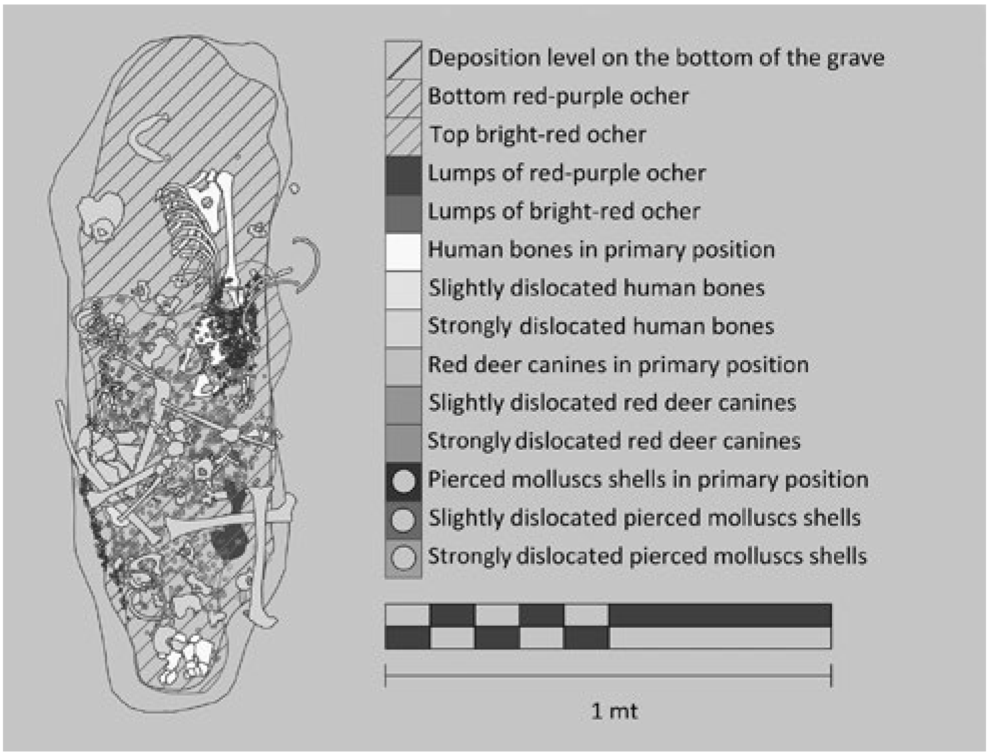


FIG. 4. CAD DRAWING OF THE FUNERARY CONTEXT OF ROMITO 9.

4 Data acquisition in CAD environment

Before managing the archaeological evidence within the GIS system, we have undertaken the digital acquisition of a great part of the graphic documentation produced during these years of excavations at Grotta del Romito. In particular, we have collected the incomplete documentation available from Paolo Graziosi's excavations (brief notes and some photographs and sketches) and both the paper and digital documentation recorded since 2000. Therefore, we have standardized various kinds of documentation in order to facilitate their management within a vector environment.

The archaeological information available in the different types of documentation has been mainly acquired in vector format through the use of a CAD system. The acquisition process, even if carried out in different phases, has adopted the following criteria. Each archaeological class has been recorded in different layers so we have produced a single vector layer for each category of remains, i.e. a layer for stone blocks belonging to the same archaeological unit, a layer for human bones belonging to the same archaeological unit, etc. Then we have digitized every single feature in XYZ coordinates referred to the archaeological grid system of the excavation.

So the final product is made of a vector visual model, both easily to orbit and to organise by theme, with several inclusive layers, each of which was intended for a particular type of information.

Specifically, we have manually vectorised the following archaeological evidence: Romito 3 and Romito 4 burial pits; the burials of Romito 7, Romito 8 and Romito 9; the pits and their contexts founded from D7 to C levels.

For the burials of Romito 3 and Romito 4, discovered in the 1960s by Paolo Graziosi, we do not have any kind of graphic documentation, so we were only able to reconstruct possible morphology of the pits according to written notes and a photograph dating to Graziosi's excavations. The two funerary pits, placed side-by-side almost at the same level, have been reproduced creating a three-dimensional polygon mesh.

Romito 7 funerary context, including the human bones, the pit and its stone blocks placed into the pit filling soil, had already been acquired by Sabina Viti (Viti 2006). Thus we have proceeded to place these vector features in the excavation reference system.

For the burial of Romito 8 we have acquired all the human bones and the stone blocks inside the filling soil and then we have created a three-dimensional mesh to reproduce the structure of the pit. Moreover, as we have done for Romito 7 and Romito 9, we reproduced virtually the inclination of the Romito 8 extensive osteological remains, giving them two or more Z values.

The 3D CAD drawing of the funerary context of Romito 9 (Fig. 4) and its associated database of osteological and ornamental elements belonging to the burial, free of unnecessary data, for this study, has been placed in the correct position on the XYZ grid coordinates. Layers are organized according to archaeological categories (osteological elements, molluscs and atrophic canines, ochre, etc.) and type of deposition: primary

Fig. 5. An external view of the cave (photo and TOF Laser scanner).

position, slightly dislocated and strongly dislocated remains (See Ortisi *et al.* in this volume).

5 Laser scanner

The 3D survey was carried out in 2007 and in 2010 using two different instruments. The first one, a 'time of flight' (TOF) laser scanner, useful or investigating objects 200m distant (optimal range 2-100m - max range 150m) with millimetre precision. The second one, a Next Engine laser scanner (Multi-stripe Laser Triangulation technology - MTL) operating in three different modalities, macro (13x10cm max distance 17cm), wide (35x25cm max distance 48cm) and extended (60x40cm max distance 78cm), in order to acquire the surface of small and medium objects with an accuracy of ±0.0381 cm.

The use of TOF laser scanner allowed us to obtain 3D point clouds by means of a high-yield and precise technology.

Moreover the scanner provides an internal digital camera, used to take pictures of surveyed objects. Then, combining the geometrical position of objects, defined from the point clouds, with the information related to the photos, it is possible to assign to each point a chromatic value in order to obtain a photorealistic rendering of the cloud (Fig. 5).

The dimension of the cave, greater than the laser scanner's field of view, and its morphology, required 17 scans, from different points of view, in order to avoid shadows and to survey the entire surface. The 17 scans have been merged using tie points.

A first general survey of the entire cave has been followed by detailed scans of some zone (burials and engravings) that necessitate an accuracy not achievable with a TOF laser scanner. The high-resolution survey has been carried out by a Next Engine laser scanner (Fig. 6).

The survey procedure adopted in this work has allowed us to obtain a detailed 3D model of the Romito cave.

6 Data Integration into GIS

In order to integrate different datasets in the same spatial context the first step has been to build up a new extended 3D reference system, in a GIS environment, based on the traditional alphanumeric excavation square grid.

Then we have scanned and positioned the general plans of the site in our reference system. These maps show, beyond the general archaeological features, the limits of the cave walls and other elements such as the main boulders constituting the topographic settings of the site. Moreover some modern anthropic features, such as banister and walkway, are part of the general plans. Some of these elements (excavation limits, limits of cave walls and boulders) have been digitised in a vector format because they constitute important references useful for data contextualisation and topographic validation.

In this environment we have then imported the vector CAD layers previously acquired (Fig. 7):

- Romito 3 and Romito 4, consisting of the reconstruction of the approximate scope of the pits as derived by historical photos and notes and by a general plan and cross-section. Unfortunately there is not sufficient information to propose a reconstruction of the skeleton remains and other features which characterise the burials.

- Romito 7, Romito 8, and Romito 9, consisting of burial pits, skeletons, grave goods and stone blocks . These burials are characterised by different levels of accuracy and 3D recording (see above). Moreover for Romito 7 and Romito 9 we have imported and integrated into GIS the associated database concerning bones and grave goods.

- Other types of evidence, as for example pits and fireplace, although not directly related to the burial pits, have been imported into the system in order to explore the functional context and its diachronic spatial modifications occurred in that part of the cave

Concerning high definition laser scanner data we have integrated 3D models (surface and ortophoto) into the GIS (Fig. 8):

- the double burials Romito 1-2 and Romito 5-6 consisting of the scanning of the casts of the skeletons placed in the rock shelter.

Fig. 6. A detailed scanning (Next Engine) of the aurochs engraved on the boulder.

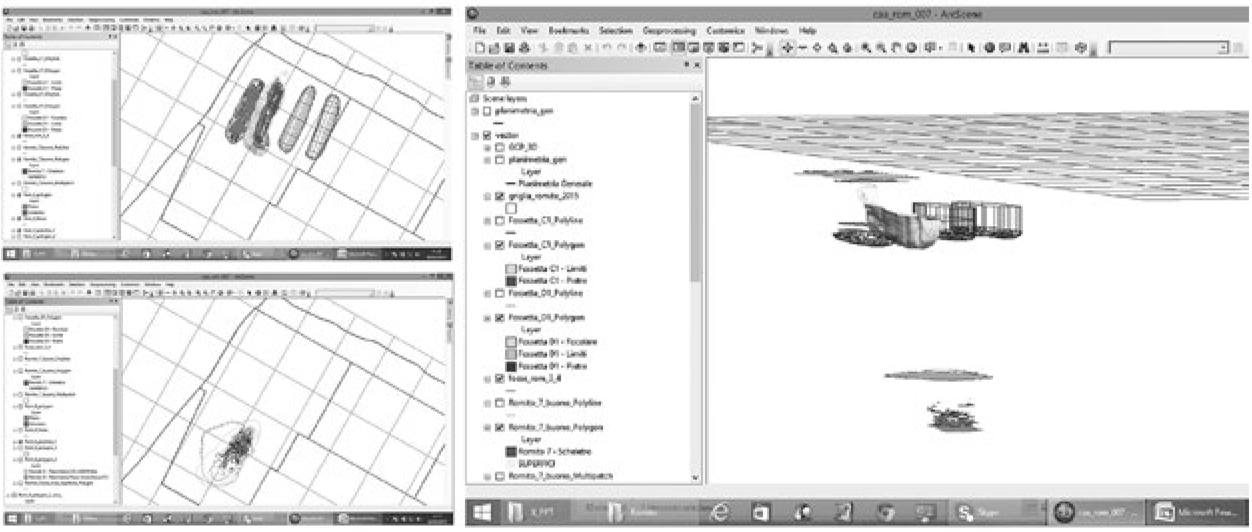


Fig. 7. Data integration: top views and 3D perspective of different CAD layers in GIS environment.

- Romito 9 consisting of the laser scanning of the burial performed during the excavation

- Rock engraving of the aurochs consisting of the laser scanning of the entire rock surface.

The integration of this data into GIS allows us also to enhance the micromorphology and the spatial orientation of the engravings. Through GIS tools we can observe in detail these variations, which are well highlighted according to the orientation of every engraved mark and explore in a virtual way the marks engraved on the boulder (Fig. 9).

Moreover the 3D model derived by laser scanner acquisition of whole site (inner cave and shelter) at a lower resolution has been imported into the GIS.

The integration of laser scanner data into our system provides an exceptional opportunity to explore in a 3D environment the Romito Cave. This 3D GIS model provides a unique context for understanding the spatial relationship and for undertaking topographical validation of the archaeological documentation (Fig. 10).

Furthermore the possibility to interrogate our data means that we can assess the consistency of the archaeological context and

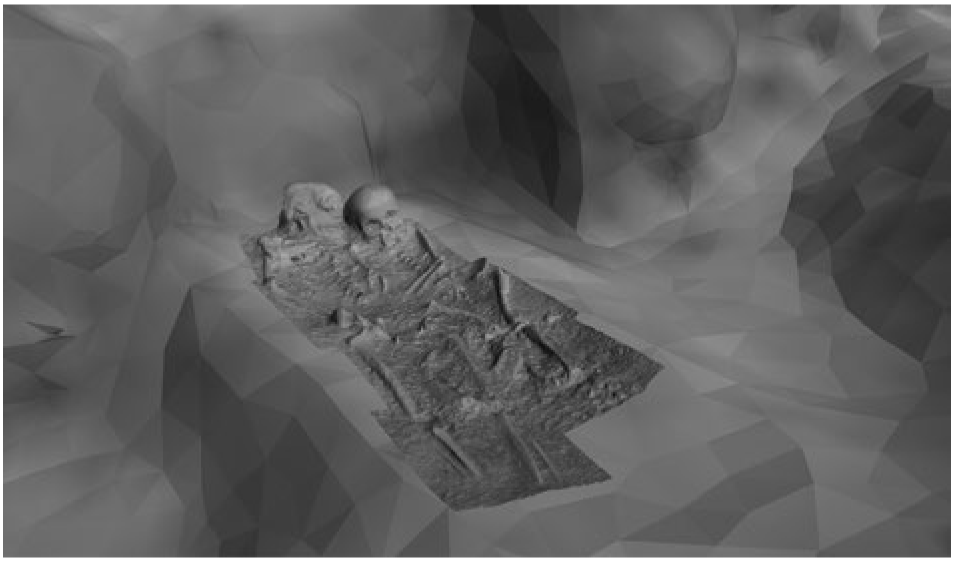


Fig. 8. Data integration: High and low resolution 3D models (surface and ortophoto) into the GIS, the double burials of Romito 1-2.

Fig. 9. Rock engraving of the aurochs, consisting in the laser scanning of the entire rock surface. Changes in shadows of engraved marks obtained through illumination of the scene.

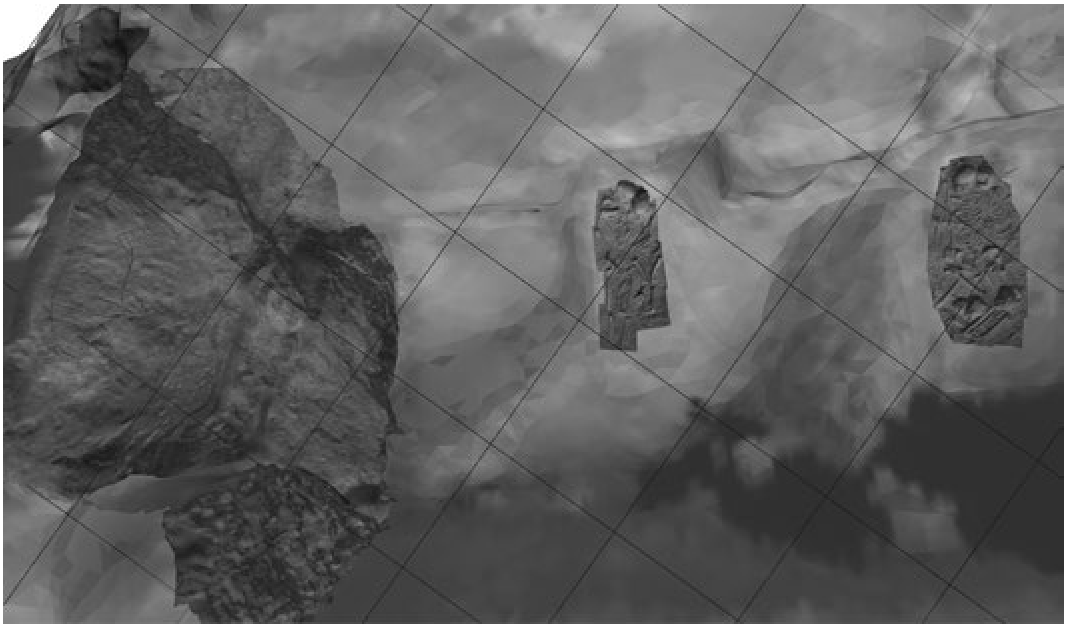


Fig. 10. Data integration: 3D spatial relationship in the shelter area.

organise thematic maps in order to perform further taphonomic analysis (Fig. 11).

7 Elaboration of data and virtual perceptions

A first phase of analysis focused on the elaboration of 3D data derived by laser scanner acquisition. As a first step we modified the scanning and trimmed out all the points of the cloud referring to the modern use of the cave. Consequently we have cut off the passageways, the banister and other modern 'disturbances' from the 3D surface. This new 'cleaned' version was used to provide an undisturbed context to the archaeological data (Fig. 12).

Moreover, in order to improve the exploration and navigation of the 3D space inside the cave we have trimmed the upper part or the 'roof' of the scanned surface. Such a new trimmed surface allows us to perceive more clearly the internal and external parts of the cave linked together, suggesting from a visual point of view that this space was once a form of large living area (Fig. 13).

A second phase of analysis concerns the elaboration of archaeological information. As we have already mentioned in the previous paragraphs the challenge is to virtually explore the Upper Palaeolithic evidence, attempting to reconstruct the Late Epigravettian living space. For this reason we elaborate the data concerning burial pits (Romito 8, 7, 3, 4), starting from the idea of spatially interpolating the data of the upper part of the burials in order to reconstruct the trend of the surfaces (supposed for Romito 3 and 4) where each pit was cut. These depositions are parallel to the western cave wall and refer to a chronological range from 12,000 to 11,000 BP ca., where the oldest burial is Romito 8 and the closest to the cave wall (see above). It is worth stressing that the pits were not contemporary and were not visible at the same time. We attempted to reconstruct a virtual surface which is referred to a wide temporal range, but it did not exist in reality. However this surface is useful for undertaking visual analyses and reconstructing the environment as it was perceived during the last phases of Late Epigravettian. In this way, through the interpolation process, which involved burial pits and other information derived by archaeological documentation, we have obtained a portion of the surface of the internal cave that could approximately be referred to the end of the Late Epigravettian living floors. In fact we do not have the heights of the top of Romito 1-2 and 5-6 burials (chronological range spanning from 11,000 to 10,000 BP ca.) excavated during the 1960s in the external area of the cave. In fact for the shelter area we have only information related to the bottom part of the burials as recorded in the 3D scanning. Thus we used the detailed scanning of the casts and the measures of the other internal burial pits as models, to reconstruct the hypothetical quotes of the upper parts of the external burials. This new set of Z values allows us to build up an approximate occupation surface which is a type of hypothetical interpolation of the possible single surfaces of the whole site referring to the last phases of the Late Epigravettian. This hypothetical surface, within the framework of our 3D model, cuts off part of the archaeological deposit and testifies that the internal and external part of the cave, today separated, constituted a unique space during the Late Epigravettian.

It is worth noting that the spatial location of the burials inside the cave follows some basic rules: the pits are parallel and narrow even if they are not contemporary. Furthermore this iso-orientation of the burials follows the geometry of the walls of the cave in that area (Fig. 14). This setting indicates that spatial memory is an important element that characterises the story of the cave during the Late Epigravettian (Martini and Lo Vetro 2014: 21).

The integration of data within the GIS system permitted the exploration of this space in a 3D environment, offering a great opportunity to relate archaeological documentation with the exact reproduction of the cave walls, that is to say the cave as a

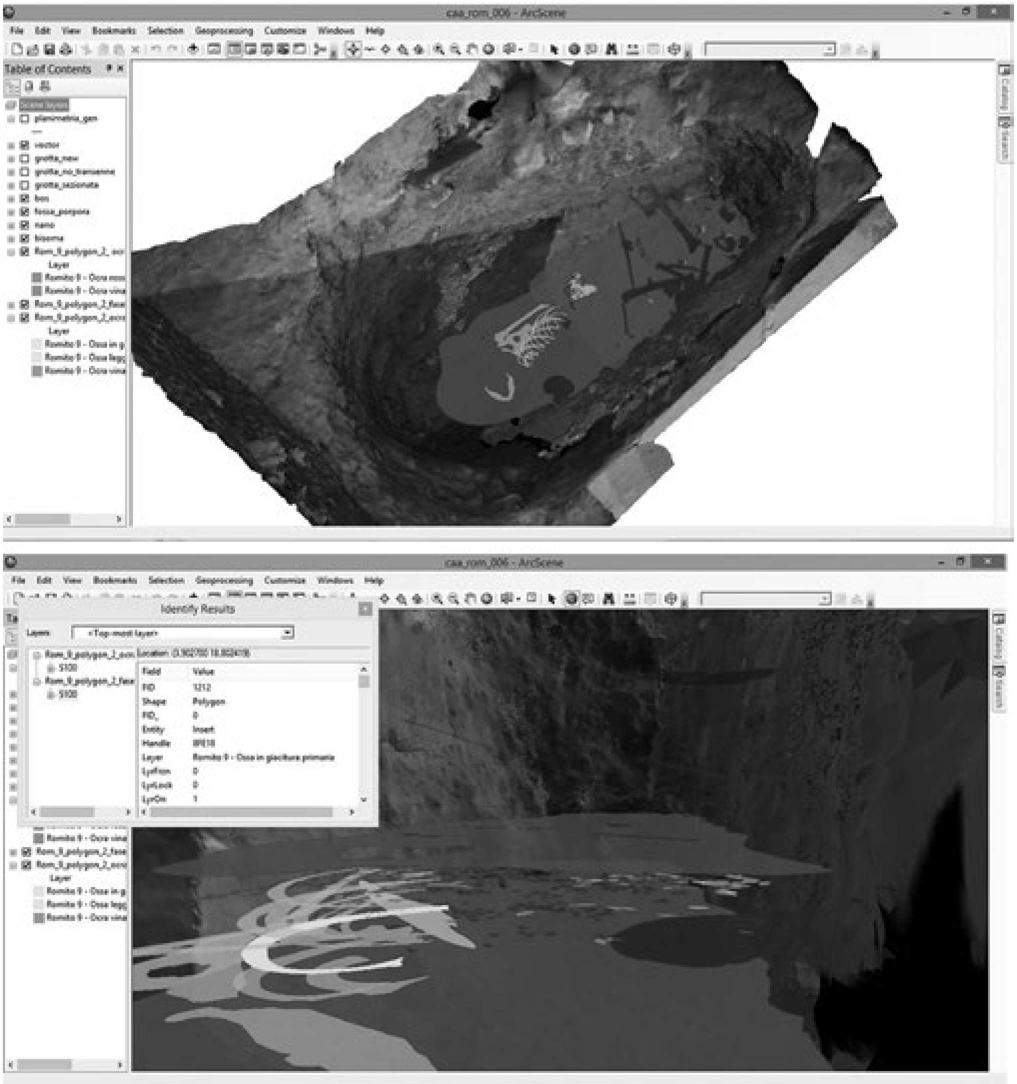


Fig. 11. Data query in a 3D environment: top view and 3D perspective of Romito 9 burial context. The detailed laser scanning of the pit has been used to contextualise the archaeological and anthropological record in order to perform taphonomic analyses.

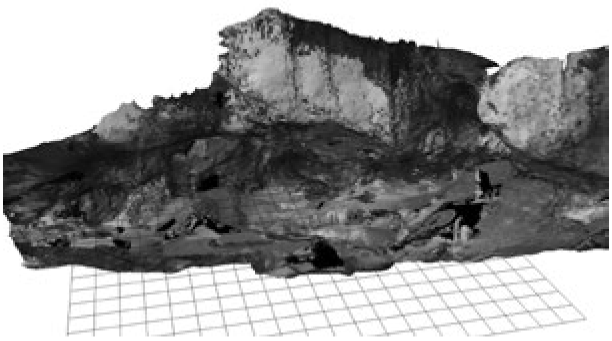


Fig. 12. Processing of the 3D scanning of the cave: passage ways, the banister and other modern 'disturbances' have been trimmed out.

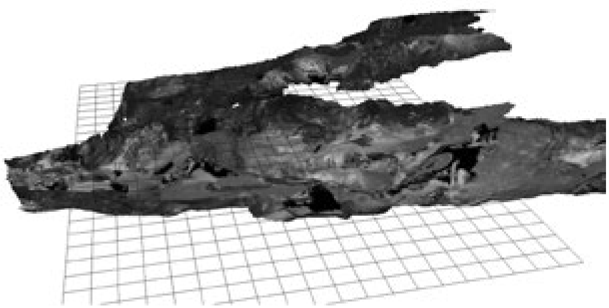


Fig. 13. Processing of the 3D scanning of the cave: the upper part or the 'roof' has been trimmed out. This new surface allows one to perceive more clearly the internal and external parts of the cave linked together.

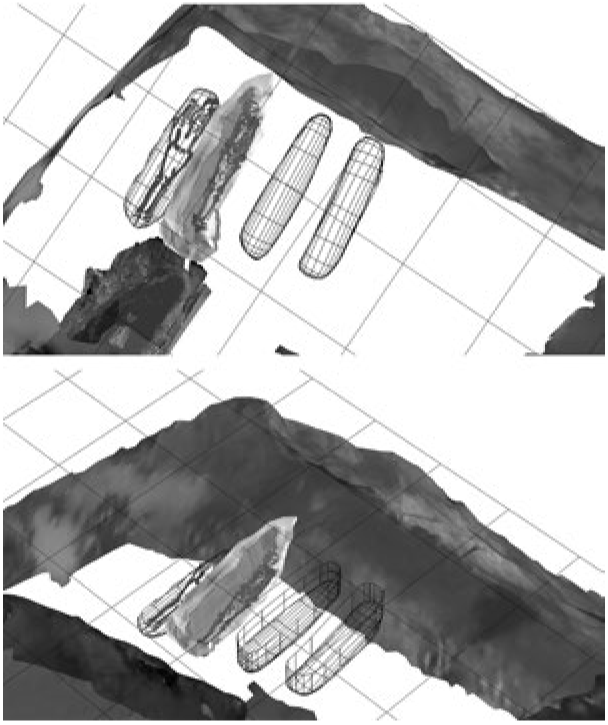


Fig. 14. Funerary evidence in the inner part of the cave: top view and a 3D perspective from the bottom level.

space. In this way the observations noted by archaeologists on site may be assessed and represented in the virtual environment.

Furthermore, the features inputted into the system, linked to databases, may be analysed to perform taphonomic interpretations.

The perception of the internal and external parts of the cave as a single volume, in which every feature is spatially related, means we can build up a unique scenario wherein we can recognise the ritual space of the cave (see Barcelo 2001). Through this holistic vision it is possible to appreciate the spatial roles of the different elements, such as the engraved boulders and the funerary areas. This confirms, and lets us visualise (Fig. 15), the interpretation of the archaeologists who recognised a single ritual space as designated by the engraved boulders that form a context for the funerary actions constituted by the two groups of burials (Martini and Lo Vetro 2014).

8 Final remarks

GIS has become an ideal tool for visual analysis, allowing us to interact in a dynamic way in a virtual space that in reality is no longer perceivable in its totality. Moreover, beyond the possibility to explore this space virtually, we can query and draw in a 3D environment, producing sketches of visual interpretation attempting to reconstruct the palimpsest of the Romito Cave. In this way visual analysis becomes a means to investigate 'palaeo-space'.

Author contributions

The paper was conceived by MDS, DLV, FM, GP. This work has been carried out in full collaboration by all the authors and contributing as follows.

Archaeological data and interpretations: F.M. and D.L.V.
GIS project design: M.D.S. and G.P.
CAD: F.E.O.
Laser Scanner: V.D.T. and P.M.
Data structure and integration of sources: M.D.S.
Visual elaboration: G.P.

Bibliography

Barcelò, J. A. 2001. Virtual reality and scientific visualisation. Working with models and hypoteses. *International Journal of Modern Physics C, 12, 4*: 569–80.
Boscato, P., Guerri, M., Ronchitelli, A. 1996. L'Abri du Romito à Papasidero (Cosenza, Italie)-Couches 4A, 5 et 6 (Fouilles P. Graziosi 1965): Données préliminaires sur l'industrie

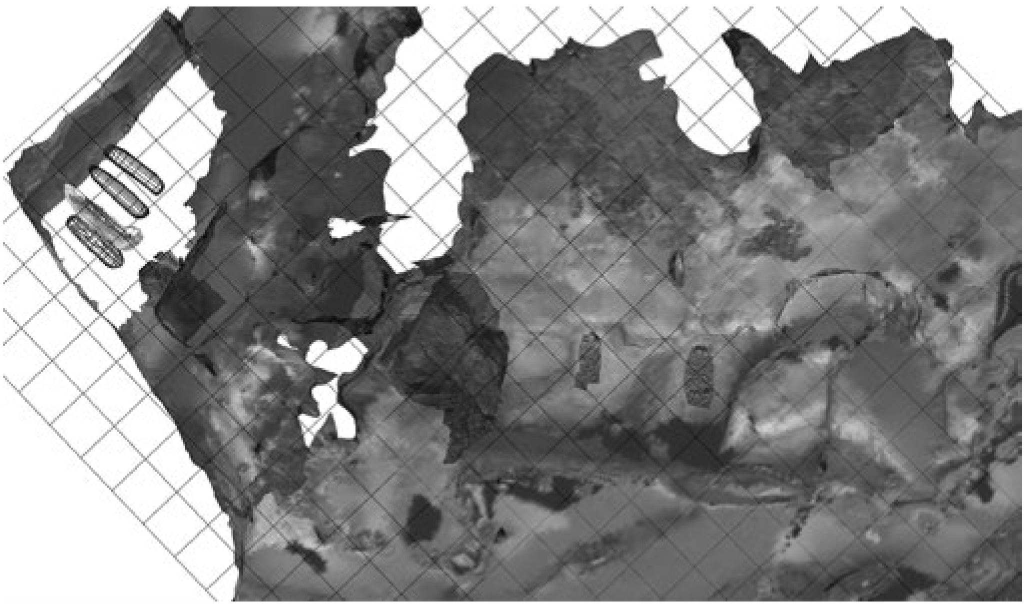


Fig. 15. An overview of the Romito palaeo-space.

litique et la faune. *Proceedings of the XIII Congress of UISPP*, Forlì: 619–27.

Cilli, C., Giacobini, G., Lo Vetro, D., Martini, F. 2004. Due zagaglie in osso decorate dalla grotta del Romito (scavi Graziosi). In *Preistoria e Protostoria della Calabria, Atti XXXVII Riunione Scientifica dell'IIPP*, 2: 657-64.

Cilli, C., Giacobini, G., Martini, F. 2006. I manufatti in materia dura animale della Grotta del Romito (Papasidero, Cosenza). In *Materie prime e scambi nella Preistoria italiana, Atti della XXXIX Riunione Scientifica dell'IIPP*, 2: 951-4.

Colonese, A. C., Ghinassi, M., Di Giuseppe, Z., Govoni, L., Lo Vetro, D., Malavasi, G., Martini, F., Ricciardi, S., Sala, B. 2011. Grotta del Romito (Cosenza): latest Pleistocene landscape. In Van Leusen, M., Pizziolo, G., Sarti, L. (eds.), *Hidden Landscapes of Mediterranean Europe, Proceedings of the International Meeting*, 2007*, Siena, British Archaeological Reports International Series* 2320: 61-70. Oxford, Archaeopress.

Colonese, A. C., Ghinassi, M., Govoni, L., Lo Vetro, D., Malavasi, G., Martini, F., Ricciardi, S., Sala, B. 2008. Late Pleistocene clastic deposits in the Romito Cave, southern Italy: a proxy record of environmental changes and human presence. *Journal of Quaternary Science 24, December 2008*: 383-98.

Colonese, A. C., Martini, F. 2007. Molluschi terrestri e disturbi antropici: evidenze epigravettiane a Grotta del Romito (Cosenza). *Bullettino di Paletnologia Italiana* 96: 1-16.

Colonese, A. C., Zanchetta, G., Fallick, A. E., Martini, F., Manganelli, G., Lo Vetro, D. 2007. Stable isotope composition of Late Glacial land snail shells from Grotta del Romito (Southern Italy): Palaeoclimatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 254: 550–60.

Craig, O. E., Biazzo, M., Colonese, A. C., Di Giuseppe, Z., Martinez-Labarga, C., Lo Vetro, D., Lelli, R., Martini, F., Rickards, O. 2010. Stable isotope analysis of Late Upper Palaeolithic human and faunal remains from Grotta del Romito (Cosenza), Italy. *Journal of Archeological Science* 37: 2504-12.

Fabbri, P. F., Graziosi, P., Guerri, M., Mallegni, F. 1989. Les hommes des sépoltures de la grotte du Romito à Papasidero (Cosenza, Italie), *Hominidae, Proceedings of the 2nd Congress of Human Palaeontology*, *Milano*: 487-94.

Ghinassi, M., Colonese, A. C., Di Giuseppe, Z., Govoni, L., Lo Vetro, D., Malavasi, G., Martini, F., Ricciardi, S., Sala, B. 2009. The Late Pleistocene clastic deposits in the Romito Cave, southern Italy: a proxy record of environmental changes and human presence. *Journal of Quaternary Science* 24: 383-98.

Graziosi, P. 1962. Découverte de gravures rupestres de type paléolithique dans l'abri del Romito (Italie). *L'Anthropologie* 66: 262–8.

Graziosi, P. 1965. Papasidero (prov. di Cosenza). *Rivista di Scienze Preistoriche* 20: 367.

Graziosi, P. 1966. Riparo del Romito (Papasidero, prov. di Cosenza). *Rivista di Scienze Preistoriche, Notiziario* 21: 422.

Graziosi, P. 1971. Dernières découvertes de gravures paléolithiques dans la grotte du Romito en Calabre. *Mélanges André Varagnac*, *Paris*: 355-7.

Lo Vetro, D., Martini, F. (eds.) 2011. *Grotta del Romito a Papasidero – Uomo, ambiente e culture nel Paleolitico della Calabria (ricerche 1966 – 2011)*. Cosenza, Editoriale Progetto 2000.

López-Garcia, J. M., Berto, C., Colamussi, V., Della Valle, C., Lo Vetro, D., Luzi, E., Malavasi, G., Martini, F., Sala, B. 2014. Palaeoenvironmental and palaeoclimatic reconstruction of the latest Pleistocene–Holocene sequence from Grotta del Romito (Calabria, southern Italy) using the small-mammal assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology* 409: 169-79.

Mallegni, F., Fabbri, P. F. 1995. The human skeletal remains from the Upper Palaeolithic burials found in Romito cave (Papasidero, Cosenza, Italy). *Bulletin et Mémoires de la Société d'Anthropologie de Paris* 7: 99–137.

Martini, F. 2006. Le evidenze funerarie nella Grotta e nel Riparo del Romito (Papasidero, Cosenza). In Martini, F. (eds.), *La cultura del morire nelle società preistoriche e protostoriche italiane. Studio interdisciplinare dei dati e loro trattamento informatico*, *Origines* 1, Firenze, Istituto Italiano di Preistoria e Protostoria.

Martini, F., Beccaro, P., Ghinassi, M., Martino, G. 2006. Caratterizzazione degli areali e modalità di raccolta della materia prima litica nel Palaeolitico superiore e nel Mesolitico in area calabro-campana: I casi studio di Grotta del Romito e di Grotta della Serratura. In *Atti XXXIX Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria. Materie prime e scambi nella preistoria italiana*, Firenze: 241–52.

Martini, F., Bisconti, M., Casciarri, S., Fabbri, P. F., Leonini, V., Lo Vetro, D., Mallegni, F., Martino, G., Noto, F., Ricci, S., Ricciardi, S., Rickards, O. 2004. La nuova sepoltura epigravettiana 'Romito 7' a Papasidero. In *Atti della XXXVII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria. Preistoria e Protostoria della Calabria* 1: 101–11.

Martini, F., Cattani, L., Colamussi, V., Colonese, A., Martino, G., Mallegni, F., Noto, F., Ricciardi, S., Rickars, O., Rolle, R. 2004. Primi risultati delle nuove ricerche nei livelli epigravettiani di Grotta del Romito a Papasidero (scavi 2000-2002). In *Atti della XXXVII Riunione Scientifica 'Preistoria e Protostoria della Calabria', Scalea, Papasidero, Praia a Mare, Tortora 29 Settembre - 4 Ottobre 2002*, Firenze: 85-99.

Martini, F., Cilli, C., Colonese, A. C., Di Giuseppe, Z., Ghinassi, M., Govoni, L., Lo Vetro, D., Martino, G., Ricciardi, S. 2007. L'Epigravettiano tra 15.000 e 10.000 anni da oggi nel basso versante tirrenico: Casi studio dell'area calabro-campana. In Martini, F. (eds.), *L'Italia tra 15.000 e 10.000 anni fa. Cosmopolitismo e regionalità nel Tardoglaciale, Atti della tavola rotonda*, Firenze: 157–207.

Martini, F., Lo Vetro, D. 2005. Grotta del Romito (Papasidero, Cosenza): recenti risultati degli scavi e degli studi. In Ambrogio, B., Tinè, V. (eds.), *Preistoria e Protostoria della Calabria. Scavi e ricerche 2003, Atti delle giornate di studio, Pellaro (RC) 25-26 Ottobre*: 5-15.

Martini, F., Lo Vetro, D. 2007. Grotta del Romito (Papasidero, Prov. Di Cosenza). *Rivista di Scienze Preistoriche* 57: 441–2.

Martini, F., Lo Vetro, D. 2014. Atti rituali e spazi cerimoniali paleolitici nell'ambiente di grotta. Le evidenze di Grotta del Romito in Calabria. In: Negroni Catacchio, N. (eds.). *Preistoria e Protostoria in Etruria. Atti dell'undicesimo incontro di studi*, *Valentano (VT) – Pitigliano (GR), 14-16 Settembre 2012* XI: 461-80.

Martini, F., Lo Vetro, D., Di Giuseppe, Z., Baglioni, L., Colonese, A. C., Lemorini, C., Mazzucco, N., Trenti, F. 2012. Strutture e sottostrutture del Paleolitico superiore di Grotta del Romito tra funzionalità e simbolismo. *Rivista di Scienze Preistoriche* LXII: 33-66.

Martini, F., Lo Vetro, D., Timpanelli, L. (in press). New insight on the Romito Shelter (Calabria): the lithic production of the Mesolithic levels. In *Proceedings of Mesolife International Conferenc., Selva di Cadore, Italy, Preistoria Alpina* 48.

Martini, F., Martino, G., Rolle, R. 2003. L'Epigravettiano finale di Grotta del Romito a Papasidero: L'industria litica degli strati C e D. *Rivista di Scienze Preistoriche* 53: 55–138.

Ortisi, F. E. 2012. *Romito 9: lettura di un'evidenza funeraria del Paleolitico Superiore mediante applicazioni fotogrammetriche e CAD*. Unpublished Master degree dissertation thesis, Università degli Studi di Firenze.

Rambelli, C., Nider, F. 2004. Grotta del Romito: il QTVR object (Quicktime Virtual Reality) della sepoltura Romito 7 come documentazione complementare. In *Atti della XXXVII Riunione Scientifica 'Preistoria e Protostoria della Calabria', Scalea, Papasidero, Praia a Mare, Tortora 29 Settembre - 4 Ottobre 2002*, II, Firenze.

Viti, S. 2001. L'ambiente CAD: tentativi di un'analisi visuale, verso un sistema informatico geografico per lo studio dei contesti preistorici nell'area di Sesto Fiorentino (Firenze). Lo stato della ricerca. *Rivista di Scienze Preistoriche* 51, 2000-2001: 471-81.

Viti, S. 2006. Modelli visuali e riproduzioni tridimensionali di evidenze funerarie della preistoria italiana. I casi studio di Romito 7 (Paleolitico Superiore) e di Pontecagnano – Tomba 6517 (Eneolitico). In Martini, F. (eds.), *La cultura del morire nelle società preistoriche e protostoriche italiane. Studio interdisciplinare dei dati e loro trattamento informatico*, *Origines* 1, Firenze, Istituto Italiano di Preistoria e Protostoria.

Visualizing Occupation Features in Homogenous Sediments. Examples from the Late Middle Palaeolithic of Grotte De La Verpillière II, Burgundy, France

Jens Axel Frick
jens-axel.frick@ifu.uni-tuebingen.de
Department for Early Prehistory and Quaternary Ecology,
Institute for Pre- and Protohistory and Medieval Archeology,
Eberhard Karls University of Tübingen, Tübingen, Germany

Abstract: Here, methodological approaches are presented to reveal otherwise-invisible archaeological features in homogenous, fine-grained aeolian/fluvial rock-shelter sediments containing archaeological deposits from the Late Middle Palaeolithic. The excavations and analyses at the site Grotte de la Verpillière II combine multiple technical solutions to build three-dimensional models of archaeological features in these sediments that are difficult or impossible to see by means of conventional observation. The meticulous piece-plotting of thousands of individual charcoal and burnt-bone fragments, lithic and faunal artifacts, and limestone fragments, has allowed fort the identification of distribution patterns of these materials that are supported by additional spatial data, lithic refits, and technological analysis. Detailed mapping and data-analysis has focused on the reconstruction and interpretation of the site occupation to establish a database and reference-site for the Middle Palaeolithic in Southern Burgundy, Saône-et-Loire.

Keywords: Côte chalonnaise, Eastern France, Three-dimensional find distribution, Late Middle Palaeolithic occupation

Introduction

An observable phenomenon of many archaeological layers in sites attributed to the Middle Palaeolithic is the predominant lack of clear, detectable settlement patterns that were accumulated by repeated occupation events. Sedimentary units in caves and rock shelters tend to be highly homogenized, but obviously contain the material remains of multiple occupation events. Identifying distinct horizons within such deposits is a challenging task, even in the case of recent excavations employing modern techniques and elaborate studies in an effort to separate entities that are assumed to be layered within homogenous sedimentary units.

Potential reasons for sedimentary homogeneity are many and varied, and include taphonomic processes (post-depositional mixture of individual occupation events by geological and biological processes), errors in excavation (failure to recognize and separate strata and finds during excavation) or unique and unexpected settlement patterns (frequently and repeated short-term occupation with uneven find-scatters within the same sedimentation process), environmental influences during and after sedimentation (e.g. carnivore and rodent activities, plant growth, wind drift, landslides and events of collapse, or cryoturbation) and even subsequent events of human occupation, which can affect the distribution of materials discarded on the surface of the site.

Here an attempt has been made to develop and apply methods that could aid in solving such clear palimpsest problems and provide high-resolution temporal indicators of occupation events and site-formation processes. In particular, studies of archaeological finds are used in combination with micromorphological and geomorphological studies in an effort to clarify the effects of small- and large-scale geological factors with the ultimate goal of identifying distinctive entities within homogenous sedimentary units. The application of isosurface analysis is used here in combination with three-dimensional studies of material remains in order to reveal patters of accumulation and discrete distributions inside stratified layers of homogenous sediments.

Based on the material record in Palaeolithic sites, archaeological methods were developed to study these materials, especially lithic and faunal refitting, raw-material studies, analyses of litho-technological reduction sequences, archaeozoological studies, but also distribution analyses within sites and layers (e.g. two- and three-dimensional find and finding distribution analyses). The aim here is to find significant patterns that justify the separation of assemblages or explain spatial distribution patterns within sediment units. These patterns can clarify modes of human occupation such as: single, multiple, short-term, long-term, repeated, frequent, erratic.

1 Regional, geological and site setting

The site of interest is the Grotte de la Verpillière II (hereafter VP II) in the Saône-et-Loire department in France. The site is located around 10 km west of Chalon-sur-Saône in the municipal of Mellecy in Germolles at the western cliff-face of the Orbize valley (see Fig. 1).

The site is situated in the eastern cliff-face of the Upper Oxfordian Montadiot massive, which was affected by the formation of Rhine-Saône-Rhône graben. Karstic processes during the Neogene resulted in the formation of a small valley that is traversed by the little creek Orbize (Bons and Wißing, 2009; Cailhol, 2014; Wißing, 2012). Karstic washing occurred along two geological fractures (around N 150° and N 15°) and formed the two sites of Grottes de la Verpillière I and II, situated 50 m apart in the same cliff-face.

VP II was discovered in 2006 by an excavation team from the University of Tübingen, under the direction of H. Floss, and

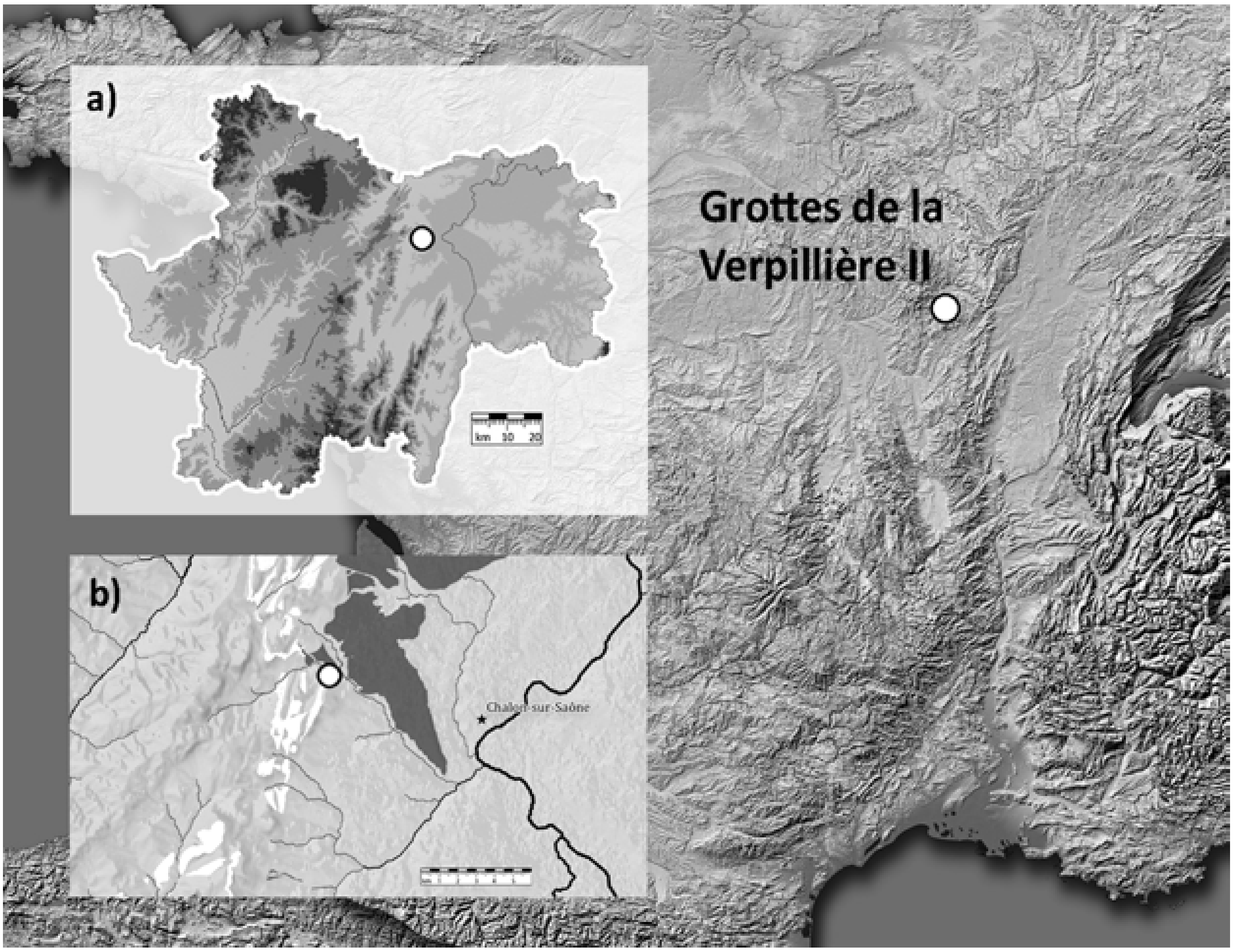


Fig. 1. Location of Grotte de la Verpillière II in France (dots refer to the position of VP II. a) Dept. of Saône-et-Loire; b) Côte chalonnaise (dark grey - distribution of paleogene sediments containing flint of the *argiles à Silex*; white - distribution of Jurassic bathonian sediments containing chert; bright blue - distribution of jurassic bajocian sediments containing chert). Base map from NASA Shuttle Radar Topography Misson 2000 (eoimages.gsfc.nasa.gov), raw material distribution map from M. Siegeris (SFB 1070 B01) with map data from Jarvis *et al.* (2008).

has since been under excavation in the form of annual field campaigns. After removing overlying beds of humic, mixed sediments (geological units GH 1 and GH 2) and massive limestone blocks from a rock collapse, the team identified stratified, nearly-undisturbed sediments in 2009 that contain Middle Palaeolithic material (GH 3, GH 4x and GH 4). These sediments are still under excavation and therefore the results of spatial analysis are preliminary. In current calculation around 12.5% to 25% of the entire area containing these sediments has been excavated at the time of this publication (see Fig. 2).

In all, the (excavated) stratigraphy of the site is around 7 m thick. The Middle Palaeolithic layers (Geological units, GH 3, 4x and 4) are stratified between two rock collapses and lie under a collapsed rock shelter and in the entrance of a corresponding cave tunnel. The second rock collapse, which sealed the Middle Palaeolithic occupation layers, is covered by mixed sediments (GH 1 and 2) containing material from Middle Palaeolithic, Upper Palaeolithic, Neolithic, Roman, Medieval and modern times. It is assumed that most of these sediments derive from the plateau above the cliff-face and have been altered by animal and floral activities (badger den and vegetation cover). The first rock-collapse (GH 8) underlying the Middle Palaeolithic occupation is covered by a highly altered flowstone (GH 7), yellow weathering sediments (GH 6, in the interior of the cave tunnel), and a sediment altered by formation (GH 5, in the entrance of the cave tunnel). A summarized stratigraphy of the site can be seen in table 1 (see also Frick and Floss 2015) and is illustrated schematically in Fig. 3:

The stratified geological units containing the Middle Palaeolithic occupation layers (GH 3, 4x and 4) are easily distinguished during excavation because of their different colour, grain-size components, and contents of calcite and silica or solidity (Frick and Hoyer 2009; Frick and Hoyer 2011; Frick and Hoyer 2012; Frick *et al*. 2013). In general, the sediment of all three stratified units is composed of a coarse-clay and fine-sand matrix (fine-to-medium quartz sand embedded in coarse clay and fine silt) with some quartz and limestone inclusions of fine gravel size. The differences of the GHs lay mostly in the amount of these coarser components: the deeper in the stratigraphy, the coarser such fragments. The sediments are a combination of a substantial amount of aeolian quartz and mica, combined with fluviatile components such as limestone fragments. Sometimes manganese and iron oxide crusts altered the limestones.

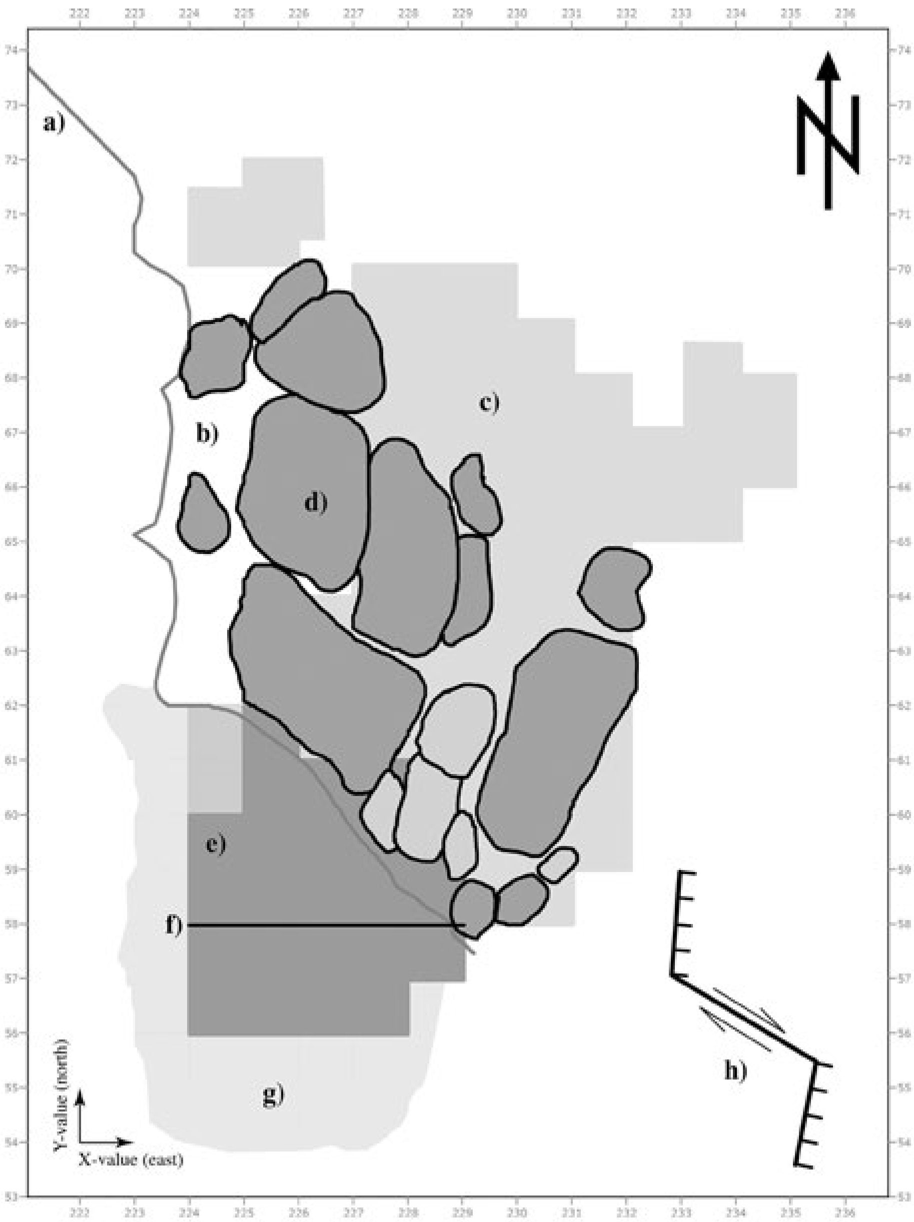


Fig. 2. Schematic map of Grotte de la Verpillière II. a) cliff face in north western direction to VP I; b) area of dense vegetation; c) area where sediments of GH 1 and 2 are almost completely removed (almost equals the potential area of intact sediments); d) area of collapsed rocks that have built the rock shelter (dark grey - blocks still in position, light gray - removed blocks); e) position of the current excavation of GH 3, GH 4x and GH 4; f) position of the schematic profile of the cave tunnel (see Fig. 3); g) size of the cave tunnel as much as could be explored, and h) illustration of geomorphological fracture directions. Basal GIS map from C. T. Hoyer (DFG FL244/5-1).

These geological units represent layers formed under similar geological conditions. Indications of single events like occupation layers are impossible to identify during excavation because of the very homogenous sedimentation and the equally similar chemical interaction of the soil with the archaeological finds (patination and chemical solution of organic material). Micromorphological analysis has shown that GH 3 (in the present-day entrance of the cave tunnel) was slightly altered by bio- and cryoturbation in the form of small root channels and chemical homogenisation (Bons and Wißing 2009; Wißing 2012).

The material from the stratified layers can be exclusively attributed to the Middle Palaeolithic. The lithic artefacts (of GH 3, GH 4x and GH 4) yield a strong Levallois component in the form of heavily centripetally-reduced Levallois cores, core-configuration flakes and finished products like oval and rectangular flakes and blades (Frick and Floss 2015). The richest geological unit (GH 3) contains: n=3,780 lithic elements, n=2,323 faunal components (bone, teeth, antler and ivory) and n=9,509 charcoal fragments (mostly <1cm). In the upper parts of GH 3, bifacial elements occur**,** including *Keilmesser* (n=6, including two with tranchet blows), n=11 bifaces, n=9 tranchet-blow blanks and n=9 preforms that can be attributed to the *Keilmessergruppen* of central Europe (Frick and Floss forthcoming). Hammerstones, anvils and cores of quartzite and sandstone are also present in all three stratified layers.

The main lithic raw material in all three geological units is flint from the *argiles à Silex*, a local material (cretaceous flint that was eroded and deposited in the Eocene) that can be found as near as 150m south and south-west of the site (Frick *et al*. 2012), which could be also detected on nearly all hill ranges of the *Côte chalonnaise*. Another material is Jurassic chert from the Bathonian and Bajocian with its nearest sources as close as 3 km to the east (Siegeris, 2014).

Tab. 1. Summarized geological units from top (GH 1) to bottom (GH 9) at Grotte de la Verpillière II (see also Frick and Floss 2015; Frick and Floss, in press).

geological layer (GH)	status	yield	sediment	thickness
1	mixed	modern material, items from the middle ages, upper and middle paleolithic artifacts	cover soil with many limestones and less humus and throw-off of the badger den (maybe also from the top of the plateau)	around 0.1 m
2	mixed	modern material, items from the middle ages, upper and middle paleolithic artifacts	soil with a big humus content, mostly bigger limestones, limestone blocks of the roof collapse, patches of cave sediments, badger den	0.2 to 3 m
3	intact	middle paleolithic artifacts	mostly aerial soil with a small fluvial component, slightly altered through bio- and kryoturbation, very find grained	0.4 to 1 m
4x	intact	middle paleolithic artifacts	mostly aerial soil with a small fluvial component, almost no alteration visible, mid-fine grained	0.05 to 0.1 m
4	intact	middle paleolithic artifacts	mostly aerial soil with a small fluvial component, almost no alteration visible, mid-fine grained	0.1 to 0.4 m
5	intact	sterile	dark-brownish soil horizon under the contemporary entrance	0.05 to 0.1 m
6	intact	sterile	yellow weathering horizon of limestones inside the cave	0.05 to 0.5 m
7	intact	sterile	weathered flowstone	around 0.1 m
8	intact	sterile	concreted limestone blocks	around 0.7 m
9	intact	possibly another find horizon	crusts and blocky deposits of limestone (only in a small depth sondage)	possibly 0.1 m

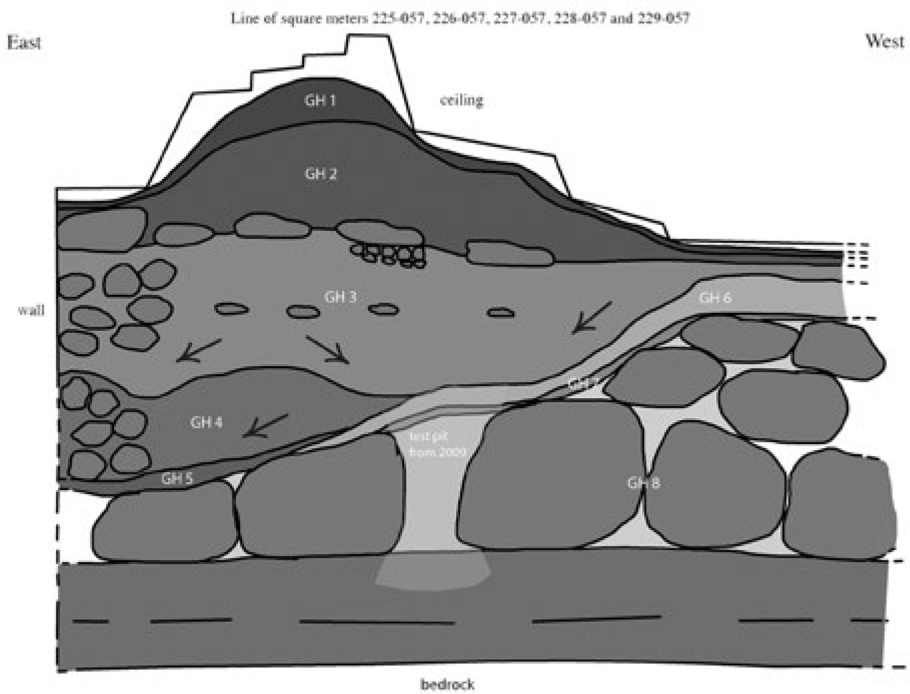


Fig. 3. Schematic geomorphological and stratigraphical setting of Grotte de la Verpillière II as detected by current excavation inside the cave tunnel (position see Fig. 2f). Left - schematic drawing of sediments overlaying the first rock collapse; right - actual profile showing the homogenous sediment of GH 3 and burrows.

The faunal component (only in GH 3 and GH 4) includes mostly bone and teeth from larger herbivores like woolly rhino (*Coelodonta antiquitatis*), mammoth (M*ammuthus primigenius*), horse (*Equus ferus*), bovidae (*Bos primigenius*/ *Bison bonasus*), and cervidae (*Cervus elaphus* and *Rangifer tarandus*). Carnivores like hyena (*Crocuta crocuta*) and bear (*Ursus sp.)* are present in small numbers (Wilk 2014). There are slight differences in the faunal components of GH 3 and 4. The analysis of n=696 bones and teeth from GH 4 (campaign 2009 to 2013) showed that woolly rhino and horse represent the biggest weight. GH 3 instead showed by weight more giant deer (*Megaloceros giganteus*), horse, red deer, bovidae and in small amounts, hyena, wolf and bear. Some bones in the size-class of bovidae and cervidae showed impact and cut marks in GH 3 and 4 (Wilk 2014; Wilk 2014).

In addition to the observations made during excavation, several scientific approaches were taken to verify geological and geomorphological and micromorphological interpretations. Ground-penetrating radar surveys (GPR) in 2009 provided insight into the size of the cave tunnel. In 2014, it was demonstrated through additional GPR survey that most of the sediment from the plateau overlying the site was eroded, and likely formed the landslide component of GH 1 and 2 as well as the talus that originally concealed the site. Another cavity was identified to the west that could be connected to the known cavity. It was also confirmed that all massive limestone blocks on the terrace of the site derive from rock collapses and overlie stratified sediments, meaning that the area of potentially-stratified sediment is much larger than expected (Leach 2014; Leach and Miller 2009).

Geomorphological surveys provided data about fractures in the cliff face, sedimentation processes, position of bedrock, stratification of the dolomitic limestones of the cliff face and the collapse of the rock shelter (Bons and Wißing 2009; Cailhol 2014; Frick 2014; Wißing 2012). Preliminary micromorphological studies of samples from sediment under the current entrance of the cave tunnel showed that GH 1 and 2 is highly altered, disturbed, mixed and containing substantial amounts of humus. In contrast, GH 3 showed only slight alteration in the form of small root-channels and a homogenisation due to cryoturbation (Floss 2009; Wißing 2012).

2 Methods

The methodological basis of this study is the meticulous three-dimensional piece-plotting of all artefacts, including traces of fire/heating such as charcoal and burnt bone. This practice is widespread in archaeology, but not universal. One aim of the current study is to explore and demonstrate the informative potential of piece-plotting methods, specifically the potential of these methods to provide insights into patterns that are otherwise impossible to detect. During excavation, the three-dimensional position of every object (mostly >2cm) was measured using a tachymeter and recorded in the excavation database using EDM for Windows (Dibble and McPherron 1996).

At VP II, every effort was made to record the three-dimensional position of all artefacts over 5 mm (e.g. lithic objects, faunal elements, burned sediment, iron oxides, limestones) using a Total Station (Leica tachymetre and laptop with EDM for Windows. Charcoal fragments were spatially measured below this size threshhold, sometimes down to a size of just one or two millimetres. All sediments from GH 3, GH 4x and GH 4 were water-screened with a mesh size of 1 mm. Artefacts from sediment units (e.g. bucket) are called collective finds.

The plotted artefacts and topographical landmarks (e.g. geological units, archaeological features**,** and the geomorphology of the rock shelter) were processed in Voxler™ to display their distributions in three dimensions. To date (campaigns 2006 to 2014), n=49,467 measurement points have been collected from the site (including n=11,793 topographical measurement points and n=17,492 single-finds, see tab. 2).

The protocol was not put in place until systematic excavation began. Restrictively, in the spatial distribution plots, it has to be acknowledged that the test pit of 2009 (indicated as shaded square in Fig. 4) was excavated much faster and mostly collective finds were made (buckets of sediment, water screened or sorted). So all finds >1cm were collected and can only referred to a sub-square metre. The next step in future needs to be to incorporate all small finds from collective finds into the study about spatial distribution.

Initial observation of the distribution of all find-categories (see Fig. 4) specific distribution zones to be further investigated. In order to do so, two find categories at a time were plotted against

Tab. 2. Exemplary extract of numbers of measurements (non-exhaustive) from VP II.

category	GH 3	GH 4x	GH 4	stratified units (GH 3, 4x and 4)	total (including all units and features
single finds	16812	55	523	17390	17492
botanic/osseous burnt material	9509	32	284	9825	9828
lithic objects (measured as single finds)	2968	27	59	3054	3104
faunal elements, like bones, teeth, antler and ivory (measured as single finds)	2221	0	159	2380	2441
limestone fragments (measured as single finds)	1520	2	19	1541	1877

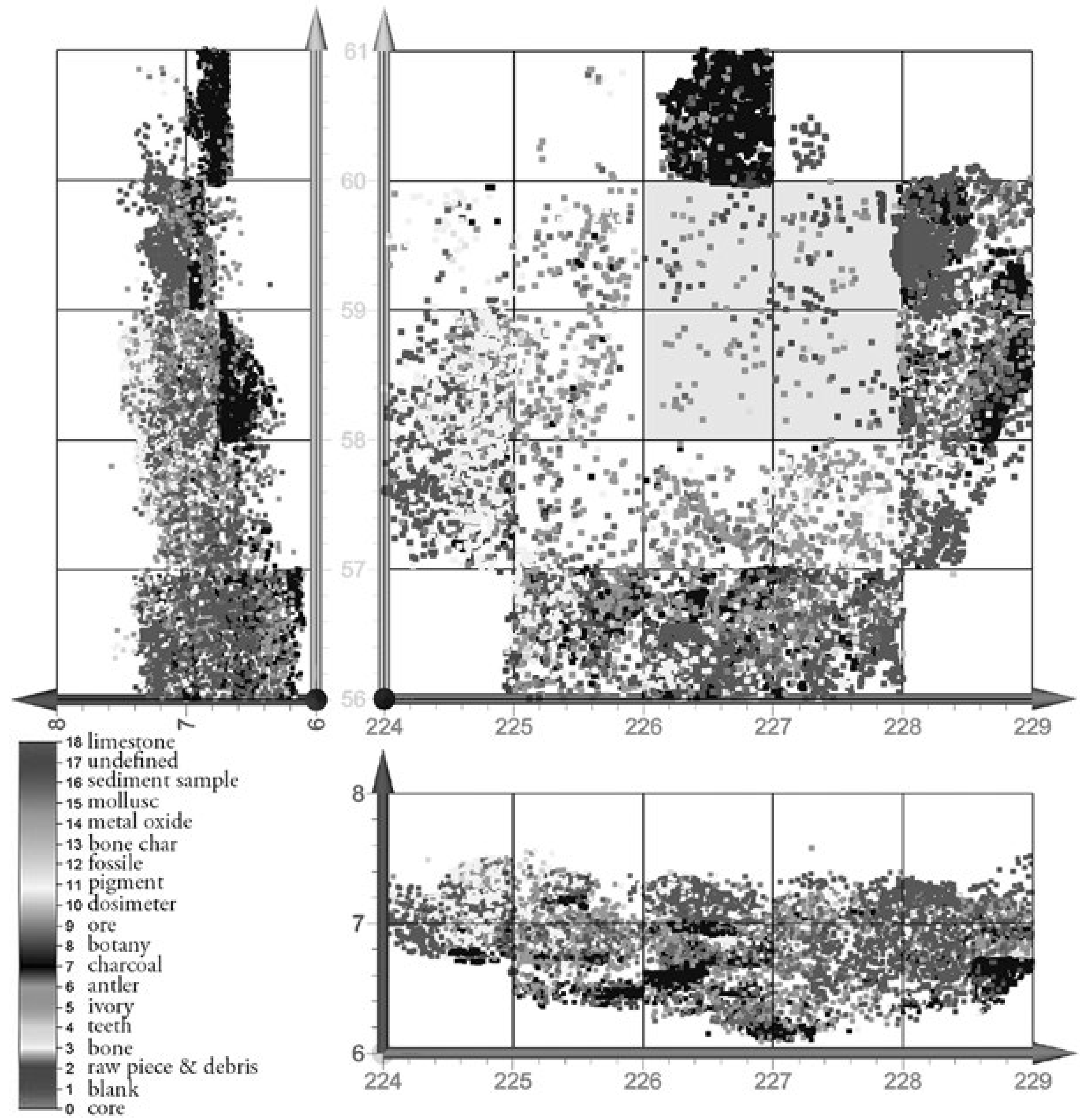


Fig. 4. Distribution of all find categories from GH 3 in top view (top right), view from east to west (top left) and south to north (bottom right). The grey-shaded square indicates the test pit from 2009, where mostly collective finds were measured.

each other (see Fig. 5 to 8 and 10), and the Voxler™ program calculated a surface (called an isosurface) that separated these two clusters from each other on the basis of points of a constant value within a volume of a three-dimensional space.

In the following section we describe the preliminary results of the spatial-distribution analysis of GH 3. As noted above, this layer is a geologically homogenous unit with minimal post-depositional disturbance, containing Middle Palaeolithic lithic artefacts and cold-weather fauna. By applying the analyses described above to a series of categorical pairs (ex: charcoal and limestone, lithic-objects and faunal-remains), we build a case for internal stratification within this homogenous sedimentary unit.

3 Results

Three-dimensional plots showing the spatial distribution of particular single-finds from GH 3 are presented in Figures 4 to 10. All three-dimensional plots are oriented in the same way (top left: view from east to west; top right: top view; bottom left: legend; bottom right: view from south to north).

The first clear separation of archaeological single-finds can be seen by plotting faunal material against lithic material (Fig. 5). Here, it can be seen that in the lower part of GH 3 the vast majority of artefacts are lithic objects. Faunal components can be found in the upper components of the layer, and primarily in

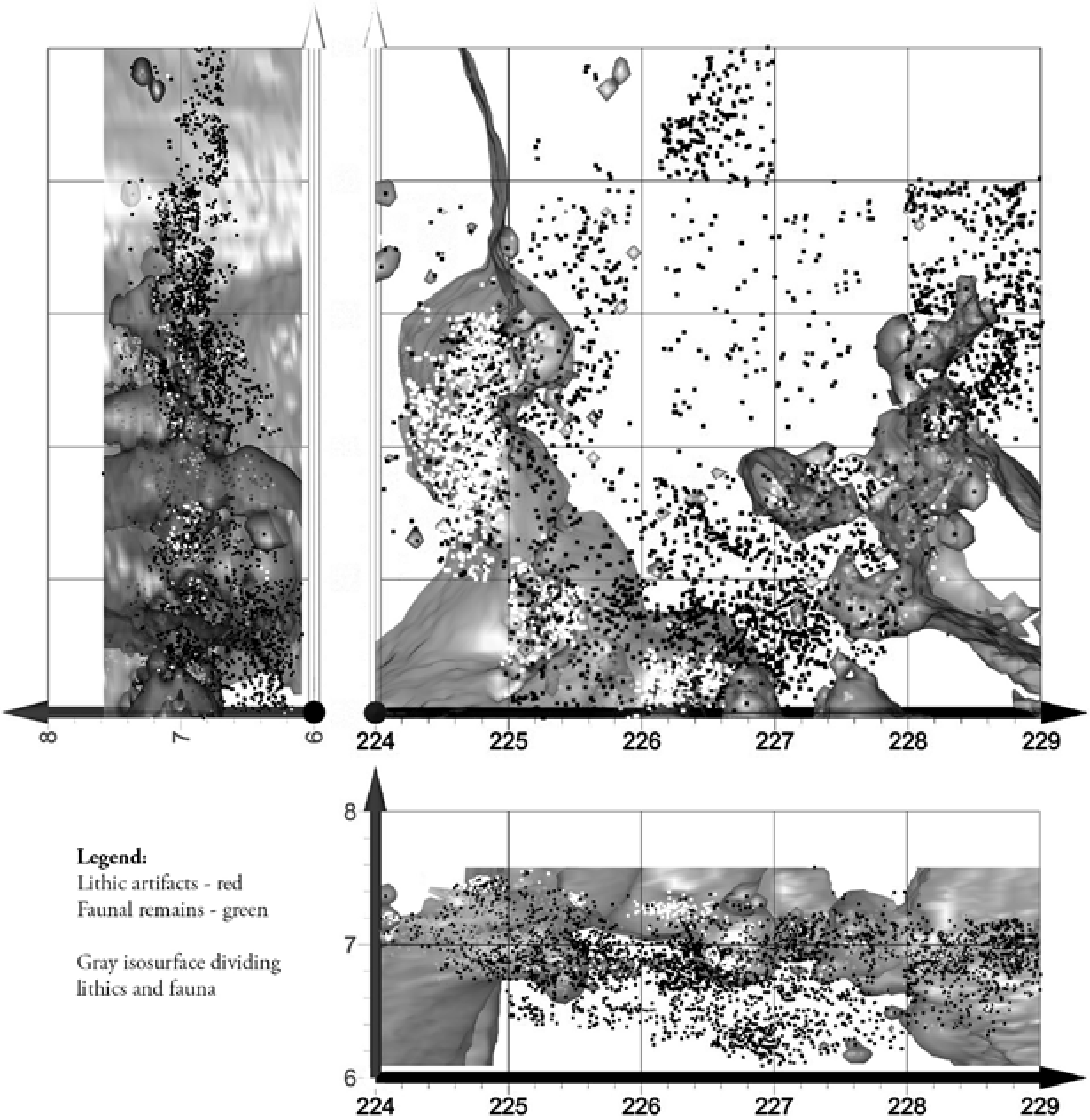


Fig. 5. Spatial distribution of lithic artefacts (Black dots) and faunal remains (white dots) inside GH 3. Grey isosurface shows the spatial division of these objects.

the western (and to a smaller extent the southern) zones of the excavation area.

The next case (Fig. 6) shows that limestone fragments and charcoals are also clearly three-dimensionally separated. In the upper parts of GH 3 many more limestone fragments are visible (mostly deriving from collapsed and dissolved blocks) than in the lower zones. The charcoal fragments are consistently clustered in distinct zones and in the lower parts of GH 3. This further suggests internal stratification within GH 3.

In the subsequent example (Fig. 7), the distribution of bones and teeth is displayed against that of charcoal fragments. Here the spatial separation of unburned faunal components and burned botanic/osseous(?) material is clearly visible.

We also examined whether a specific lithic component (Levallois elements) was spatially-clustered or not (Fig. 8). The Levallois elements derive here from single-finds and collective finds. As the Fig. 8 indicates there is little patterned distribution of these elements, aside from a restriction for the most part to the upper zones of GH 3.

This seems also to be the case for bifacial elements. Figure 9 shows the distribution of all lithic single-finds vs. the distribution of strictly bifacial elements (see Frick and Floss, in press).

The final example (Fig. 10) shows the spatial distribution of burnt/heated material (bones n=8, lithic objects n=200 and sediment n=69) plotted against the distribution of charcoal

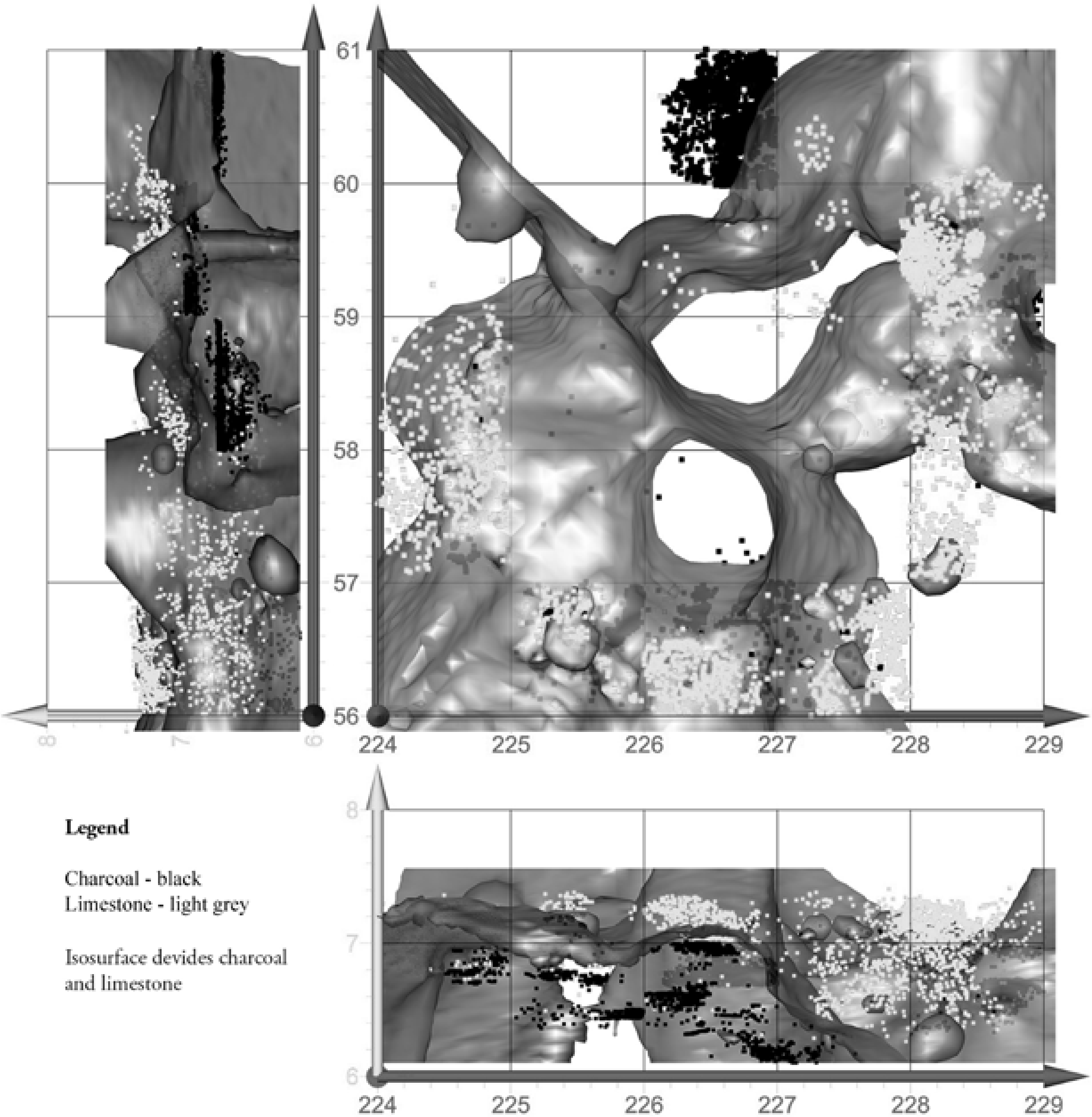


Fig. 6. Spatial distribution limestone and charcoal fragments inside GH 3. Isosurface divides them clearly.

fragments. Interestingly, the distributions of charcoal fragments and of other burned/heated material are mutually exclusive.

4 Discussion

The presented three-dimensional plots of find-categories from GH 3 indicate distinct patterns of distribution within an otherwise homogenous sedimentary matrix. If two find categories at the same time are plotted against each other and Voxler^{TM} calculates a surface, there are some clear visible gaps in the spatial distribution of artefacts. Indications derive here from fauna vs. lithic (Fig. 5), limestone vs. charcoal fragments (Fig. 6) and fauna vs. charcoal (Fig. 7) and botanic/osseous vs. burnt stone and sediments (Fig. 10). There are distinctive distribution patterns visible. By plotting artefacts from the same category (here: Levallois components and bifacial elements), this spatial distribution pattern is not visible. These artefacts seem to be erratic distributed (Fig. 9 and 8).

The spatial patterning of burnt material and charcoal fragments (Fig. 10) offers new insights into the processes that formed and affected GH 3. In the case of *in situ* fireplaces, we would expect all classes of burned material to be clustered (with the inclusion of ashes and rubified sediments).

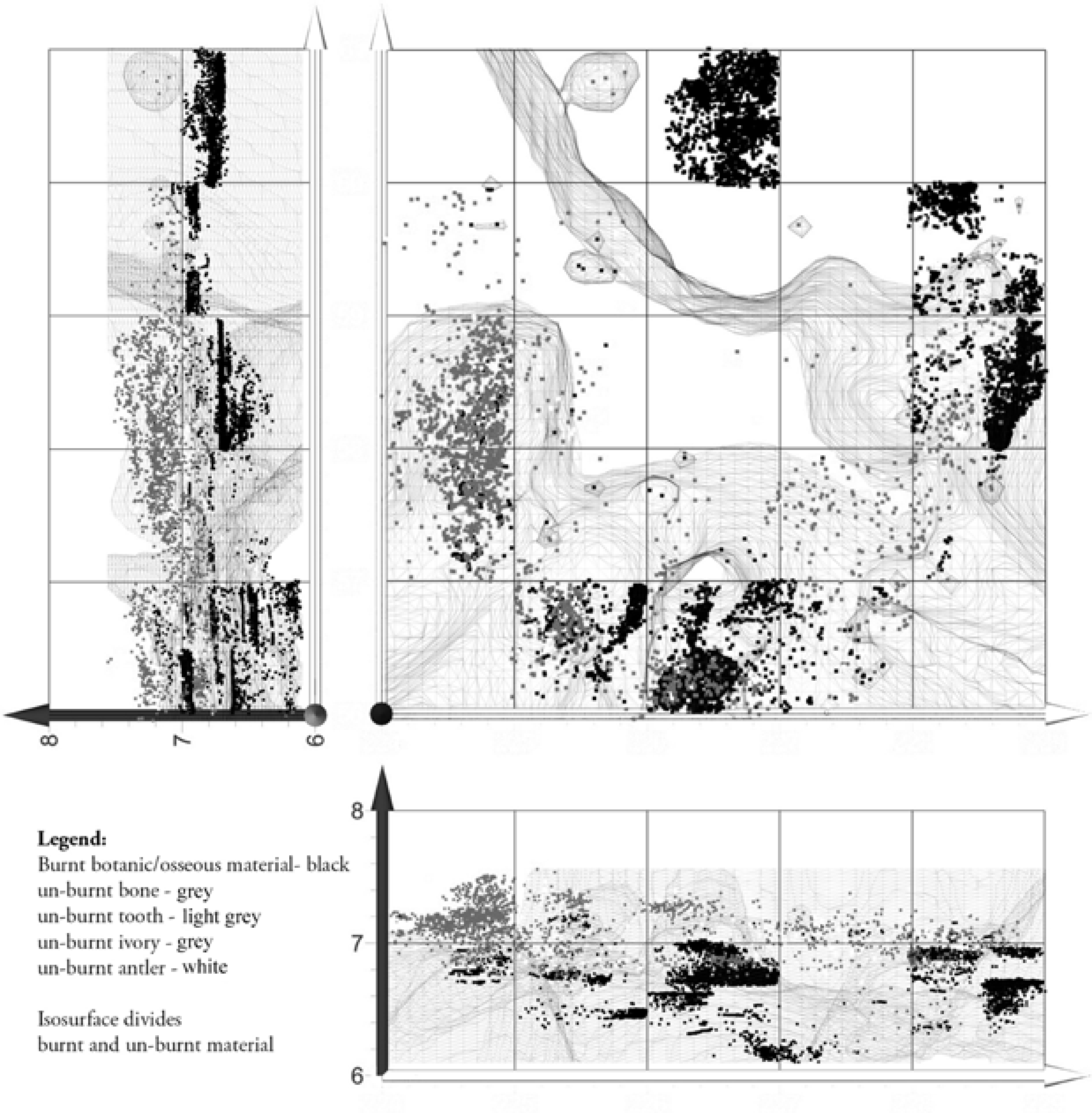


Fig. 7. Spatial distribution of un-burnt faunal remains (bones, teeth, ivory and antler) and burned botanic/osseous fragments. Isosurface divides them clearly.

What we observe in GH3 are horizontal lenses of the lighter components of burning events: smaller particles of charcoal and sometimes burnt bone. Our geomorphological and micromorphological observations (e.g. Wißing 2012) show that the sediment of GH 3 contains a major aeolian component, and GPR suggests that a large area of the Pleistocene rock shelter now lies under the collapsed shelter-roof in front of the excavated area. Based on these observations, we conclude that the lenses of charcoal/burnt-bone that we see in the plots shown above are the result of wind-transportation of these materials from hearths positioned to the northeast. The spatial distribution of the charcoal fragments also indicates, if it was transported and deposited by aeolian sedimentation, that the sedimentation was low-energetic, of close distance and quite homogenous. Evidence against causes of natural fire is indicated in the presence of more than 200 heat-altered lithic objects from GH 3.

A potential explanation for the mutually-exclusive distribution zones of charcoal and limestone-fragments (Fig. 6) could be that in times and places of charcoal sedimentation no limestone were deposited. This could easily be the case if we assume that the charcoal was deposited during and shortly after occupation events (cold to very cold climate) and the limestones were

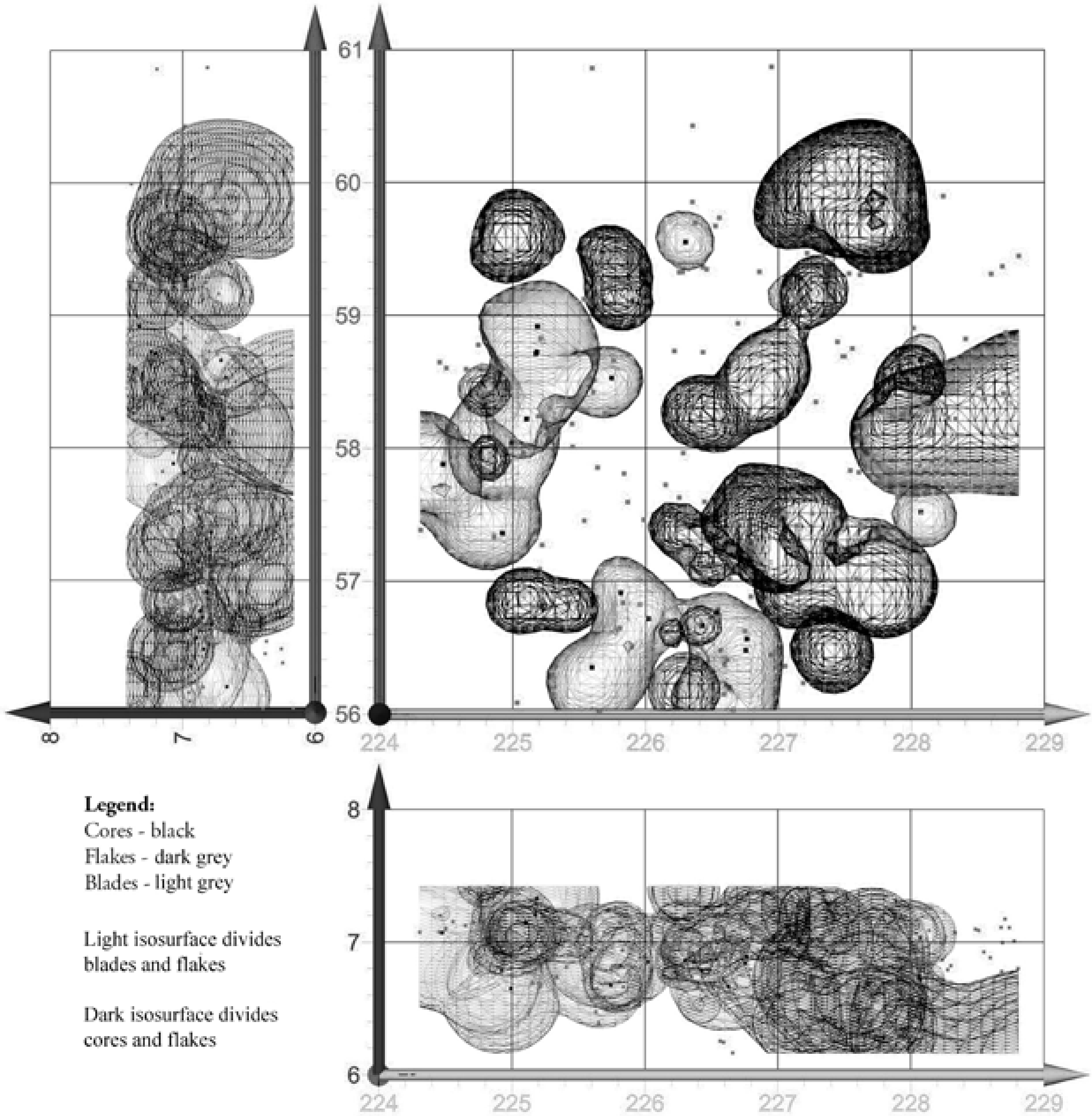


Fig. 8. Spatial distribution of Levallois elements inside GH 3. Spatial distribution and isosurfaces show no clear division between these elements.

deposited by rockfall events (defrosting during the beginning of warmer climates).

The accumulation of faunal components in the upper part of GH 3 and in the western part of the cave-tunnel could be explained by a phenomenon that can be detected in other cave sites, such as Kebara Cave (Speth *et al*. 2012) or Abric Romaní (Carbonell 2012). If we assume that the main occupation occurred under the rock shelter, the far interior of the shelter and the area of the cave tunnel make logical areas for toss-zones and rubbish dump, further from the active occupation area and less likely to attract carnivores.

At this juncture, refitted lithic objects (refitting sessions conducted in 2010 and 2013) do not provide much additional information. As can be seen in Fig. 11, some broken pieces lying next to each other could be identified and refitted. In general, refitted objects presenting reduction sequences are distributed horizontally, or at least in distinguishable layers. Only one thermal refit contradicts this picture (violet line in Fig. 11). If further refits support horizontal distribution patterns, we would expect that animal activities (or other bioturbation) account for this fact.

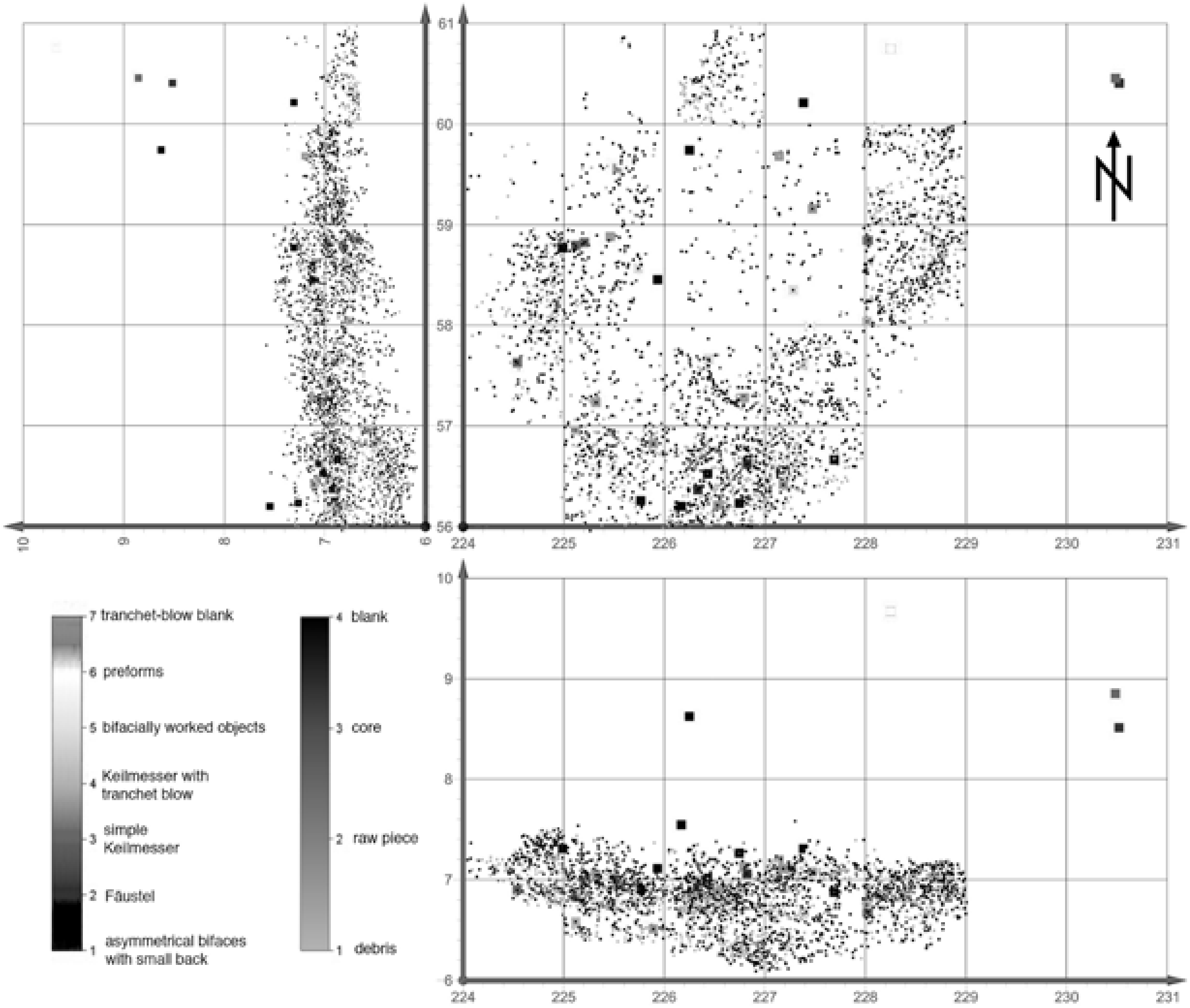


Fig. 9. Spatial distribution of bifacial elements inside GH 3. They are also randomly scattered in X and Y, only by height can they be attributed to the upper parts of GH 3 (see Frick and Floss, in press).

5 Conclusion

The primary research question driving this study is: Does GH3 represent a mixture of discarded materials from many occupation events, or can distinct stratigraphic units be identified within it in spite of its sedimentary homogeneity? At present, we cannot answer this question definitively. The visualisation of particular patterns of spatial distribution show that the archaeological material found in these layers is not thoroughly mixed, and that discrete patterns can be identified through the methods described above. At present, we are lacking important components of the archaeological record at VP II, and hope that continued excavation will provide a more complete picture.

Nonetheless, this paper demonstrates the utility of careful piece-plotting and of the mapping of isosurfaces within homogenous sedimentary units. If we take it that this scattered material is only minimally post-depositional altered in its position, as micromorphological and geomorphological observation indicate (Floss 2009; Wißing 2012), we could denominate these layers as a cumulative palimpsest (following Bailey 2007). Refining models of site use in the Middle Palaeolithic through these and related approaches has important implications for our understanding of Neanderthal behaviour at the local scale. One potential interpretation of the patterns suggested at VP II is one of repeated site use, frequently or seasonally, but without the systematic performance of the same tasks at the same places in the camp as has been demonstrated for example at extensively-used Magdalenian base camps like Pincevent (Bodu *et al.* 2006) or Gönnersdorf (Bosinski 1979). Archaeological sites like Abric Romaní (e.g. Carbonell 2012) demonstrate that clear, visible occupation structures can be detected by meticulous, long-term, and interdisciplinary studies. Reasearch at VP II is ongoing, and the study presented here is one component of a project that aims to add substantially to current knowledge about Neanderthal behaviour, including landscape-use, subsistence, and technology, in Eastern France.

Grotte de la Verpillière I and II are important sites in the Palaeolithic landscape of southern Burgundy containing hundreds of sites, which is otherwise mostly composed of un-

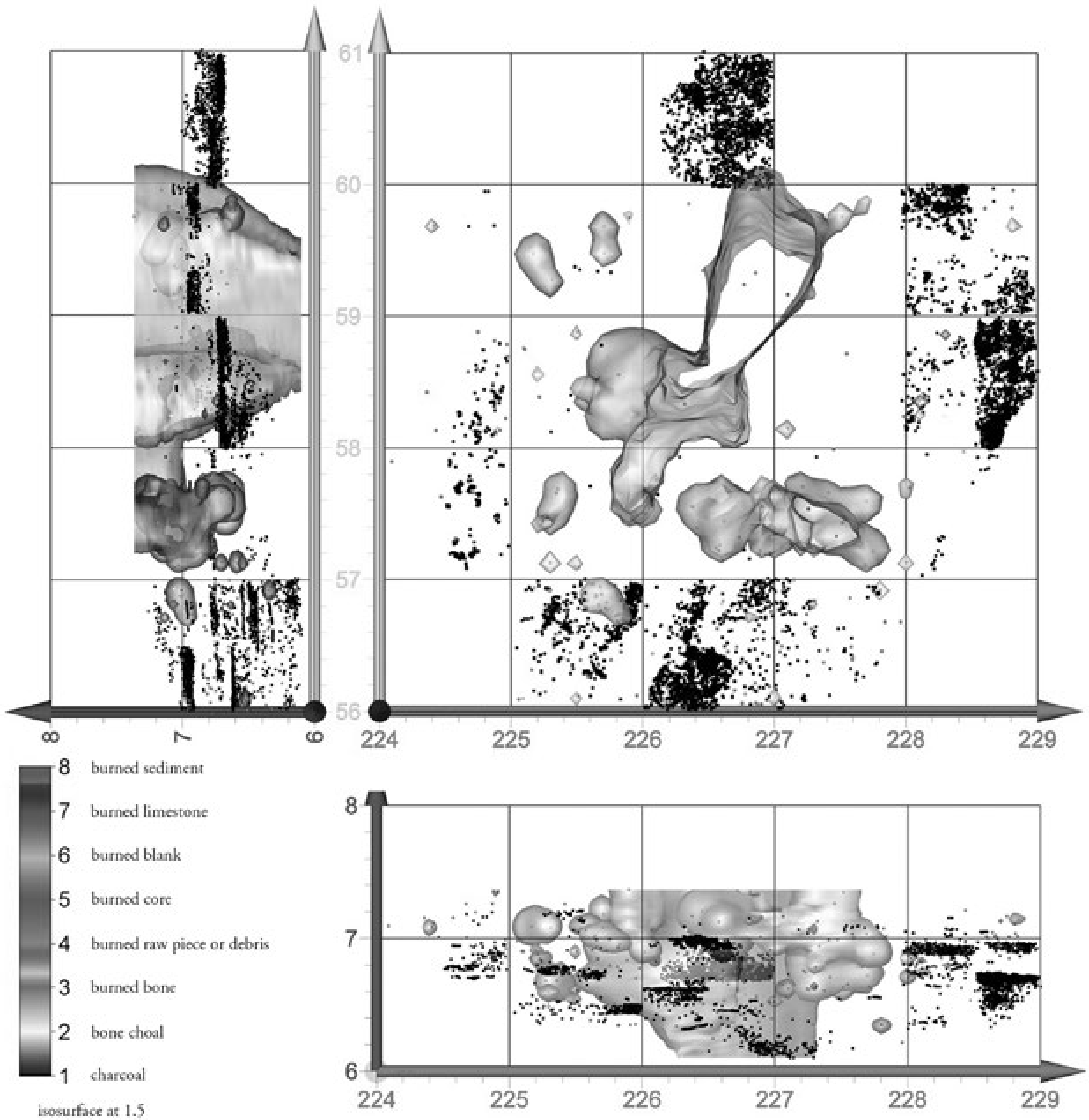


Fig. 10. Spatial distribution of all burned material. Interestingly, the distribution of charcoal fragments does not correspond to the distribution of the other burned materials.

excavated open-air sites (surface collections) or sites that were excavated prior to modern excavation techniques. In a radius of 50 km, these sites are the only high-resolution sources for the study of Late Middle Palaeolithic and early Upper Palaeolithic occupations of this region (Frick and Floss 2015). The data that comes out of continued excavation at VP II has potential to provide regionally-specific insight into Neanderthal behaviour and site-use.

Acknowledgments

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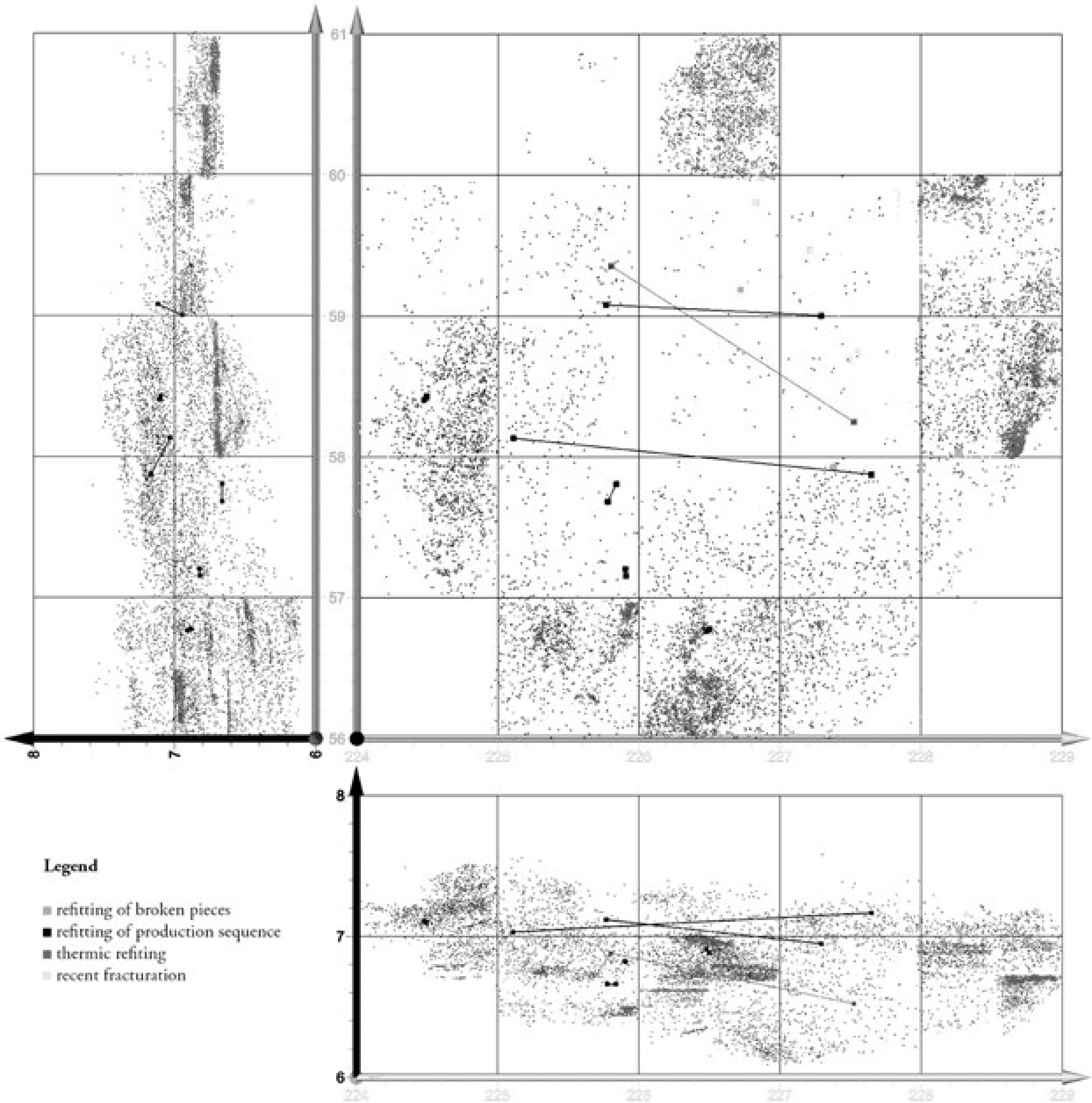

Fig. 11. Refitted lithic objects from sessions conducted in 2010 and 2013. The refits (depicting production sequence) indicate the option of layers inside the sediments. Note the single thermic refit that contradicts this picture. Smaller dots display the total single find distribution of GH 3, GH 4x and GH 4.

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Bibliography

Bailey, G. N. 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26, 2: 198-223.

Bodu, P., Julien, M., Valentin, B., Debout, G., Averbouh, A., Bemilli, C., Beyries, S., Bignon, O., Dumarçay, G., and Enloe, J. G. 2006. Un dernier hiver à Pincevent: Les Magdaléniens du niveau IVO (Pincevent, La Grande-Paroisse, Saine-et-Marne). *Gallia Préhistoire* 48: 1-180.

Bons, P., and Wissing, C. 2009. Aspects of local geological structure in connection with the palaeolithic cave site in Germolles (Commune de Mellecey, France). In H. Floss (ed.), *Rapport de fouille programmée. Lieu-dit: Les Grottes de La Verpillière I et II à Germolles*. S.R.A. Dijon and Abteilung für Ältere Urgeschichte und Quartärökologie: 1-11. Tübingen, Dijon.

Bosinski, G. 1979. *Die Ausgrabungen in Gönnersdorf 1968-1976 und die Siedlungsbefunde der Grabung 1968*. Wiesbaden, F. Steiner.

Cailhol, D. 2014. Étude du karst de la région de Mellecey (Saône et Loire). In H. Floss, C. T. Hoyer, J. A. Frick, K. Herkert (eds.), *Project Collective du Recherche: Le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuelle 2014*. Abteilung für Ältere Urgeschichte und Quartärökologie, Tübingen S.R.A. Dijon, Tübingen Dijon: 156-71.

Carbonell, E. 2012. *High resolution archaeology and Neanderthal behavior: time and space in level J of Abric Romaní (Capellades, Spain)*. Springer, New York.

Coolidge, F. L., Wynn, T. 2005. Working memory, its executive functions, and the emergence of modern thinking. *Cambridge archaeological journal* 15 1: 5-26.

Dibble, H. L., Mcpherron, S. P. 1996. *A Multimedia Companion to The Middle Palaeolithic Site of Combe-Capelle Bas (France)*. Philadelphia, University of Pennsylvania Museum.

Floss, H. 2009. *Rapport de fouille programmée. Les Grottes de La Verpillière I et II à Germolles*. Sérvice Régional d'Archéologie, Dijon and Abteilung für Ältere Urgeschichte, Universität Tübingen, Dijon and Tübingen.

Frick, J. A. 2014. Les travaux à la Grotte de la Verpillière II en 2014. In H. Floss, C. T. Hoyer, J. A. Frick, K. Herkert (eds.), *Project Collective de Recherche: Le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuel 2014*. Abteilung Ältere Urgeschichte und Quartärökologie, Tübingen: 99-155.

Frick, J. A., and Floss, H. 2015. Grotte de la Verpillière II, a Late Middle Palaeolithic reference site in southern Burgundy. In A. Maier (ed.), *57th Annual Meeting of the Hugo Obermaier Society. Heidenheim, 7-11 April 2015*: 34-5.

Frick, J. A. and Floss, H. (in press). Analysis of bifacial elements from Grottes de la Verpillière I and II, Germolles, Burgundy, France. *Quaternary International*. Available at: http://dx.doi.org/10.1016/j.quaint.2015.10.090

Frick, J. A. and Floss, H. 2015. Grotte de la Verpillière II, Germolles, France: Preliminary insights from a new Middle Palaeolithic site in southern Burgundy. In S. Sázelová, M. Novak and A. Mizerova (eds.). *Forgotten Times, Spaces and Lifestyles*, Masaryk University: 53-72. Brno.

Frick, J. A. and Hoyer, C. T. 2009. *Grabungs- und Dokumentationshandbuch für Germolles 2009*. Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Tübingen.

Frick, J. A. and Hoyer, C. T. 2011. *Grabungs- und Dokumentationshandbuch für die Grabung Germolles 2011*. Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Tübingen.

Frick, J. A. and Hoyer, C. T. 2012. *Handbuch zur Grabung Germolles 2012. Handbook of the excavation*. Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Tübingen.

Frick, J. A., Hoyer, C. T., Heckel, C.E., Herkert, K., Floss, H. 2013. *Handbuch zu Ausgrabung 2013. Handbook of the Excavation 2013*. Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Tübingen.

Frick, J. A., Hoyer, C. T., Herkert, K., Floss, H. 2012. Comparative heating experiments on flint from the Côte Chalonnaise, Burgundy, France. *Anthropologie (Brno)* 50, 3: 295-321.

Jarvis, A., Reuter, H. I., Nelson, A. J., Guevara, E. 2008. *Hole-filled seamless SRTM data V4*. International Centre for Tropical Agriculture (CIAT). Avalable at: http://srtm.csi.cgiar.org. [Accessed: 22 June 2015].

Leach, P. A. 2014. Ground-Penetrating Radar Investigation at Archaeological Sites in Fuissé, Mellecey, and Saint-Martin-sous-Montaigu, France. In H. Floss, C. T. Hoyer, Frick, J. A., Herkert, K. (eds.), *Projet Collectif de Recherche: Le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuel 2014*. Sérvice Régional d'Archéologie, Dijon and Abteilung für Ältere Urgeschichte, Universität Tübingen, Dijon and Tübingen: 182-201.

Leach, P. A. and Miller, C. 2009. Ground-Penetrating Radar investigation of cave Verpillière II, Germolles, France. In Floss, H. (ed.), *Rapport de fouille programmée. Lieu-dit: Les Grotte de La Verpillière I et II à Germolles*. S.R.A. Dijon and Abteilung für Ältere Urgeschichte und Quartärökologie, Tübingen, Dijon and Tübingen: 1-15.

Mcpherron, S. P. 2005. Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32, 7: 1003-14.

Münzel, S. C. 2014. Die Fauna aus der Verpillière II, GH 4. In H. Floss, C. T. Hoyer, J. A. Frick, K. Herkert (eds.), *Projet Collectif de Recherche: Le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuel 2014*. Sérvice Régional d'Archéologie, Dijon and Abteilung für Ältere Urgeschichte, Universität Tübingen, Dijon and Tübingen: 225-32.

Siegeris, M. 2014. Report about the fieldwork in Southern Burgundy, 2014. In: Floss, H., Hoyer, Ch. Th., Frick, J. A. and Herkert, K. (eds.), *Project Collective de Recherche: le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuel 2014*. Abteilung Ältere Urgeschichte und Quartärökologie, Tübingen: 244-54.

Speth, J. D., Meignen, L., Bar-Yosef, O., Goldberg, P. 2012. Spatial organization of Middle Palaeolithic occupation X in Kebara Cave (Israel): Concentrations of animal bones. *Quaternary International* 247: 85-102.

Verpoorte, A. 2006. Neanderthal energetics and spatial behaviour. *Before Farming* 2006, 3: 1-6.

Wilk, A. 2014. Détermination ostéologique et évaluation archéozoologique des vestiges fauniques des Grottes de la Verpillière à Germolles. In H. Floss, C. T. Hoyer, J. A. Frick, K. Herkert (eds.), *Les Grottes de la Verpillière à Germolles, commune de Mellecey (Saône-et-Loire). Fouille programmée pluriannuelle 2013-2015. Rapport intermédiaire 2013*. Sérvice Régional d'Archéologie, Dijon and Abteilung für Ältere Urgeschichte, Universität Tübingen, Dijon and Tübingen: 107-13.

Wilk, A. 2014. Die Tierknochenfunde aus Germolles, Grottes de la Verpillière. Archäozoologische Bestimmung. In H. Floss, C. T. Hoyer, J. A. Frick, K. Herkert (eds.), *Projet Collectif de Recherche: Le Paléolithique supérieur ancien en Bourgogne méridionale. Genèse, chronologie et structuration interne,* évolution *culturelle et technologique. Rapport annuel 2014*. Sérvice Régional d'Archéologie, Dijon and Abteilung für Ältere Urgeschichte, Universität Tübingen, Dijon and Tübingen: 214-24.

Wissing, C. 2012. *Geoarchäologische Untersuchungen in Germolles. Strukturgeologische, paläontologische und mikromorphologische Untersuchungen des Fundstellenkomplexes der Verpillière Höhlen und deren Umfeld in Germolles, Commune de Mellecey, Saône-et-Loire (71), Frankreich*. Abteilung für Ältere Urgeschichte und Quartärökologie, Magister's thesis. Eberhard Karls Universität Tübingen.
Wynn, T., Coolidge, F. L. 2004. The expert Neanderthal mind. *Journal of Human Evolution* 46: 467-87.
Wynn, T., Coolidge, F. L. 2012. *How to think like a Neanderthal*. Oxford, Oxford University Press.

A New Palaeolithic Burial From Grotta Del Romito (Calabria, Italy). A Digital Restitution

Francesco Enrico Ortisi[1]
ortisienrico@hotmail.com

Domenico Lo Vetro[1, 2]
dlovetro@unifi.it

Giovanna Pizziolo[3]
pizziolo@unisi.it

Michele De Silva[1]
mdesilva@unifi.it

Claudia Striuli[1]
claudia.striuli@gmail.com

Pier Francesco Fabbri[4]
pierfrancesco.fabbri@unisalento.it

Fabio Martini[1, 2]
fmartini@unifi.it

[1] Università degli Studi di Firenze, Dipartimento di Storia, Archeologia, Geografia, Arte, Spettacolo (SAGAS), Firenze, Italy
[2] Museo e Istituto Fiorentino di Preistoria, Firenze, Italy
[3] Università degli Studi di Siena, Dipartimento di Scienze Storiche e dei Beni Culturali, Siena, Italy
[4] Università del Salento, Dipartimento di Beni Culturali, Lecce, Italy

Abstract: The latest research carried out in Grotta del Romito, a Palaeolithic site located in northern Calabria, has brought to light a new Palaeolithic burial (Romito 9). The complexity of this archaeological evidence, also affected by a disturbance to the burial pit that altered the deposition's context ab antiquo*, has required a suitable strategy of excavation and documentation for the funerary context in order to read the taphonomic and post-depositional processes. The creation of a visual model representing the funerary evidence in a CAD environment has led to the virtual reproduction of the original archaeological context. This model, based on the processing of a very detailed graphic and photogrammetric documentation and linked to a database, provided an effective support to the interpretations and has allowed us to better investigate the deposition context and the subsequent events connected to the breach of the burial.*

Keywords: Late Upper Palaeolithic, Burials, CAD, Digital model.

Introduction: the burial context

Grotta del Romito (Papasidero, Northern Calabria), with its rare examples of rock art and multiple burials, is one of the most significant Palaeolithic sites on the Italian peninsula (Martini and Lo Vetro 2011) (Figs. 1 and 2). The cave was occupied almost uninterruptedly during the Upper Palaeolithic from ca. 24,000 to 10,000 BP, until the Early Mesolithic (9,000 BP c.a.). A further frequentation of the cave is attested by scarce remains which refer to the Middle Neolithic. The latest research (since 2000) carried out at the site by the University of Florence, led to the discovery of the 9th Palaeolithic burial (Romito 9).

'Romito 9', dating back about 17,000 years uncal. BP (Evolved Epigravettian), is the oldest among nine burials found at the site (Craig *et al*. 2010; Martini 2006; Martini and Lo Vetro 2011). It belongs to a young individual laid supine, with the legs slightly bent, on a red ochre bed and endowed with rich ornamentation. This ornamentation comprises thousands of artefacts including a hundred pierced red deer (*Cervus elaphus*) atrophic canines and almost 1500 pierced marine molluscs shells (*Cyclope neritea*). The violation of the burial, which disturbed the original deposition about 1000 years after, caused considerable displacement of some of the osteological and ornamental materials which were found at a higher height than the original surface of the deposition.

The complexity of this archaeological evidence, compounded by the fact that it was also disturbed *ab antiquo* necessitated the adoption of appropriate excavation and documentation strategies in order to better understand the taphonomic and post-depositional processes.

1 Aims and goals

In this perspective our main goal is to obtain accurate information related to the burial evidence which allows one to visualise and manage the single data as part of a consistent

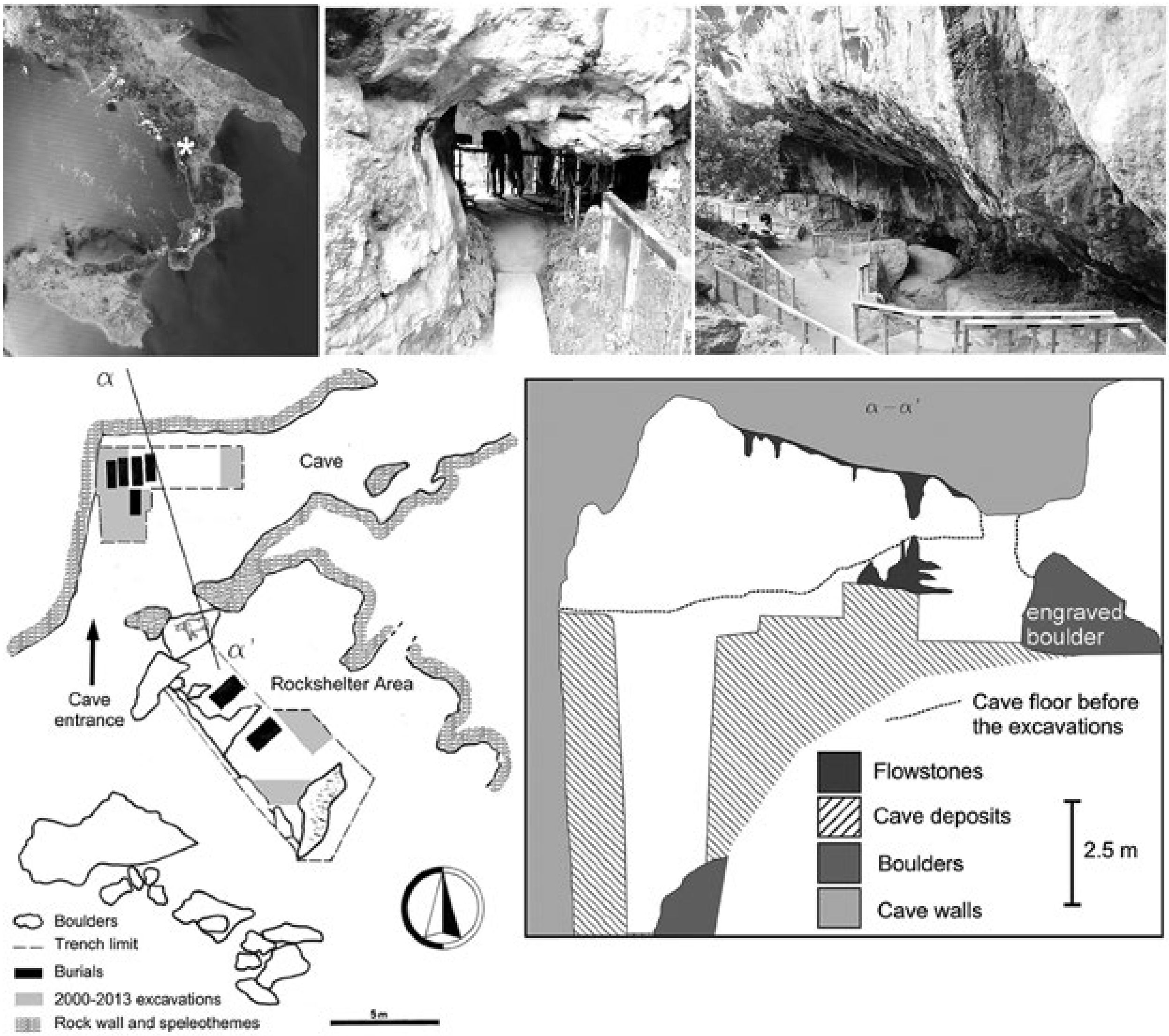

Fig. 1. Location maps, views, plan and cross-section of the site.

whole context. The vector dataset may provide the geometrical, stratigraphical and topological information that may be linked to further anthropological and archaeological data and consequently utilised to perform taphonomic interpretation. The building up of a visual model in CAD environment may satisfy our needs included the possibility to record 3D data. At this stage our aim is directed to acquire and elaborate the information related to Romito 9 burial in order to reproduce in a virtual and dynamic environment or through a visual model (Frisher *et al*. 2002; Viti 2006) the archaeological evidence discovered during the excavation.

We have chosen to perform vector acquisition through CAD, which allows us to manage easily 3D data. Furthermore, due to logistic and spatial characteristics of the burial excavation we have recorded archaeological data taking advantage of photogrammetric approach. Among different technological options, we have chosen a solution composed of different applications which may fit different needs as data capture, logistic constraints and geometrical validation. The technology used does not in itself represent a new method but, in our view, it is interesting to apply it in a disturbed burial prehistoric context in order to provide information useful and handily to perform the reconstruction of the burial and of its post depositional processes. The building up of this visual elaboration has been subsequently included in the wider general model of the cave in which the archaeological information derived by traditional drawings and maps, photogrammetry and laser scanner data are overlaid, compared and elaborated within a GIS framework.

2 Methods

Due to excavation characteristics related to burial evidence, logistic constraints related to cave environment, and the need to have detailed information of the burial context, we can move from a traditional documentation process towards a system based on photogrammetric data.

As we have already mentioned, in order to provide a general overview of the Romito 9 burial, a visual model of the funerary evidence within a vector CAD environment (Ortisi 2012) was created.

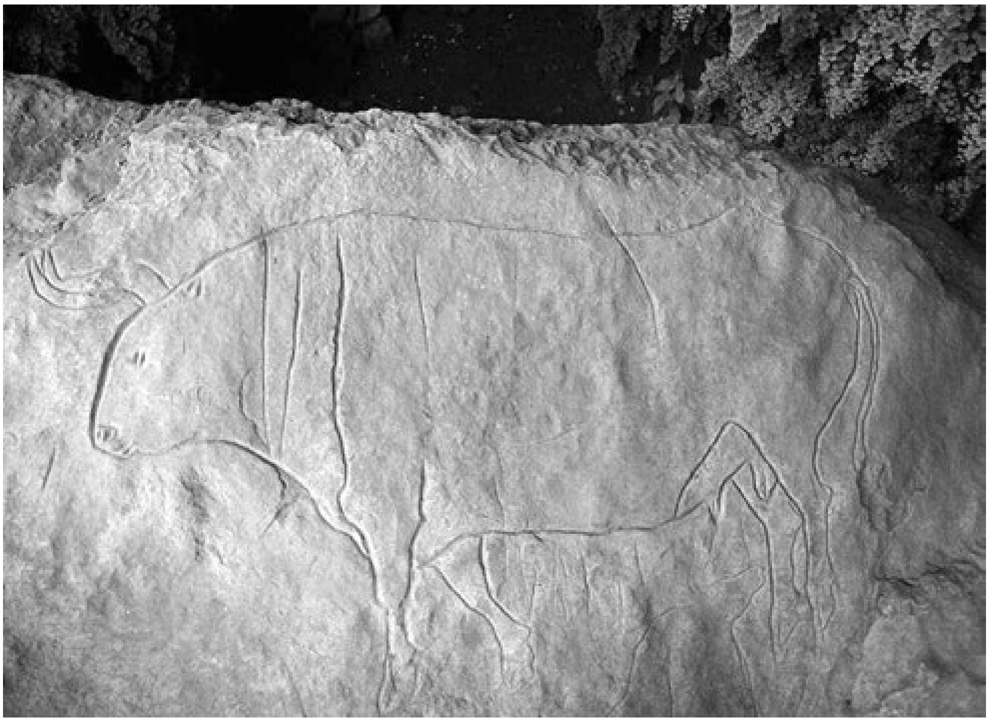

Fig. 2. The *Bos Primigenius* engraved on a large rock in the rock shelter.

The building up of the model has been organised through various preparatory stages and for each one of these specific software was used. In order to correct optical flaws in the photographs (pincushion or barrel distortion), the shareware software Nikon Capture NX was used, which thus contributed to adapt raster images before the perspective rectification process. The properly processed images have been adjusted for perspective issues. This technique involved approximately 80 selected photographs. During this stage we have used Perspective Rectifier, Italian shareware software produced by Rectifier Soft.

The last step before vectorization was the creation of the photomaps (Fig. 3). The patchwork of multiple frames has been processed separately and then merged together, according to checkpoints or common areas (Mascione 2007). The realization of the photomap, 1:1 scale, was performed using Adobe Photoshop CS5, which helped normalize the colour properties of each frame; then AutoCAD 2010 allowed merging with the object snap function. The new raster images, the photomaps, already scaled and rectified, were produced in both formats .tiff and .jpeg. These represented the basis for the vectorization process.

The vectorization process was performed using AutoCAD 2010, with the visual model output file is suffixed .dwg. Every feature is positioned in x, y, z coordinates, recorded also on traditional maps. In several cases, as for long bones, features are recorded through the acquisition of several height point values which allowed three-dimensional management.

The model consists in a series of layers, each one related to a group of archaeological data (Fig. 4). Osteological elements, molluscs and atrophic canines were grouped depending on their spatial location within the burial pit: i.e. the primary position remains; the slightly dislocated remains; and the strongly dislocated remains. This distinction determined the development of the three vector layers for each of these remains (skeletal parts, molluscs, red deer canines):

- a first vector layer related to the items *in situ* which have therefore not been involved in the disturbance of the burial pit.
- a second vector layer related to the slightly dislocated remains which were not in their original position due to several post-depositional processes or because of the disturbance to the grave.
- a third vector layer related to the strongly dislocated remains due to the grave post-depositional processes.

3 Discussion and Preliminary Results

As a general result, the visual model allowed us to perceive the burial context and its spatial relationship. During the excavation, the original position of the skeleton could not be assessed in its entirety owing to the major dislocation of many of the bones. The observation of bones and archaeological features in a 3D environment allowed us to observe the main changes that occurred (Fig. 5), enhancing the features dislocated as well as the empty areas within the burial pit. Further questions may arise through the observation of thematic layers which refer also to the degree of dislocation of the features. From this visual analysis a first preliminary elaboration of the possible original position of the skeleton has been attempted (Fig. 6).

Moreover, the position of several of the red deer canines has been enhanced; these were found grouped in the primary deposition, in close proximity to the upper arms, indicating

Fig. 3. Romito 9 photomap.

that these items refer to bracelets placed on or near the wrists and forearms.

The visual model also enabled a representation of the quantitative distribution of the ornaments. About 1500 pierced marine molluscs shells (*Cyclope neritea*), in both the primary and secondary positions were found (Fig. 7). Through the distribution model obtained by this quantitative analysis it was possible to observe that the pierced shells probably adorned a sort of blanket (probably leather or fur) covering the individual from the abdomen to the feet.

This visual model is a very useful tool for the interpretation and better understanding of the original deposition of the individual and the subsequent events related to the violation of the burial.

4 Conclusions

The creation of a visual model representing the funerary evidence in a CAD vector environment has led to the virtual reproduction of the original archaeological context. This model, based on the processing of very detailed graphic and photogrammetric documentation and linked to a database, provided an effective support for the interpretations and has assisted the reconstruction of the depositional context and the subsequent events that disturbed the burial. The vector model has also enabled the quantitative distribution of the pierced *Cyclope neritea* shells found both in primary and secondary positions, perhaps relating to a hypothetical robe or blanket. On the basis of this visual model a specific taphonomic study is well underway.

Bibliography

Craig, O. E., Biazzo, M., Colonese, A. C., Di Giuseppe, Z., Martinez-Labarga, C., Lo Vetro, D., Lelli, R., Martini, F., Rickards, O. 2010. Stable isotope analysis of Late Upper Palaeolithic human and faunal remains from Grotta del Romito (Cosenza), Italy. *Journal of Archaeological Science* 37, October 2010: 2504-12.

Lo Vetro, D., Martini, F. (eds.) 2011. *Grotta del Romito a Papasidero – Uomo, ambiente e culture nel Paleolitico della Calabria (ricerche 1966 – 2011)*. Cosenza, Editoriale Progetto 2000.

Martini, F. 2006. Le evidenze funerarie nella Grotta e nel Riparo del Romito (Papasidero, Cosenza). In F. Martini (eds.), *La cultura del morire nelle società preistoriche e protostoriche italiane. Studio interdisciplinare dei dati e loro trattamento informatico*, *Origines* 1, Firenze, Istituto Italiano di Preistoria e Protostoria.

Mascione, C. 2007. *Il rilievo strumentale in archeologia*. Roma, Carocci.

Ortisi, F. E. 2012. *Romito 9: lettura di un'evidenza funeraria del Paleolitico Superiore mediante applicazioni fotogrammetriche e CAD*. Unpublished Master's degree dissertation thesis, Università degli Studi di Firenze.

Viti, S. 2006. Modelli visuali e riproduzioni tridimensionali di evidenze funerarie della preistoria italiana. I casi studio di Romito 7 (Paleolitico Superiore) e di Pontecagnano Tomba 6517 (Eneolitico). In F. Martini (ed.), *La cultura del morire nelle società preistoriche e protostoriche italiane. Studio interdisciplinare dei dati e loro trattamento informatico*, *Origines* 1, Istituto Italiano di Preistoria e Protostoria: 347-62. Firenze.

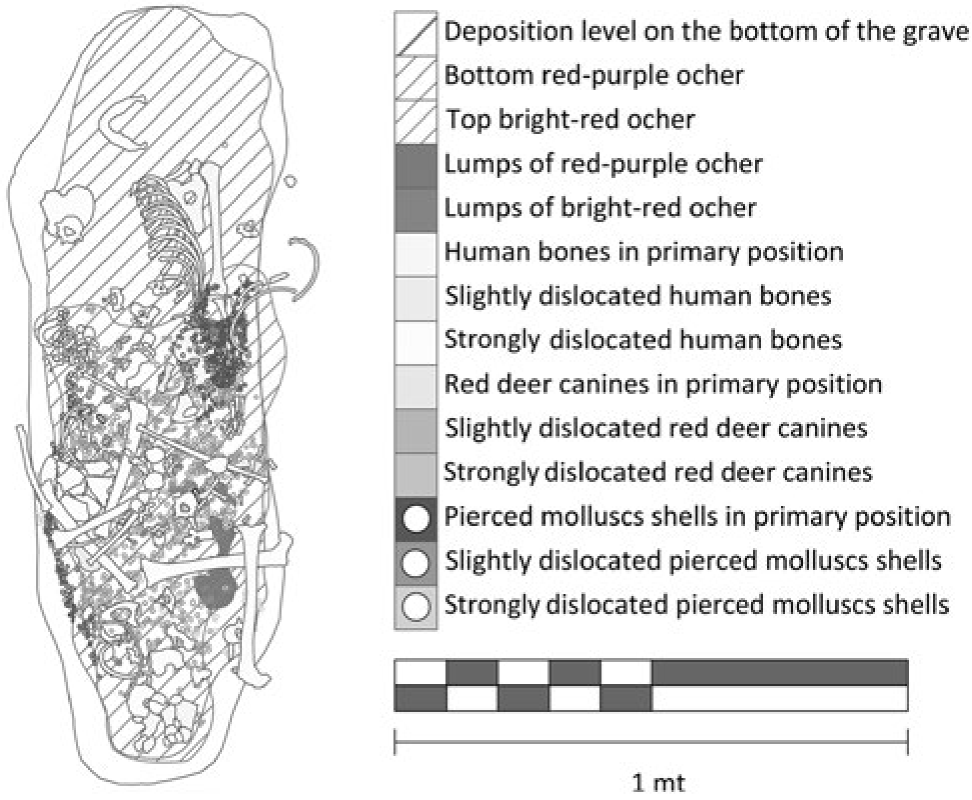

FIG. 4. THE VECTOR MODEL OF THE EVIDENCE DISTRIBUTION INSIDE THE GRAVE. TOP VIEW.

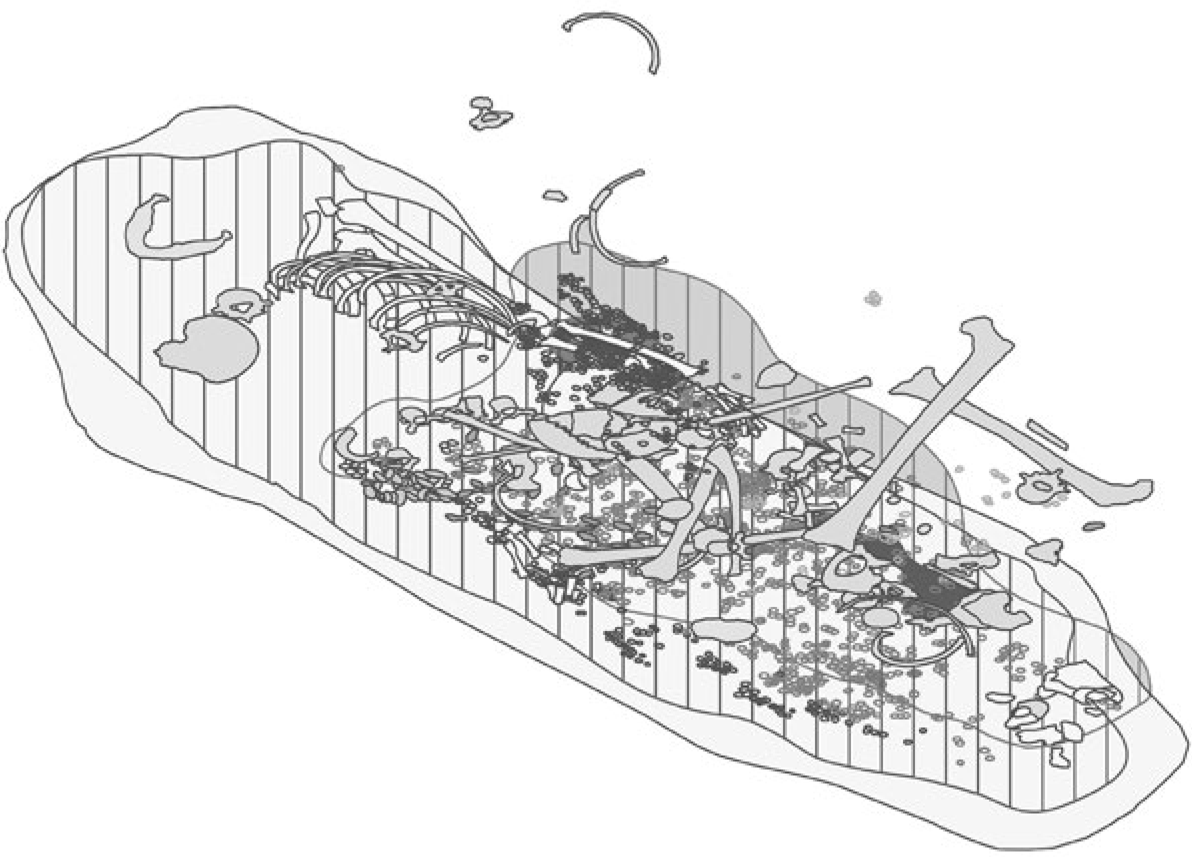

FIG. 5. THE VECTOR MODEL OF THE EVIDENCE DISTRIBUTION INSIDE THE GRAVE. AXONOMETRIC VIEW.

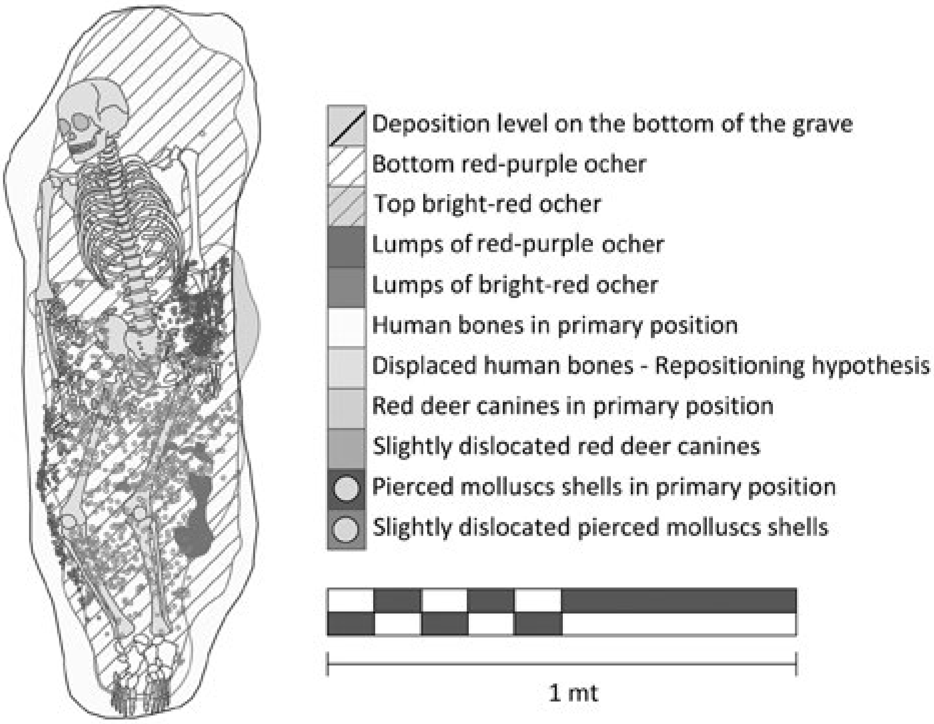

Fig. 6. Hypothetical reconstruction of the original location of the skeletal remains.

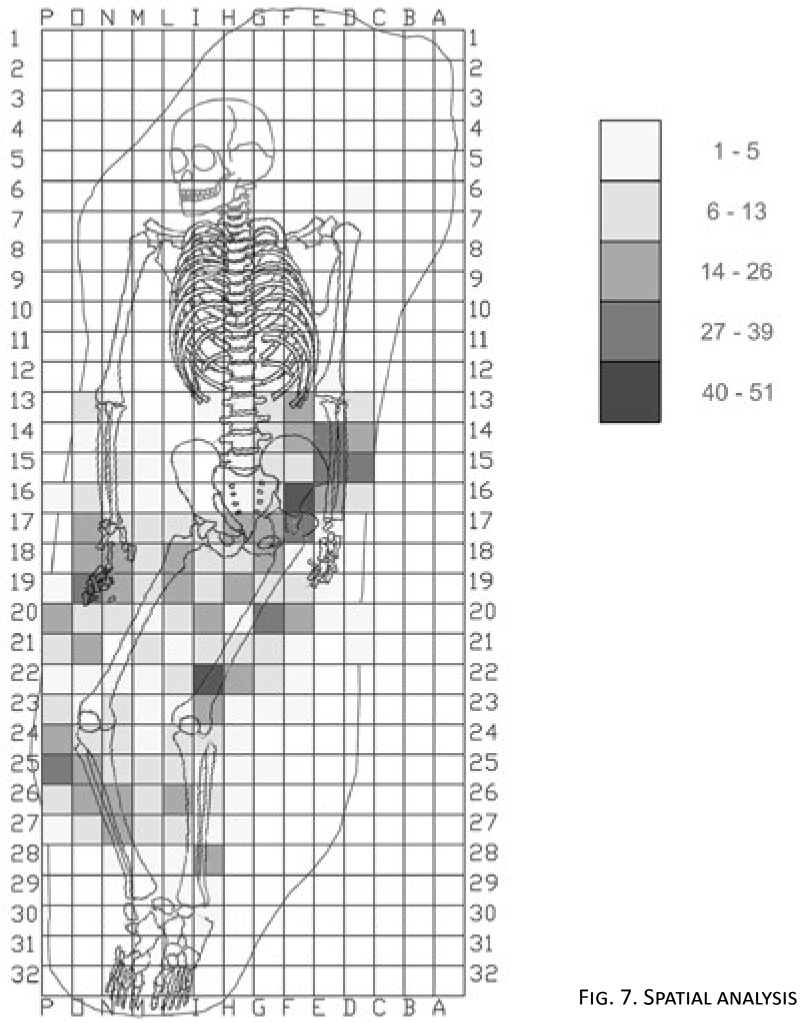

Fig. 7. Spatial analysis of the mollusc distribution.

Frisher, B., Niccolucci, F., Ryan N. S., Barceló, J. A. (2002) From CVR to CVRO: the Past, Present and Future of Cultural Virtual Reality. In Niccolucci F. (ed.), Virtual Archaeology, Proceedings of the VAST Euroconference, Arezzo, 24-25 November 2000. British Archaeological Reports International Series 1075: 7-18. Oxford, Archaeopress.

Predicting the Accumulative Consequences of Abandonment Processes.
Intra-site Analysis of Lakeside Settlements

Katia Francesca Achino(1)
katiafrancesca.achino@uab.cat

Juan Antonio Barceló(1)

Micaela Angle(2)

1 Quantitative Archaeology Lab, Department of Prehistory,
Autonomous University of Barcelona, Spain.
2 Soprintendenza Archeologica del Lazio e dell'Etruria Meridionale, Roma, Italy.

Abstract: Over the past thirty years, predictive models have been mainly applied to inter-site scale (macro level) spatial analysis, in order to detect the archaeological sites' location and to predict the probability of presence of remains in non-surveyed areas. We believe that archaeologists can take full advantage of these statistical methods in an intra-site perspective (micro level) spatial analysis. In this paper we suggest how to predict the spatiality of the abandonment and post-depositional processes in the case of Villaggio delle Macine (Rome-Italy), using a geostatistical approach. This pile dwelling was discovered below the water-level of the lake in 1984. Recently, a progressive lake's water drop due to climatic factors and uncontrolled water-takings led to the partial emersion of the site. The data presented referred to two groups of archaeological indicators (i.e. faunal remains and wood posts), obtained by extended surveys carried out at the site from 2001 to present day.

Keywords: Intra-site analysis, Surface surveys, Abandonment, Pile-dwelling, Bronze Age

Introduction

The archaeological record as it is appears in the present should be understood as a palimpsest: it is the material result of multiple depositional processes that have been acting over time. In order to reconstruct the most likely original deposition, we should go backwards to the activities carried out at the site during its occupation, and analysing the potential effects of different deformation processes (post-depositional disturbances and taphonomic effects) occurred after the site's abandonment. Biasing effects of events having occurred over time may have strongly altered the surface of our deposit, affecting the preservation status of finds as well as their spatial distribution. Different reasons and modalities of abandonment may also influence the preservation of evidence. In our case-study we need to take into account and to integrate all these aspects, due to the nature of the selected variables (i.e. wood posts and discarded faunal remains). Assuming that these materials are ruined wooden structures and secondary refuse we may hypothesise that the abandonment would not have strongly modified the spatial distribution of the most stable elements of the ancient buildings (posts) and the organic discard of animal processing (animal bones). The spatial location of both features may have prevented these two material categories from being moved for reuse: the posts were confined to the lake-marl sediment and fragmented animal bones were considered as useless waste. According to this assumption, it is not possible to distinguish between the effects of the abandonment processes and the post-depositional disturbance on these artefacts' spatial distribution. As a future perspective, analysis of this issue could be extended to other material categories.

1 Materials and Methods

The archaeological data presented in this study are related to the site of Villaggio delle Macine. This is an exceptional case of pile dwellings for the central Tyrrhenian Italian area, dated to the late Early Bronze age – Early Middle Bronze age (19th-16th c BC) (Angle *et al.* 2014; Angle 2007; Angle *et al.* 2002; Chiarucci 1985; 1986-88; 1995-6; Zarattini 2003). It was discovered in 1984, just below the water surface of the Albano crater lake (Rome) and started to be excavated as an underwater site. From 2001, a drastic drop in the lake's water level due to climatic factors and uncontrolled water-taking led to the partial emersion of the site. Consequently, some excavation campaigns in limited key areas and surveys were carried out in 2001, 2003, 2009 and 2012 (Fig. 1).

Ongoing research particularly focuses on the material evidence recovered during the surveys performed during 2001, 2009 and 2012, referred to the last phase of the site's life and its abandonment. At Villaggio delle Macine many archaeological markers, both ecofacts and artefacts were recovered; the first category includes bones (also bone industry, such as deer bones worked to obtain axe handles and awls), seeds, fruits, piles, ashes and drying kilns. In the second category fall *Grotta Nuova facies* ceramics, bronze artefacts (axes and daggers), lithic industry (lithic cores, flakes and *débitage*), ambers, glassy faïence, clay fishing weights and a large number of millstones and grindstones (from which the site's toponym derives). In this paper we focus on the analysis of two classes of evidence, i.e. organic refuse (faunal remains) and wood posts, in order to analyse the spatial variability of their frequency in the area

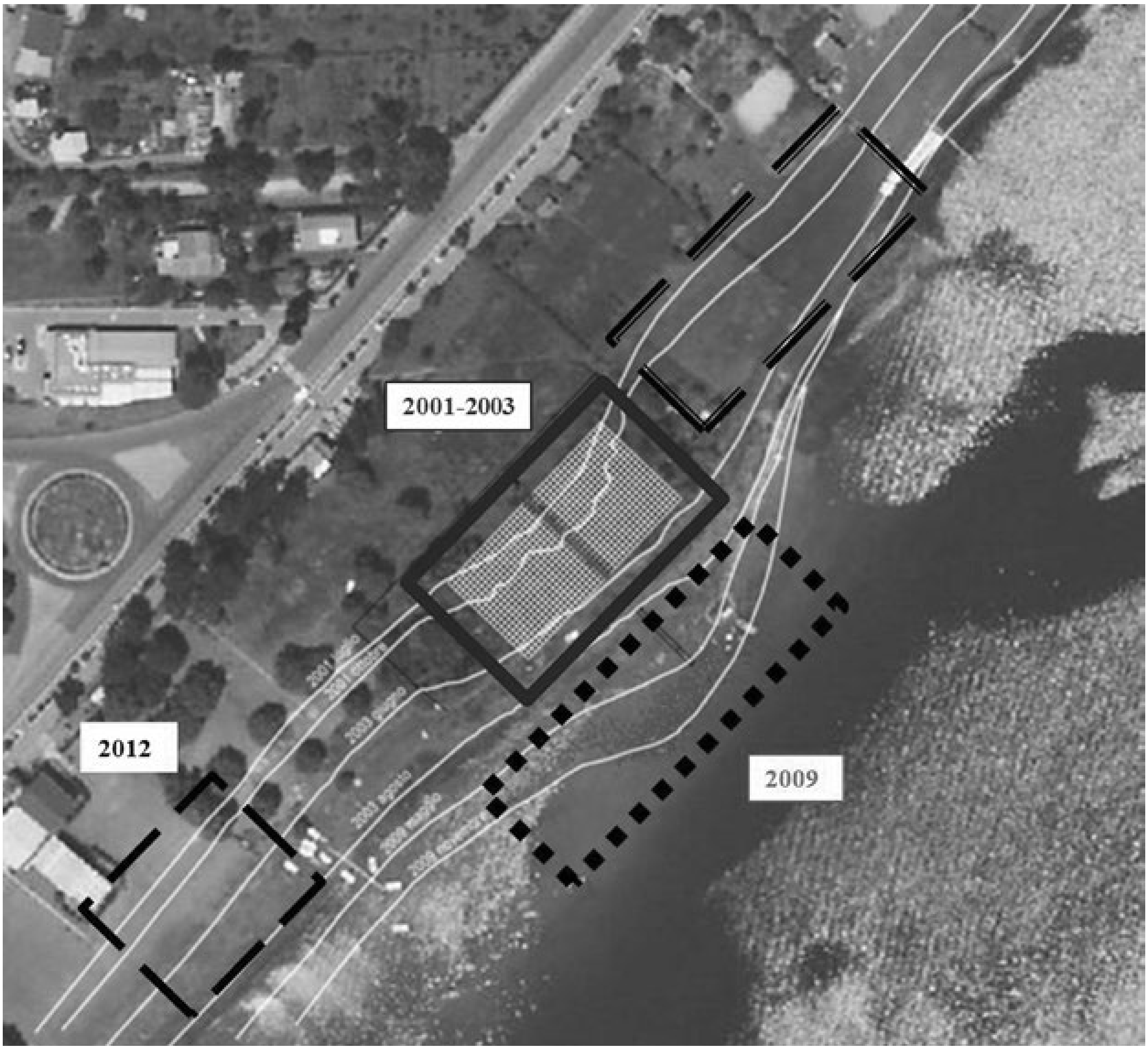

Fig. 1. Spatial distribution of the surface surveys carried out during 2001, 2003, 2009 and 2012.

of our interest. These categories have been selected because of their opposite nature: the posts, as part of the ancient buildings, are presumably less influenced by the post-depositional disturbances. On the contrary, the garbage, especially the faunal waste, has been significantly affected by such deformation processes, showing a high level of fragmentation. The comparison between these two variables can help to shed some light on the formation of our archaeological palimpsest. The data have been analytically organised in a geo-referenced frequency table (Fig. 2). The frequencies of finds have been counted within centroid coordinates of 50 square centimetres each, used as reference units of measurement.

From a theoretical point of view, we can define the material evidence as the consequences of an action *x* performed during some time interval *t*, at a location *z*. For instance, during the first occupation of a lakeside settlement, the inhabitants built their houses (action *x*), in a location *z*. Meanwhile, they perform social actions (as butchery or cooking practices) along a time interval *t*, in the same location z, and around, generating as a consequence some refuse material, that accumulates in the vicinity of the area where the action was performed. When inhabitants abandoned the settlement they left behind this evidence, the refuse as well as, in most cases, the wooden piles of buildings; all, in fact, that constitutes our archaeological deposit. Then, in general terms, when people leave a settlement (Schiffer 1972) they may or may not induce consciously strong modifications on the spatial distribution of the material evidence accumulated during the site's occupation, which were preserved until the time of the archaeological excavation. Not only the abandonment but also and especially the subsequent post-depositional disturbances may have affected and altered the spatial patterns of original accumulations, due to the complex combination of natural as well as cultural deformation mechanisms. In this paper we intend to predict the intensity of spatial alterations induced by abandonment and post-depositional processes occurred at the Villaggio delle Macine, by studying the spatial variability of the archaeological finds (both built space remains and garbage). We assume that if an homogenous, uniform, spatial

X	Y	FAUNAL REMAINS	POSTS
81,25	78,25	1	7
81,25	77,75	0	4
80,75	77,75	8	0
80,25	76,25	0	3
79,25	76,75	2	0
79,75	76,25	0	4
82,25	77,25	5	0
82,25	76,25	0	1
82,25	76,75	6	0
84,75	76,25	0	5
80,75	62,75	3	0
81,25	62,75	0	6
81,25	63,25	2	0
80,75	61,75	3	7
81,25	61,75	0	0
81,25	62,25	2	10
81,75	62,25	3	0
49,25	35,25	0	2
49,75	37,25	7	1

Fig. 2. Example of geo-referenced frequency table: the frequencies of faunal remains and posts counted within centroid coordinates.

distribution is attested independently of the functional category of the archaeological evidence, there is a high probability that the original depositional pattern would have been modified by post-depositional effects of the evolution of the lake shore. The lake's water level has increased after the site's abandonment but we cannot know when exactly, nor are we able to understand if the process has been slow or sudden. Some Classical written sources (Dionysius of Halicarnassus (I, 71, 3), Titus Livius (V, 13,15,16), Valerius Maximus (I, 6,3) and Cicero (De divinitate 44, 100) reported that an odd rise in the water level occurred in the 398 BC. Although their fictional reconstruction explained this change in water level as the product of *prodigia*, Valerius Maximus provided important information about the substantial stability of water levels (through the words *solitum stagni modum*). Moreover, during this time span (398-400 BC) the construction of an outflowing stream structure is thought to have been carried out (D'Ambrosio *et al.* 2009: 128): this would have ensured the stability of water levels up to the recent drop in the lake's level that led to the partial emersion of the site. The changes in water level might have caused re-arrangement of the material evidence that might explain an homogeneous and uniform spatial distribution of finds on the surface. On the contrary, if we can proof that spatial uniformity is not the norm, and we detect spatially different accumulations dependent on the functional category of the material evidence, then we will infer that the original spatial differentiation of social actions may have been preserved in good measure.

The spatial density of the material effects, i.e. garbage and posts, may be interpreted as a function of the probability that an action was performed at that spatial point *s1*. In other words, when the frequency values at certain locations (*s1, s2*…) are higher than in other ones (*s3*, *s4*…), it is most likely that the action was carried out where material evidence was more abundant (Barceló and Maximiano 2007; 2008). Areas where the spatial frequency is the highest may be defined as attraction points for material consequences. The underlying idea is that changes in the probability of the 'prior' (performance of action during the past) determine changes in the probability value of the 'posterior' (the material effects recovered in the archaeological record). However, having to infer the cause ('prior') from its results ('posterior') in a probabilistic way, we have to rebuild the real frequency that was generated in the past by the action. Using a frequency-based dataset we can estimate the spatial probability density function associated to each location. Once we know the relationship between the action and its archaeological descriptor, this function applied to the location of the archaeological finds can be a good estimator of the spatial variability of action in the area. In order to analyse the spatial relationships among sample data we apply the theories of stochastic processes and statistical inferences, known as geostatistics. This is a set of statistical methods used to describe and predict spatial and temporal phenomena (Fotheringham *et al.* 2000, Haining 2003, Lloyd and Atkinson 2004; De Smith *et al.* 2007; Barceló and Maximiano 2007; Diggle and Ribeiro 2007; Cressie and Wickle 2011; Chilès and Delfiner 2012).

2 Geostatistical approach: interpreting the spatial distribution of material evidences

Using a geostatistical approach, we can explore the spatial variability of two categories, i.e. refuse and posts, through the analysis of the first-order as well as the second-order properties of the spatial distributions. First order properties of a spatial pattern of variation are indicative of the intensity of the process at particular locations. If each observation constitutes a repetition of the action, having generated the deposition of this material evidence at this particular location, the mean number of events per unit area can be calculated (Diggle 2013; Barceló and Maximiano 2007) and the spatial or the 2D Kernel estimation graph (Silverman 1986; Beardah 1999; Beardah and Baxter 1996, 1999; Delicado 1999; Barceló 2002; Barceló and Maximiano 2007; 2008; Grove 2011) can be understood in terms of intensity variations. Nevertheless, in archaeology hardly ever can we assume that the count of sherds is an estimation of the number of times an action was repeated. Instead we assume that the number of non-fitting shreds is linearly related to the probability that the action was performed where the sherd was found.

If the social action was repeatedly performed at random we may expect a chaotic distribution of its material markers with a high degree of spatial entropy. Nevertheless, in most cases social actions are performed in an intrinsically better or worse spatial location for some purpose; their position could be relative to some other location for another action or the reproduction of the same action (Barceló 2005). A unimodal histogram or 2D KDE, which fits a bivariate normal distribution (Ahsanullah 1985, Kotz *et al.* 2000), will be read in terms of the higher probability that all sherds come from a single depositional event. Failure of the statistical test of a single depositional event can be explained in terms of errors in the categorization of the archaeological materials or intrinsic spatial randomness in the original action. Multimodality in the spatial histogram or the 2D KDE can appear when the same action was performed more or less synchronously, at different independent locations. Uniformity – the Poisson null hypothesis assumption – would only be expected in the case of lack of spatial awareness by the agents that created the original spatial distribution, or as a result of a reduction of entropy consequence of post-depositional processes. In general, the higher the modality the more uniform is the spatial distribution and the lower is the probability of determining the original location of the social action. To test the uniformity, irregularity or concentrated patterns of the spatial distribution of each archaeological category we can use Mardia's skewness and kurtosis Multivariate test (Mardia 1985; Kankainnen *et al.* 2004, Barceló and Maximiano 2007), as well as the Nearest Neighbour analysis (Clark and Evans 1954; Hodder and Orton 1976; Hammer and Harper 2006). Variability in the spatial distribution of archaeological evidence can also be explained in terms of second-order properties: using the analysis of the relationships between the different frequencies of archaeological features the spatial dependence attested between these events in sub-regions can be calculated. Among the most important second-order properties to characterise a spatial process is autocorrelation. This is a useful mathematical tool to explore whether repeated spatial patterns are attested. For instance, positive spatial autocorrelation between frequencies of sherds of animal bones or wood posts suggests that neighbouring sampling units have the same quantities, and we can conclude a certain degree of uniformity over an area of precise extension. Otherwise, negative spatial autocorrelation informs that very different values are assumed between neighbouring spatial units, and uniformity cannot be desumed; it can be an additional indicator of a certain degree of accumulation at distinctive places within the site. Finally, when spatial autocorrelation is zero, the frequencies of the material consequences of a single action appear to be randomly distributed. There are many different ways to measure the degree of spatial autocorrelation such as Geary's C, Moran's I and the semivariogram, which is the plot of the variance of the concentration values relative to the distance between data points (Cressie 1993; Bailey and Gattrell 1995; Houding 2000; Fotheringham *et al.* 2000; Diggle 2003; Hanning 2003; Lloyd and Atkinson 2004). Using the analysis of second order properties that characterise the spatial distribution of archaeological refuse material, we can predict the most probable location of the original social action in the site. Hence, the variation in frequencies of fragmentary animal bones and remains of wood posts in different locations is a measure of probability of consuming meat and residential activities at certain locations. The higher this value is in a location *s1*, the more likely it is that the action was carried out there (Barceló and Maximiano 2007; 2008). Furthermore, we can estimate the intensity of the probability an action performed at a particular place, even in the case that the said area has not been archaeologically explored, if we have calculated the second order properties of areas around it. Once the autocorrelation value is known for particular variables in a defined area, using interpolation methods it is possible to create a prediction about the values assumed by these variables in other sectors located at a known distance that have not yet been sampled. The purpose is to generate a grid of data values from an existing set using two-dimensional spatial interpolation methods. Grid generation is typically a process based on weighted averages of values at nearby points. The assumption is that each grid cell or intersection is likely to be similar to other values in its neighbourhood. In the case of kriging, the weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points. Kriging is unique among interpolation methods in that it provides an easy method for characterising the variance, or the precision, of predictions (Burrough and McDonnell 1998; De Smith *et al.* 2009). The brief theoretical framework provided summarises the main steps for a geostatistical study. Through the application of those tools to our case-study we will test their usefulness and potential weakness.

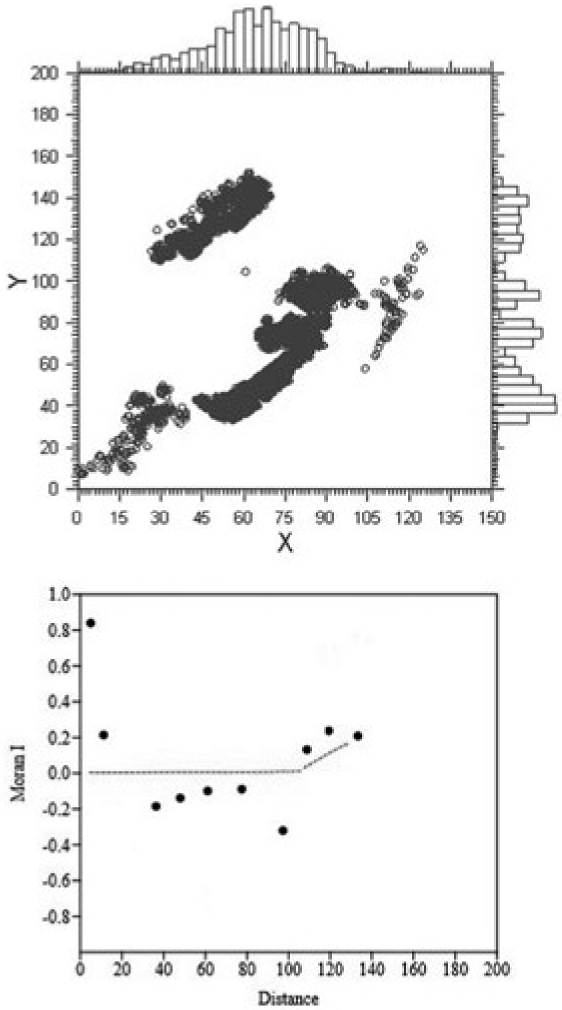

Fig. 3A. Spatial distribution of all faunal remains recovered during the surface surveys of 2001, 2009 and 2012 (Systat 13 Software, Sigma Plot). 3B. The Moran I results for all faunal remains recovered during the surface surveys of 2001, 2009 and 2012 (Past Software (http://folk.uio.no/ohammer/past)).

3 Distributional analysis of archaeological data and spatial variability: preliminary results

The spatial distribution of two markers, i.e. posts and garbage, found during the surveys carried out from 2001 to 2012 are the object of this analysis. In particular, we will focus on identifying density variability within different sub-sectors of our defined area, in order to reconstruct the spatial patterns followed by these markers. First of all, we have considered the entirety of such an area that coincides with the surface surveyed during 2001, 2009 and 2012. A number of issues related to this choice need to be mentioned: for instance, the surveyed area did not correspond to the total extension of the site, due to the largest part of it being still submerged, especially at the earliest stages of the research (2001). Afterwards, the spatial limits of

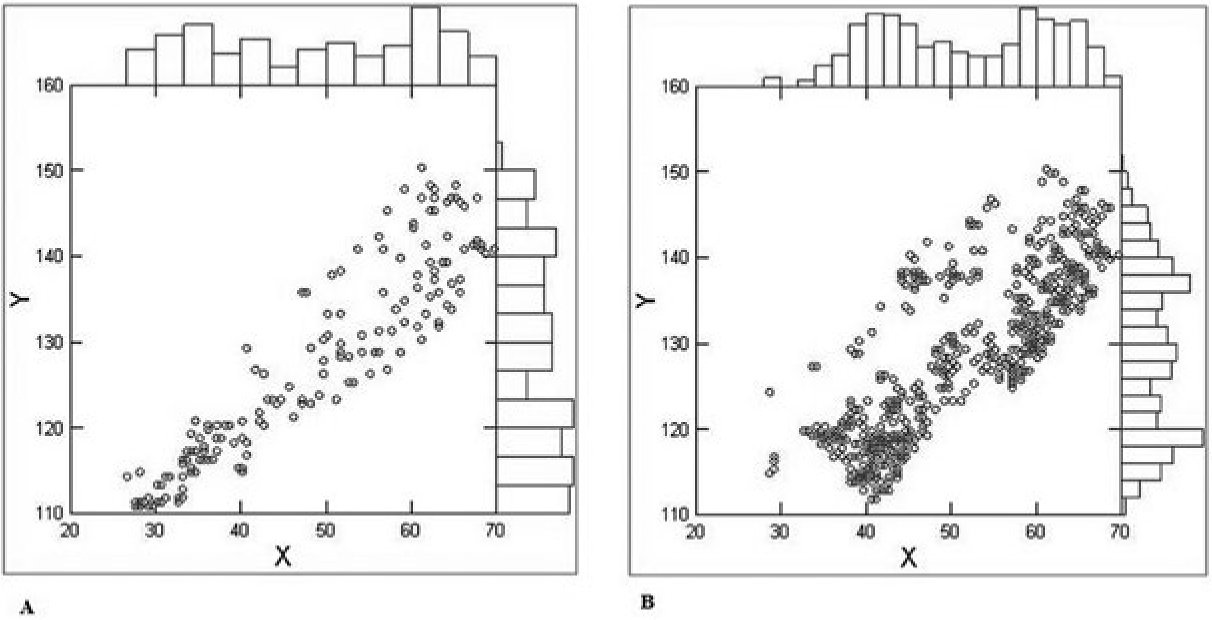

Fig. 4A. The spatial distribution of faunal remains recovered during the surface surveys of 2001. 4B. The spatial distribution of posts recovered during the surface surveys of 2001 (Systat 13 Software, Sigma Plot)

the surveys were defined by environmental boundaries, such as the vegetation and the seasonal variability of the shoreline. Is our geostatistical model able to overcome these issues in order to analyse the entirety of the area? Are interpolation techniques able to predict the spatial distribution of material evidence in the underwater or unavailable sectors within the area? In attempt to answer these questions we chose to focus on the refuse (faunal remains) found during the surveys. All zooarchaeological finds recovered during the surface surveys of 2001, 2009 and 2012, are graphically rendered in a combined histogram and scatter plot (Fig. 3a). The empty area in the centre of the distribution was surveyed during the 2003. The study of these data is still on-going and will be added to the dataset in the future.

In order to explore the spatial pattern of our distribution we define the Poisson distribution as null hypothesis, i.e. the absence of recognisable accumulation. In other words, if this hypothesis fits to our data, we would obtain evidence of a random spatial distribution of refuse. In this case, each location should have similar frequency values to this material category. In case the null hypothesis has a positive texting, we would conclude that the site's abandonment and the post-depositional disturbances might have obscured the original spatial patterns that would have reflected the spatial location of activities. Their combined action could provoke the homogenisation of data, leading to a decrease of the entropy. If the Poisson distribution as null hypothesis is on the contrary rejected, spatial accumulations of refuse would be attested. This means that the frequency values of finds would vary in different spatial locations and the spatial patterns may represent the original location of activities carried out during the past. The site's abandonment, as well as the post-depositional disturbances, may not necessarily have distorted on a significant scale the spatial patterns within the original archaeological record.

As for the Villaggio delle Macine's surface materials, the results of the Kolmogorov-Smirnov test suggest that the spatial distribution of the general palimpsest of fragmentary animal bones does not fit the Poisson distribution (p value=0.303). This means that spatially differentiated accumulations of refuse may exist. Furthermore, autocorrelation results are indicative of spatial heterogeneity. For instance, the semivariogram shows a non-linear model that does not fit the Poisson distribution; furthermore, a strong variability is attested whereby the Moran I results. Hence, while some variance values increase with the distance, other decrease in the same condition (Fig. 3b). The irregularity of spatial entropy measured in the case of archaeozoological remains recovered at the surface of the site, the low frequencies and the lack of spatial contiguity, do not allow the prediction of probable frequencies at the scale of the site. Prediction is only possible within restricted spatial areas. Consequently, the spatial distribution of finds had to be carried out separately for each micro-area (2001 and 2009) (cf. Fig. 1). First of all we focused on the data from the 2001 surveyed area. We started the analysis from the first order properties, in attempt to determine what spatial model can be fitted to our samples. The relationships between the mean of each bone sherd and/or post and their nearest neighbours was analysed, with the aim of determining what spatial model could be fitted to our samples. This relation is graphically visualized through the 'minimum spanning tree' that optimises the result; in addition, the points were circumscribed into a convex hull. The results provided by the Nearest Neighbour analysis and Kolmogorov-Smirnov test suggest that the spatial distribution of our data from the 2001 survey area does not fit the Poisson distribution. Spatial accumulations of both categories may be attested in the analysed area. In particular, the posts (Fig. 4b) seem to be distributed over a wide area and progressively become rarer towards the centre of the distribution; that is, the spatial frequency is higher at the borders of the surveyed area than in its centre. Refuse (Fig. 4a) is instead attested in a more circumscribed sector (Fig. 4). Furthermore, in order to explore the variation of frequencies across the considered space (the second order properties), the spatial regularity and

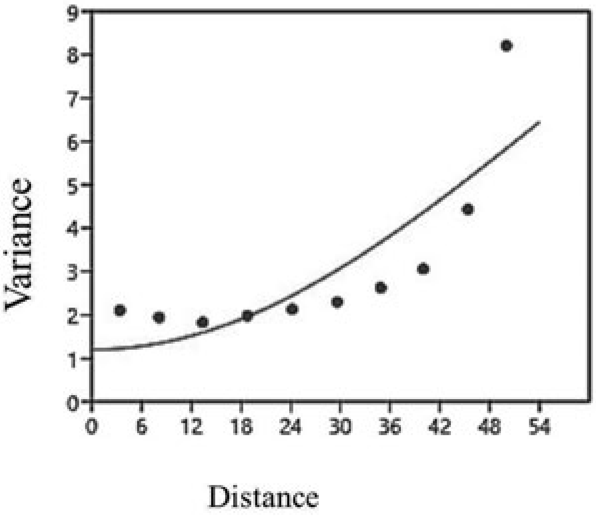

Fig. 5. Semivariogram of the faunal remains recovered during the surface surveys of 2001 (Past Software (http://folk.uio.no/ohammer/past)).

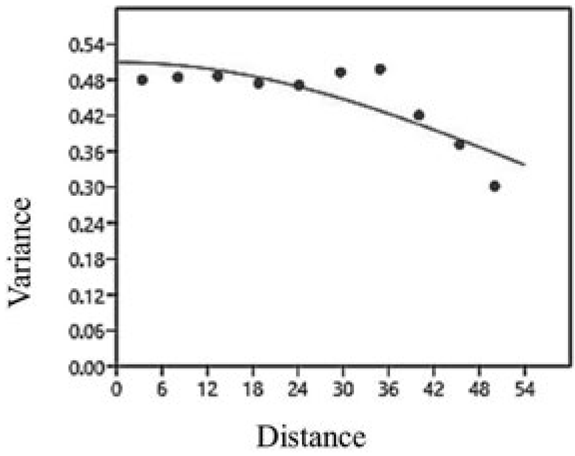

Fig. 7. Semivariogram of the posts recovered during the surface surveys of 2001 (Past Software (http://folk.uio.no/ohammer/past)).

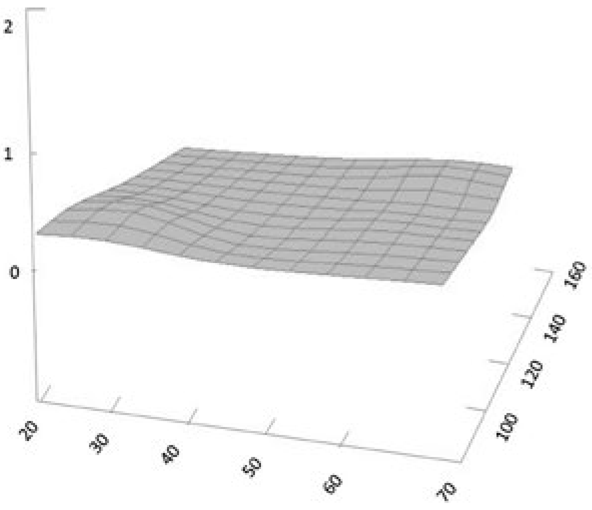

Fig. 6. Graphical results of the kriging for the faunal remains recovered during the surface surveys of 2001 (Systat Software, Sigma Plot).

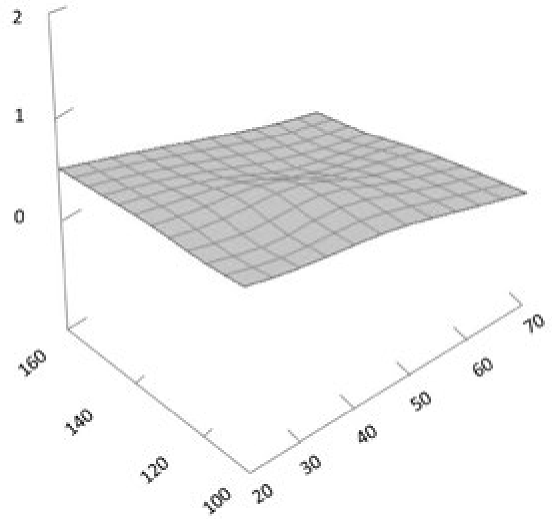

Fig. 8. Graphical results of the kriging for posts recovered during the surface surveys of 2001 (Systat Software, Sigma Plot).

autocorrelation are tested whereby the Mardia's skewness and kurtosis Multivariate test, as well as the Moran I index. The results provided suggest that spatial autocorrelation is absent for both categories and that relevant relationships between neighbour frequencies of finds do not occur. Moreover, the bi-normality condition is not fitted to our sample, suggesting that a single event of intentional accumulation for posts as well as refuse is unlikely. In this condition it is also useful to verify the rate of correlation between the values that each category assumes in correspondence with the increase of distance *h*. Using this analysis, the semivariogram can predict the value of the variables in un-sampled areas located at a known distance. For instance, in the case of refuse, the results of spatial interpolation (calculated with kriging technique) confirm graphically the scenario proposed by the semivariogram. Hence, the function increases at the asymptote, i.e. when the distance *h* increases the variance also increases; a small nugget effect is attested (Fig. 5). Consequently, the data are spatially distributed according to explicitly non-uniform model: the majority of finds are concentrated in two opposite areas with a relatively empty space – and hence partially uniform – in between (Fig. 6). The results of spatial interpolation for the posts suggest a more homogeneous spatial model. In the semivariogram (Fig. 7) the variance decreases in correspondence with the increase of distance *h*. The linearity in the posts' accumulation suggests possible alignments: the spatial connectivity is probably due to the partial preservation in situ of the deeper portions of ancient built structures (Fig. 8).

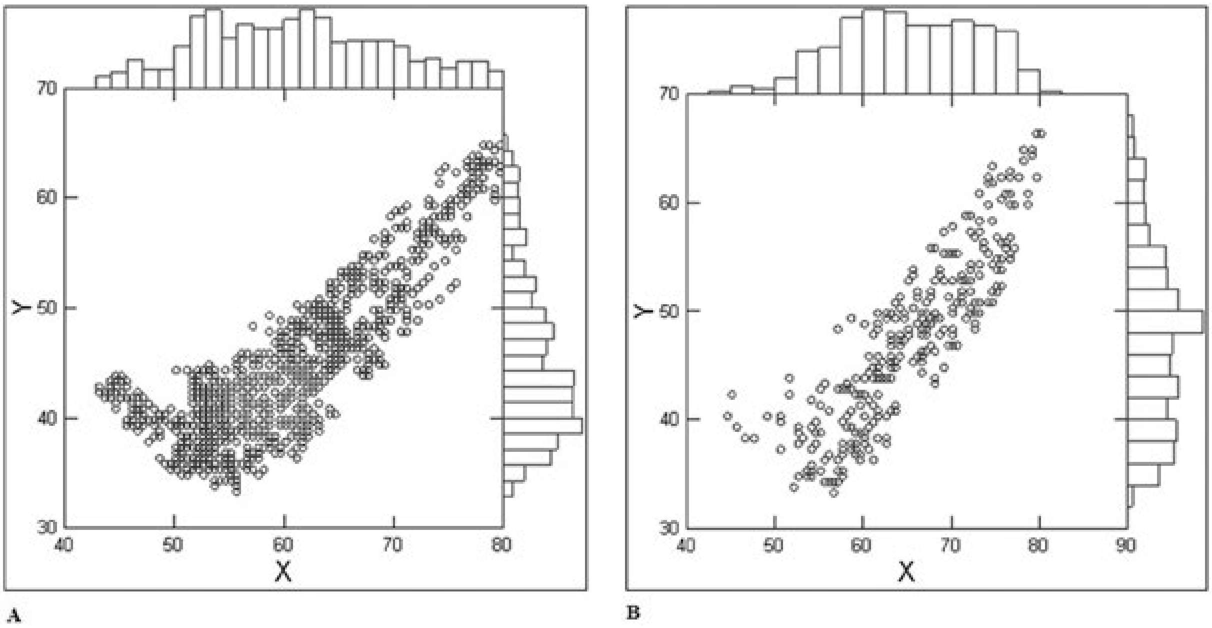

Fig. 9A. The spatial distribution of faunal remains recovered during the surface surveys of 2009; 9B The spatial distribution of posts recovered during the surface surveys of 2009 (Systat Software, Sigma Plot).

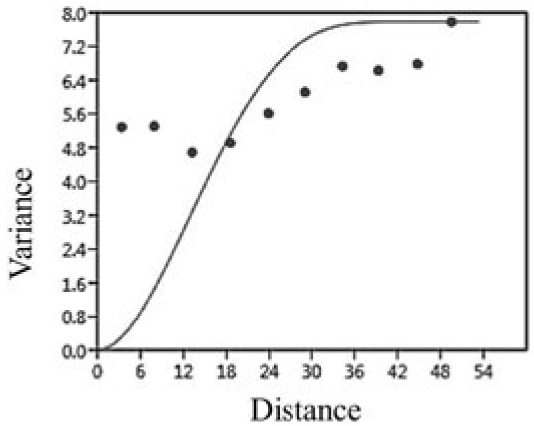

Fig. 10. Semivariogram of the faunal remains recovered during the surface surveys of 2009. (Past Software (http://folk.uio.no/ohammer/past)).

The same step-by-step analyses have been performed on garbage and posts recovered in the 2009 surveyed area, situated south of 2001's surveyed area. The results provided by the Nearest Neighbour analysis and Kolmogorov-Smirnov test suggest that the spatial distribution of our data does not fit the Poisson distribution. Then, the material evidence of both categories suggests a model of accumulation and a similar spatial pattern. However, the faunal remains (Fig. 9A) seem to be more clustered than the posts within the sub-area considered (Fig. 9). The application of the smallest-rectangle seems to optimise the result provided by the Nearest Neighbour analysis, replacing the role played by the minimum spanning tree and the convex hull utilized for the previously analysed sub-area (2001). Specifically, a delimiting convex-hull is not suitable for the 2009 surveyed sector, as it does not fit the contour of the coordinates spread. The results provided confirm that both categories are distributed following a spatial heterogeneous and non-uniform model. A single differential accumulation may be identified, in both cases, surrounded by a significant empty area. The semivariogram for the refuse shows an increasing monotonic function: when the distance *h* increases, the correspondent values of variance increase (Fig. 10). Interpolation techniques by kriging confirm the same accumulative scenario. In the case of posts, the semivariogram shows a small nugget effect. The high values of variance are concentrated in the first portion of the function and then they decrease corresponding to the increase of the distance *h* (Fig. 11). As a consequence, we may assume the spatial connectivity between the posts, which seem to be distributed linearly. The detection of an accumulation linearly deformed also confirms the partial preservation of the deepest portion of ancient built structures in their original location.

4 Discussion

By exploring the spatial distribution of two archaeological markers, an attempt to predict the accumulative consequences of abandonment process was carried out. In other words, we tackled two possible occurrences: if the Poisson distribution as null hypothesis was fitted to our data, an homogenised pattern would be identified, originating from the material result of abandonment and post-depositional disturbances. They had distorted the original spatial distribution of finds. On the contrary, if the Poisson distribution as null hypothesis was rejected, different spatial patterns would be identified. They would reflect the original spatial distribution of material evidence in the locations where social actions have been performed during the past. According to the results obtained, two different patterns can be reconstructed. An accumulative model characterised the spatial distribution of bone sherds. The

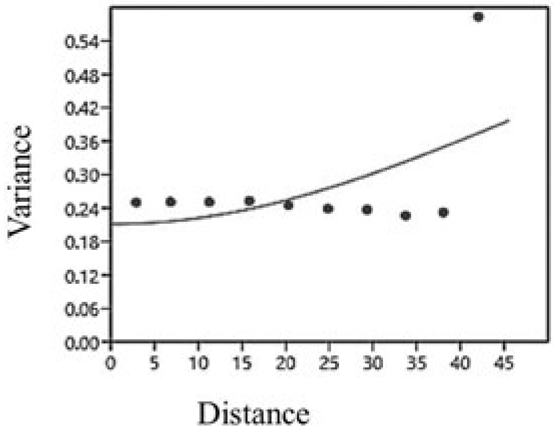

Fig. 11. Semivariogram of posts recovered during the surface surveys of 2009 (Past Software (http://folk.uio.no/ohammer/past)).

high rate of fragmentation shown by the evidence could have well caused the medium level of spatial irregularity observed in the analysed areas. The refuse can be interpreted as the material results of activities carried out during the past in particular locations; the waste products of these activities were discarded and left behind by inhabitants. The central role played in our case-study by post-depositional disturbance, which provoked a strong stratigraphy compression (even leading, in 2009, to the unification of the archaeological record in one very shallow layer, a few centimetres deep, near the shore), could also explain the high level of fragmentation that characterised the archaeological materials. On the contrary, the spatial distribution of posts highlighted the presence of alignments. Probably the deeper sections of ancient structures have been preserved in situ and they have not been strongly affected by post-depositional processes.

This research has furthermore highlighted some issues in our analysis that, as a future perspective, we would like to overcome. First of all, one of the most important problems we had to tackle was the spatial resolution of our data. As was shown by the analysis carried out for the entire surveyed region, a unitary approach does not provide valuable predictions. Therefore the best strategy seems to be starting the analysis from the single areas. Consequently the results obtained can be further compared in order to generalise these assumptions to make them more reliable. This could represent a first step forward towards a required cross validation of the model. However, in order to fully achieve this goal, we should expand our research in two directions: first by adding to our sample the material evidence recovered by the survey carried out during 2003. This would fill the current gap of data within the region considered. We will also test whether this could also help overcoming the difficulty of realising unitary predictions for the entirety of the surveyed region. In addition to this we will look at predictions within a subset of documented excavation units in order to verify whether the known results obtained from the surface are comparable with those provided by the last predictions. Finally, it is important to highlight that the mathematics of prediction at the intra-site level showed some limitations. Although the kriging is a well-known method for spatial prediction, it seems to be too general in this case; therefore, since in our case-study it only succeeds partially, we want to explore also alternative spatial prediction methods, as mentioned above, notably the thin-plate splines which offer higher fidelity to the original spatial frequencies of the markers.

Acknowledgements

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Bibliography

Ahsanullah, M. 1985. Some Characterizations of the Bivariate Normal Distribution. *Metrika* 32 (1): 215-8.

Angle, M., Cerino, P., Granata, G., Mancini, D., Malinconico, R. and Tomei, N. 2014. Il sito su impalcato ligneo del Villaggio delle Macine a Castel Gandolfo. In E. Calandra, G. Ghini, Z. Mari (eds.), *Atti del Convegno 'Decimo Incontro di Studi sul Lazio e Sabina', Roma, 4-6 giugno 2013*: 315-318. Roma, Lavori e Studi della Soprintendenza per i Beni Archeologici del Lazio.

Angle, M. 2007. Comune di Castel Gandolfo. Villaggio delle Macine. In C. Belardelli, C. (ed.), *Repertorio dei siti protostorici del Lazio. Province di Roma, Viterbo e Frosinone*. Firenze, All'Insegna del Giglio.

Angle, M., Lugli, F., Zarattini, A. 2002. Lago Albano: il 'Villaggio delle Macine'. In S. Rizzo (ed.), *Roma Città del Lazio*. Roma, De Luca Editori d'Arte.

Bailey, T. C. and Gattrell, A. C. 1995. *Interactive Spatial Data Analysis*. Essex, Longman Scientific and Technical.

Barceló, J. A. 2002. Archaeological Thinking: between Space and Time. *Archaeologia e Calcolatori*. 13: 237-57.

Barceló, J. A., and Maximiano, A. 2007. The Mathematics of domestic spaces. Paper presented at the *Archaeology of the Household Workshop* (Barcelona 2006). Available from: http://prehistoria.uab.es/barcelo/publication/mathdomspaces.pdf [Accessed: 19 June 2015].

Barceló, J. A., and Maximiano, A. 2008. Some Notes Regarding Distributional Analysis of Spatial Frequencies. In Posluchny, A., Lambers, K. and Herzog, I. (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, 2-6 April 2007*: 282-8. Bonn, Dr. Rudolf Habelt GmbH.

Baxter, M. J., and Beardah, C. C. 1996. Beyond the Histogram-improved Approaches to Simple Data Display in Archaeology using Kernel Density Estimates. *Archeologia e calcolatori*. 7(1): 397-408.

Baxter, M. J., Beardah, C. C., and Wright, R. V. S. 1997. Some Archaeological Applications of Kernel Density Estimates. *Journal of Archaeological Science*. *24* (4): 347-54.

Beardah, C. C. 1999. Uses of Multivariate Kernel Density Estimates in Archaeology. In Dingwall, L., Exon, S., Gaffney, V., Laflin, S. and Van Leusen, M. (eds.), *Archaeology in the Age of the Internet. CAA97. Computer*

Applications and Quantitative Methods in Archaeology. Proceedings of the 25th Anniversary Conference, University of Birmingham, April 1997: 107:5-12. Oxford, Archaeopress.

Beardah, C. C., and Baxter, M. J. 1999. Three-dimensional data display using Kernel Density Estimates. In J. A. Barceló, I. Briz, A. Vila (eds.), *New Techniques for Old Times. CAA98. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 26th Conference. Barcelona, March 1998*: 163-70. Oxford, Archaeopress.

Burrough, P. A. and Mc Donnell, R. A. 1998. *Principles of Geographical Information Systems*. Oxford, Oxford University Press.

Chiarucci, P. 1985. Materiali dell'età del Bronzo nelle acque del Lago Albano. *Archeologia Laziale* VII: 34-9.

Chiarucci, P. 1986-88. Il 'Villaggio delle Macine' nel Lago Albano. *Annali Benacensi* IX: 407-19.

Chiarucci, P. 1995-6. Il villaggio delle Macine sommerso nelle acque del Lago Albano, *Bollettino di Archeologia Subacquea* II-III: 176-83.

Chilès, J.P. and Delfiner, P. 2012. *Geostatistics: Modeling Spatial Uncertainty*. Hoboken, Wiley and Sons Publication.

Clark, P. J. and Evans, F. C. 1954. Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations. *Ecology*: 445-53.

Cressie, N. 1993. *Statistics for Spatial Data.* New York, Wiley.

Cressie, N. and Wickle, C. 2011. *Statistics for Spatio-temporal Data*. New York, Wiley.

D'ambrosio, E., Giaccio, B., Lombardi, L., Marra, F., Rolfo, M.F., Sposato, A. 2009. L'attività recente del centro eruttivo di Albano tra scienza e mito: un'analisi critica del rapporto tra il Vulcano Laziale e la storia dell'Area Albana. In G. Ghini, and Z. Mari (eds.), *Atti del Convegno 'Quinto Incontro di Studi sul Lazio e Sabina', Roma, 4 – 6 marzo 2009*: 125-36. Roma, L'Erma di Bretschneider.

Delicado, P. 1999. Statistics in archaeology: New directions. In Barceló, J.A., Briz, I. and Vila, A. (eds.), *New Techniques for Old Times. CAA98. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 26th Conference. Barcelona, March 1998I:* 29-37. Oxford, Archaeopress.

De Smith, M. J., Goodchild, M. F. and Longley, P. 2009. *Geospatial Analysis: a Comprehensive Guide to Principles, Techniques and Software Tools*. Leicester, Troubador Publishing Ltd.

Diggle P. J. 2003. *Statistical Analysis of Spatial Point Patterns*. New York, Academic Press.

Diggle, P. J. and Ribeiro, P. J. 2007. *Model-based Geostatistics*. New York, Springer.

Diggle, P. J. 2013. *Statistical Analysis of Spatial and Spatio-Temporal Point Patterns*. New York, CRC Press.

Fotheringham, A. S., Brunsdon, C., Charlton, M. E. 2000. *Quantitative Geography: Perspectives on Spatial Data Analysis*, London, Sage Publications Ltd.

Grove, M. 2011. A Spatio Temporal Kernel Method for mapping changes in Prehistoric land use Patterns. *Archaeometry 53* (5): 1012-30.

Haining, R. 2003. *Spatial Data Analysis in the Social and Environmental Sciences.* Cambridge, Cambridge University Press.

Hammer, O. and Harper, D. 2006. *Paleontological Data Analysis*. Oxford, Blackwell Publishing.

Hodder, I. R. And Orton, C. 1976. *Spatial Analysis in Archaeology*. Cambridge, Cambridge University Press.

Houlding, S. W. 2000. *Practical Geostatistics: Modeling and Spatial Analysis*. Berlin, Springer.

Kankainen, A., Taskinen, S. and Oja, H. 2004. On Mardia's tests of multinormality. In M. Hubert, G. Pison, A. Struyf, S. Van Aelst (eds.), *Theory and Applications of Recent Robust Methods*: 153-64. Basel, Birkhäuser Basel.

Kotz, S., Balakrishnan, N., Johnson, N. L. 2000. Bivariate and Trivariate Normal Distributions. *Continuous Multivariate Distributions: Models and Applications* 1. Hoboken, Wiley and Sons Publication.

Lloyd, C.D. and Atkinson, P.M. 2004. Archaeology and Geostatistics. *Journal of Archaeological Science* 31 (2): 151-65.

Mardia, K. V. 1985. Mardia's Test of Multinormality. In Kortz, S. and Johnson, N. L. (eds.), *Encyclopedia of Statistical Sciences* 5. New York, Wiley.

Schiffer, M. B. 1972. Archaeological context and systemic context. *American Antiquity*: 156-65.

Silverman, B. W. 1986. *Density Estimation for Statistics and Data Analysis*. London, Chapman and Hall.

Zarattini, A. 2003. Il Villaggio delle Macine: indagini nel lago di Albano (Castel Gandolfo, RM). In A. Benini and M. Giacobelli (eds.), *Atti del II Convegno di archeologia subacquea. Castiglioncello, 7-9 settembre 2001*, 12. Bari, Edipuglia.

Reconstructing the Boom of Prehistoric Hunter-Gatherer Population Size in Finland by Agent and Equation-Based Modelling

Tarja Sundell[1]
tarja.sundell@helsinki.fi

Martin Heger[2]

Juhana Kammonen[3]
juhana.kammonen@helsinki.fi

[1] Department of Philosophy, History, Culture and Art Studies, University of Helsinki, Finland
[2] Medisapiens Ltd, Helsinki, Finland
[3] Institute of Biotechnology, University of Helsinki, Finland

Abstract: This paper discusses the boom of Finnish hunter-gatherer population size in the Neolithic Stone Age. The marked increase in the population size is based on the summed probability distribution of archaeological radiocarbon dates and the analyses of the Stone Artefact Database. These provide evidence for a marked increase in the archaeological signal 4000-3500 cal. BC followed by a distinct weakening. At the time, the climate was at its thermal maximum, which contributed positively to the terrestrial and marine ecosystem resources. In this paper we aim to find out the processes behind the increased size of the human population by employing agent and equation-based modelling. Prehistoric population fluctuations also have consequences to the present day genetic diversity. These can be studied by population genetic simulations where evolutionary forces i.e. mutation, migration and genetic drift are incorporated. We employ population simulations to follow genetic changes over hundreds of generations and evaluate the effects of a Neolithic population size to the present day genetic diversity

Keywords: Prehistoric population, Agent-based modelling, Equation-based modelling, Population simulation, SimuPOP

Introduction

A number of studies on prehistoric population dynamics and fluctuations in Finland have been conducted recently (e.g. Oinonen *et al*. 2010; Tallavaara *et al*. 2010; Hertell and Tallavaara 2011; Rankama and Kankaanpää 2011; Kammonen *et al*. 2012; Tallavaara and Seppä 2012; Sundell *et al*. 2014; Sundell 2014; Manninen and Knutsson 2014). Furthermore, prehistoric population processes that are unapproachable by other means have been studied by archaeological and genetic population simulations (Sundell *et al*. 2010, 2013; Sundell and Kammonen 2015). Simulations can be used to simulate populations either forward in time or backward in time into the coalescent (the most recent common ancestor), i.e. coalescent simulations.

In this work we expand upon our prior studies on prehistoric population events and fluctuations in the area. We apply the forward in time population genetics simulation environment simuPOP, which allows continuous development of the simulation model. With forward in time simulations virtual populations are created and simulated through their entire histories. The simulated populations are then sampled and analyzed and the results compared with real data from present day genetic diversity. Here, we adjust the individual mortality rate to model the newly researched environmental conditions affecting food resources availability at the time (Helama *et al*. 2013; Oinonen *et al*. 2014).

SimuPOP (Peng and Kimmel 2005), a Python-operated forward time population genetics simulation environment, was used in this study (http://simupop.sourceforge.net/). We chose simuPOP as it is the most versatile forward time population simulation software available. SimuPOP consists of a number of components from which users assemble a suitable simulator. The simulations were run in the Ukko supercomputer of the Department of Computer Science at the University of Helsinki.

1 Materials and methods

In this paper we test the effect of different levels of mortality on the genetic diversity. We simulate two different scenarios: constant mortality rate vs. varying mortality rate (Fig. 1). In the varying scenario the events are based on evidence from tree-ring sensitivity (Helama *et al*. 2013) and knowledge from major tropical volcanic eruptions during the last 500 years (Fischer *et al*. 2007) affecting the climate. In the varying scenario initially unfavourable living conditions for hunter-gatherers are later followed by better food availability in the area (Oinonen *et al*. 2014). These events are included in the mortality rates in our simulations.

We performed two different population genetic simulation scenarios moving forward in time. We used the same demographic model as in our previous work (Sundell *et al*. 2013; Sundell and Kammonen 2015) to be able to make comparisons and draw conclusions between different parameters. An overview of the general simulation model is illustrated below (Fig. 1).

The simulations start with small pioneer populations of 250 females and 250 males simulated with a fluctuating start. This

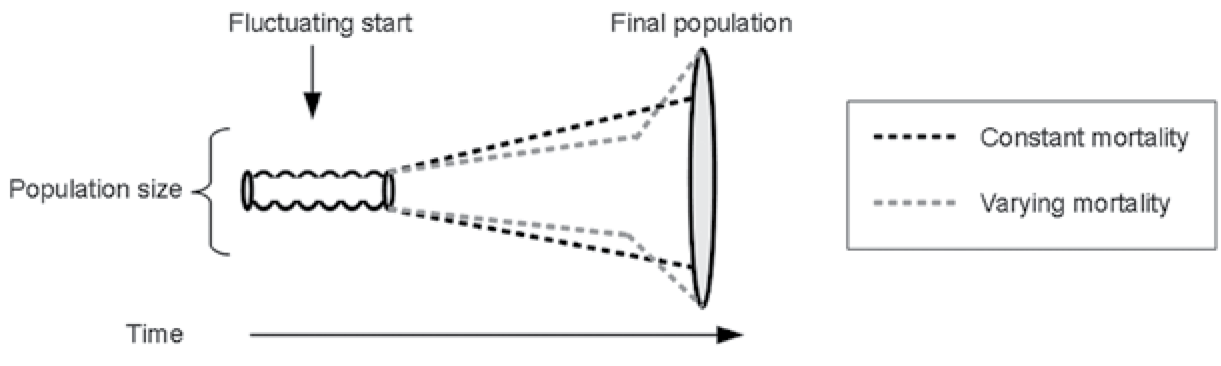

Fig. 1. The general model of prehistoric demography in Finland used in these simulations. The width of the cone represents the relative population size at the time before present (BP).

mimics the very small population consisting of first postglacial pioneers arriving to Finland *c.* 11,000 BP (the same setting is also used in our previous population simulations). In this simulation we use density-based clustering of individuals that captures subpopulation fine-structure more accurately (Sundell and Kammonen 2015). The simulated individuals now have separate information fields for geographical longitude and latitude (x and y coordinates). In order to simulate fine-structured subpopulations, we now employ a density-based clustering method called DBSCAN (Density Based Spatial Clustering of Applications with Noise) (Ester *et al*. 1996) to divide individuals into subpopulations based on geographical distance. The method promises to find clusters of arbitrary shape and have good efficiency on large databases of thousands of objects. Evidently, a simulated population of individuals with spatial location serves as a large database. DBSCAN is widely used in geospatial applications (e.g. Wang *et al*. 1997, 2000; Handl *et al*. 2005).

In this paper we reconstruct the boom of prehistoric hunter-gatherer population size in Finland by agent and equation-based modelling. The key elements and parameters in our simulation scenarios are:

The simulations begin at 11,000 BP when the first postglacial pioneers settled the region following the retreat of the continental ice sheet. The pioneer population consists of 250 females and 250 males divided into two subpopulations according to evidence from radiocarbon datings (Oinonen *et al*. 2010; Kammonen *et al*. 2012). We employ a scenario with fluctuating population size in the initial phase, reminiscent of serial founder effects. Serial founder effects often take place in real world founding populations. Here, the population size fluctuates between 240-630 individuals. Both subpopulations have the same size change rate, with population minima reached *c*. every 200 years. The simuPOP package accepts absolute BP years only. The composition of the Archaic European background population is the same as used previously (Sundell *et al*. 2013). The background population evolves separately for 12,000 years and a snapshot is saved every 2000 years. The Archaic European background population includes 50,000 individuals. Total population is set to reach a maximum of 25,000 individuals in the first scenario shortly before 5750 BP to correspond to the accumulating archaeological evidence for a Stone Age population peak in Finland (Tallavaara *et al*. 2010; Tallavaara and Seppä 2012; Sundell *et al*. 2014). In the second scenario, with the varying mortality levels, the final population reaches *c*. 30,000 individuals.

We calculated two basic indicators of genetic diversity: the number of haplotypes (A) and haplotype diversity (Ĥ) in a sample. The first is a direct count of different haplotypes (differing in at least one nucleotide position or microsatellite locus in mtDNA and Y chromosomes, respectively). Ĥ (Nei 1987) is based on population haplotype frequencies and measures the probability of observing two different haplotypes when sampling two random chromosomes or, as in this case, haploid individuals, from a population. Haplotype diversity is calculated with the formula $\hat{H} = n(1-\sum x_i^2)/(n-1)$ where *N* is the number of individuals and x_i the frequency of the *i*th haplotype. These definitions of A and Ĥ are the same as in our previous simulations (Sundell *et al*. 2013; Sundell and Kammonen 2015) to allow comparisons between different simulation instances during the development of the methodology. Mitochondrial DNA (mtDNA) is maternally transmitted and simulated as a 631 bp DNA sequence, corresponding to HVS-I and HVS-II of the mtDNA control region. Hypervariable segments (HVS) of mtDNA are the segments that typically are sequenced when mtDNA lineages are studied. Any nucleotide at any position can mutate creating new variation. The mutation rates used in the simulations are based on values published in Heyer *et al*. 1997, 2001; Kayser and Sajantila 2001 and Sigurdardottir *et al*. 2000. In order to make the model more realistic, the chromosomes were initialized with actual Finnish genetic data including distinct mutations (Hedman *et al*. 2007). In addition, a binary approximation for the mtDNA nucleotides was used in order to save random access memory during the simulation (Kammonen 2013).

2 Results

We carried out two simulation scenarios with different mortality rates. The genetic effects were measured with two basic indicators of genetic diversity: haplotype diversity (Ĥ) and the number of haplotypes (A) in a sample. The results of our simulations demonstrate that, as expected, the mortality rate has a great effect on the genetic diversity of a population. Interestingly, in the second, varying mortality rate scenario the haplotype diversity is lower in all of the four results (the mitochondrial DNA haplotype diversity, mitochondrial haplotype number, Y chromosomal DNA haplotype diversity and Y chromosomal DNA haplotype number) despite the

Agent-based modelling

- The population is simulated with true census numbers i.e. the whole population
- The simulation moves forward in ten-year-steps.
- Both mitochondrial DNA and Y chromosomes are simulated including mutation
- Reproductive ages are set at 20-60 years for males and 20-40 years for females
- The mobility and mating of individuals depends on the density-based clustering of groups.
- Each mating produces 1 to N offspring according to a Poisson distribution. Offspring is produced for each pair until it, together with the surviving part of the population, reaches the population size at the next simulation step
- The maximum lifespan of individuals is 60 years
- The simulated population is age-structured, i.e. generations overlap

TAB. 1.

Equation-based modelling

- Two simulation scenarios used in this paper:
  1. Constant mortality rate of 0.15/10 years (black line in Fig. 1)
  2. Varying mortality rate according to the equation-based model of resource need vs. resource availability (grey line in Fig. 1)

$$mortality = \frac{e_{needed}}{e_{available}} * 0{,}15/10yrs$$

- The mortality is based on random sampling

TAB. 2.

Starting point, gene flow and final population

- Pioneer population of 250 females and 250 males divided into two subpopulations
- Fluctuating start for the first 2000 years (serial founder effect)
- Internal gender-specific mobility: the mobility rate of females is ten times larger than that of males, corresponding with a patrilocal population
- Four separate simulation checkpoints selected to evaluate the indicators of genetic diversity compared with previous simulations (Sundell et al. 2013; Sundell and Kammonen 2015) (Tab. 1 in this paper)
- Each simulation scenario is run 50 times to obtain enough replicates for evaluation of random variation to the result
- Density-based clustering of individuals captures subpopulation fine-structure (Sundell and Kammonen 2015)

TAB. 3.

	Checkpoint	Time BP	Simulation steps
1	Starting point	11,000	0
2	Population starts to grow	9,000	200
3	Sampling before the population split	7,000	400
4	Population peak	5,750	525

TAB. 4. SIMULATION CHECKPOINTS. IN EVERY CHECKPOINT, A RANDOM SAMPLE OF 1000 INDIVIDUALS IS EXTRACTED FROM THE POPULATION EXTANT AT THE TIME. IF TOTAL POPULATION SIZE AT THIS POINT IS SMALLER THAN 1000, ALL INDIVIDUALS IN THE POPULATION ARE INCLUDED IN THE SAMPLE. CHECKPOINTS ARE USED TO MEASURE DIFFERENT GENETIC EFFECTS IN THE SIMULATIONS.

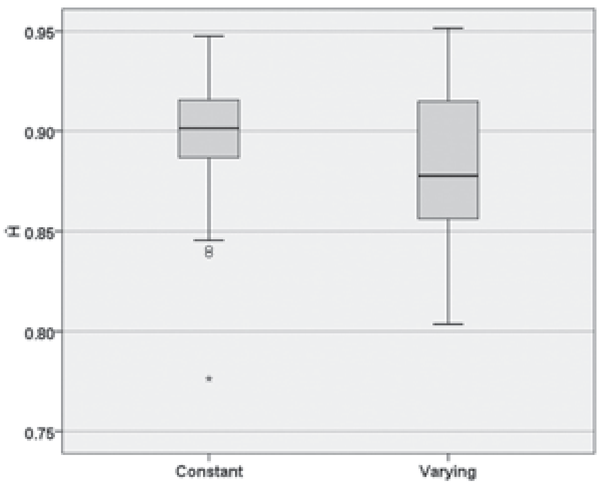

Fig. 2. The mitochondrial (631 bp HVS-I and II) haplotype diversity (Ĥ) in the final population (5750 BP) with scenarios 1 and 2 with 50 simulation replicates, each with a sample of 832 individuals. The number of individuals in a sample corresponds to the sample size in Palo *et al*. 2009 enabling direct comparison between the simulations and the real world.

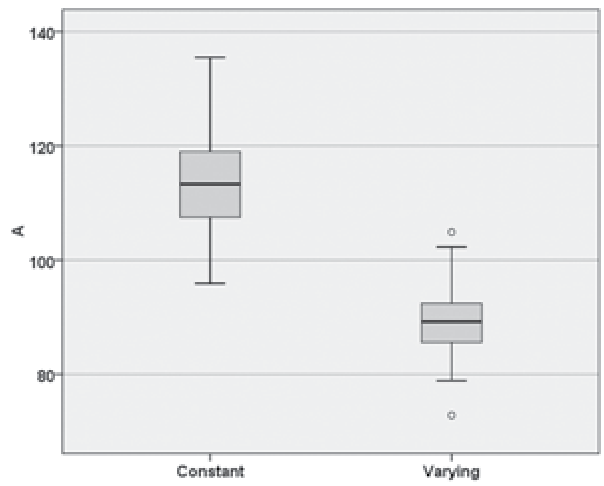

Fig. 3. The number of mitochondrial (631 bp HVS-I and II) haplotypes (A) in the final population (5750 BP) with scenarios 1 and 2 with 50 simulation replicates, each with a sample of 907 individuals. The number of individuals in a sample corresponds to the sample size in Palo *et al*. 2009 enabling direct comparison between the simulations and the real world.

very low mortality rate towards the end of the simulation. This is due to the elevated mortality rate after the fluctuating start, mimicking the real world phenomena including harsher natural conditions (Fischer *et al*. 2007; Helama *et al*. 2013) that affected food availability followed by high productivity of the terrestrial and marine ecosystems (Oinonen *et al*. 2014).

Our results are illustrated in the four boxplots below (Figs 2-5). The simulation result datasets were visualized with IBM SPSS's PASW Statistics 18, boxplot utility (SPSS Inc. 2009). The boxes contain 50% of the observed values. The vertical lines that end in a horizontal stroke, whiskers, give information about the spread of the data: approximately 95% of the data lie between the inner fences. The stroke in the middle implies the median of the observations.

The mitochondrial DNA haplotype diversity and haplotype number

The Y chromosomal DNA haplotype diversity and haplotype number

3 Discussion

In this paper we expand upon our prior studies on prehistoric population events and fluctuations in Finland. Here, we test the effect of different levels of mortality on the genetic diversity by simulating two different scenarios: constant mortality vs. varying mortality. We performed two simulation scenarios including permutations of the following parameters: fluctuating population growth during the first 2000 years, different mortality rates, internal gender-specific mobility between subpopulations, constant gene flow and adjusted individual mobility model to follow a widely acknowledged method known as density-based clustering.

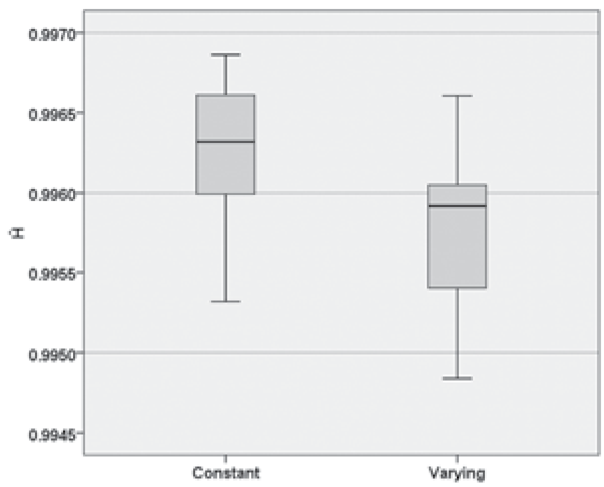

Fig. 4. The Y chromosomal haplotype diversity (Ĥ) in final population (5750 BP) with scenarios 1 and 2 with 50 simulation replicates, each with a sample of 907 individuals. The number of individuals in a sample corresponds to the sample size in Palo *et al*. 2009 enabling direct comparison between the simulations and the real world.

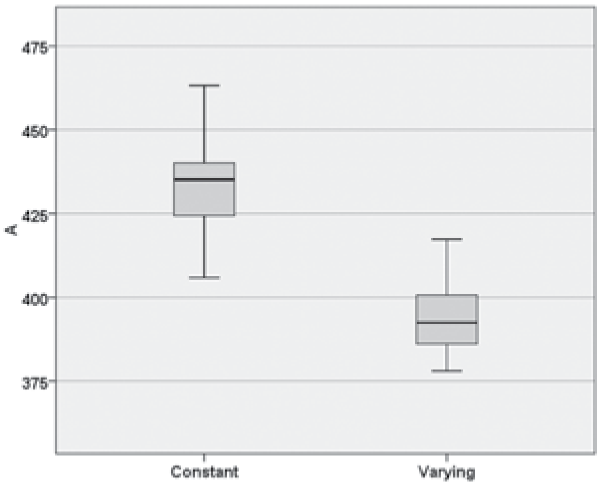

Fig. 5. The number of Y chromosomal haplotypes (A) in final population (5750 BP) with scenarios 1 and 2 with 50 simulation replicates, each with a sample of 907 individuals. The number of individuals in a sample corresponds to the sample size in Palo *et al*. 2009 enabling direct comparison between the simulations and the real world.

Prehistoric population fluctuations and their consequence to the present day genetic diversity can be studied by population simulations where evolutionary forces i.e. mutation, migration and genetic drift are incorporated. A genetic simulation approach, including several separately simulated parameter combinations, enables us to evaluate which population scenarios are most likely to be true and, at the same time, exclude the least compatible scenarios when modelling past demographic events. Our population simulation is a good example of the methodological development of simulations enabled by accumulating research results incorporated in new research. The varying mortality rate, used in this paper, is based on the environmental conditions (Fischer *et al*. 2007; Helama *et al*. 2013) and hunter-gatherer food availability in the area (Oinonen *et al*. 2014) acquired through new research.

The results of our simulations demonstrate that, as expected, the mortality rate has a great effect on the genetic diversity of a population. In the second, varying mortality scenario, the haplotype diversity is lower in all of the four results despite the very low mortality rate towards the end of the simulation. This is due to the elevated mortality rate after the fluctuating start which has no time to compensate towards the end of the simulation by the lowered mortality rate towards the end. Since the mortality rate has a significant effect on the final genetic diversity of a population, it has to be taken into account when planning the future simulation parameters.

Bibliography

Ester, M., Kriegel, H. P., Sander, J., Xu, X. 1996. A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise. In Simoudis, E., Han, J., Fayyad, U. M. (eds.). *Proceedings of 2nd international Conference on Knowledge Discovery and Data Mining (KDD-96)*: 226-31. AAAI Press.

Fischer, E. M., Luterbacher, J., Zorita, E., Tett, S. F. B., Casty, C., Wanner, H. 2007. European climate response to tropical volcanic eruption over the last half millennium. *Geophysical Research Letters* 34, L05707: 1-6. Available at doi: 10.1029/2006GL027992.

Handl, J., Knowles, J., Kell, D. B. 2005. Computational cluster validation in post-genomic data analysis. *Bioinformatics* 21: 3201–12.

Hedman, M., Brandstätter, A., Pimenoff, V., Sistonen, P., Palo, J. U., Parson, W., Sajantila, A. 2007. Finnish mitochondrial DNA HVS-I and HVS-II population data. *Forensic Science International* 172: 171-8.

Helama, S., Holopainen, J., Macias-Fauria, M., Timonen, M., Mielikäinen, K. 2013. A chronology of climatic downturns through the mid- and late- Holocene: tracing the distant effects of explosive eruptions from palaeoclimatic and historical evidence in northern Europe. *Polar Research* [S.l.]. Available at:<http://www.polarresearch.net/index.php/polar/article/view/15866>. [Accessed: 27 March 2015] doi:http://dx.doi.org/10.3402/polar.v32i0.15866.

Hertell, E., Tallavaara, M. 2011. Hunter-Gatherer Mobility and the Organization of Core Technology in Mesolithic North-Eastern Europe. In T. Rankama (ed.), *Mesolithic Interfaces. Variability in Lithic Technologies in Eastern Fennoscandia*. Monographs of the Archaeological Society of Finland 1: 95-100.

Heyer, E., Puymirat, J., Dieltjes, P., Bakker, E., De Knijff, P. 1997. Estimating Y Chromosome Specific Microsatellite Mutation Frequencies Using Deep Rooting Pedigrees. *Human Molecular Genetics* 6, 5: 799-803.

Heyer, E., Zietkiewicz, E., Rochowski, A., Yotova, V., Puymirat, J., Labuda, D. 2001. Phylogenetic and Familial Estimates of Mitochondrial Substitution Rates: Study of Control Region Mutations in Deep-Rooting Pedigrees. *American Journal of Human Genetics* 69, 5: 1113-26.

Kammonen, J., Sundell, T., Moltchanova, E., Pesonen, P., Oinonen, M., Heger, M., Haimila, M., Onkamo, P. 2012. Bayesian Spatial Analysis of Archaeological Finds and Radiocarbon Dates: An example from Finland 4000-3500 cal BC. In Zhou, M., Romanowska, I. Wu, Z., Xu, P., Verhagen, P. (eds.), *Revive the Past: Proceedings of the 39th Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Beijing, 12-16 April 2011*: 318-25. *Amsterdam, Pallas Publications.*

Kammonen, J. 2013. *Improving the throughput of the forward population genetic simulation environment simuPOP*. Unpublished MSc thesis, Department of Computer Science, University of Helsinki.

Kayser, M., Sajantila, A. 2001. Mutations at Y-STR loci: implications for paternity testing and forensic analysis. *Forensic Science International* 118: 116-21.

Manninen, M. A., Knutsson, K. 2014. Lithic raw material diversification as an adaptive strategy – Technology, mobility, and site structure in Late Mesolithic northernmost Europe. *Journal of Anthropological Archaeology* 33: 84-98. Available at doi:10.1016/j.jaa.2013.12.001.

Nei, M. 1987. *Molecular evolutionary genetics*. Columbia University Press.

Oinonen, M., Pesonen, P., Alenius, T., Heyd, V., Holmqvist-Saukkonen, E., Kivimäki, S., Nygrén, T., Sundell, T., Onkamo, P. 2014. Event reconstruction through Bayesian chronology: Massive mid-Holocene lake-burst triggered large-scale ecological and cultural change. *The Holocene* 24, 11: 1419-27.

Oinonen, M., Pesonen, P., Tallavaara, M. 2010. Archaeological radiocarbon dates for studying the population history in eastern Fennoscandia. *Radiocarbon* 52: 393–407.

Palo, J. U., Ulmanen, I., Lukka, M., Ellonen, P., Sajantila, A. 2009. Genetic markers and population history: Finland revisited. *European Journal of Human Genetics* 17: 1336-46.

Peng, B. and Kimmel, M. 2005. SimuPOP: a forward-time population genetics simulation environment. *Bioinformatics* 21: 3686-7.

Python Programming Language. [Accessed 22 June 2015] http://www.python.org.

Rankama, T. and Kankaanpää, J. 2011. First evidence of eastern Preboreal pioneers in arctic Finland and Norway. *Quartär* 58: 183-209.

Sigurdardottir, S., Helgason, A., Gulcher, J.R., Stefansson, K., Donnelly, P. 2000. The Mutation Rate in The Human mtDNA Control Region. *American Journal of Human Genetics* 66: 1599-609.

SPSS INC. (2009). PASW Statistics for Windows, Version 18.0. Chicago.

Sundell, T. 2014. *The past hidden in our genes. Combining archaeological and genetic methodology: Prehistoric population bottlenecks in Finland*. Unpublished PhD thesis, Department of Philosophy, History, Culture and Art Studies. University of Helsinki.

Sundell, T., Heger, M., Kammonen, J., Onkamo, P. 2010. Modelling a Neolithic Population Bottleneck in Finland: A Genetic Simulation. *Fennoscandia Archaeologica* XXVII: 3-19.

Sundell, T., Kammonen, J., Heger, M., Palo, J., Onkamo, P. 2013. Retracing Prehistoric Population Events in Finland Using Simulation. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. & Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 93-104. Amsterdam, Amsterdam University Press.

Sundell, T., Kammonen, J., Halinen, P., Pesonen, P., Onkamo, P. 2014. Archaeology, genetics and a population bottleneck in prehistoric Finland. *Antiquity* 88: 1132-47.

Sundell, T. and Kammonen, J. 2015. A Density-Based Simulation Approach for Evaluating Prehistoric Population Fluctuations in Finland. In Giligny, F., Djindjian, F., Costa, L., Moscati, P. & Robert, S. (eds.). *CAA 2014, 21st Century Archaeology. Concepts, Methods and Tools: Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*: 605-10. Oxford, Archaeopress.

Tallavaara, M., Pesonen, P., Oinonen, M. 2010. Prehistoric population history in eastern Fennoscandia. *Journal of Archaeological Science* 37: 251-60.

Tallavaara, M. and H. Seppä 2012. Did the mid-Holocene environmental changes cause the boom and bust of hunter-gatherer population size in eastern Fennoscandia? *The Holocene*. 22, 2: 215-25.

Wang, W., Yang, J., Muntz, R. 1997. 'STING: A Statistical Information Grid Approach to Spatial Data Mining'. *Proceedings of the International Conference on Very Large Databases* (VLDB'97), 25-27 august, Athens, Greece: 186-95. Wang, W., Yang, J., Muntz, R. 2000. 'An approach to active spatial data mining based on statistical information. *IEEE Transactions on Knowledge and Data Engineering* 12, 5: 715-28.

Archaeology, Geomorphology and Palaeosurfaces Studies: a Multidisciplinary Approach for Understanding the Ancient Laos Territory

Vincenzo Amato[(1)]
vincenzo.amato@unimol.it

Cristiano Benedetto De Vita[(1)]
cr.devita@gmail.com

Francesca Filocamo[(2)]
frafilo@yahoo.com

Alfonso Santoriello[(2)]
asantori@unisa.it

Francesco Uliano Scelza[(2)]
frul72@yahoo.com

[1] Università del Molise, Italy
[2] Università di Salerno, Italy

Abstract: This paper describes the results of the project 'Landscape archaeology in the territory of ancient Laos', a collaboration between the Superintendency of Calabria, the University of Paris 1 Panthéon-Sorbonne, the Centre Jean Bérard in Naples (USR 3133 CNRS – École Française de Rome) and the Department of Heritage Science of University of Salerno. The aim of the project, started in 2009, is to understand the ancient landscape dynamics in the coastal area of northern Calabria. In the last two centuries the landscape has been deeply modified by human contemporary activities. In this context many archaeological evidence persist in a chaotic framework. In such circumstances we defined a multidisciplinary research strategy. In particular a geomorphological and pedo-stratigraphical approach was applied to the archaeological survey. The information was used to build matrix-profiles aimed at the analysis of influencing factors regarding the presence of archaeological evidence on investigated surfaces.

Keywords: Palaeosurfaces, Geomorphology, Landscapes, Ancient Greek colonization

Introduction

The paper defines an approach intended to evaluate the influence of depositional and post-depositional processes of archaeological evidence detectable on erosional palaeosurfaces. The portion of the territory was surveyed in the 'Archeologia dei Paesaggi nel contesto territoriale della Valle del Lao' project, a collaboration between the Soprintendenza Archeologica della Calabria, the Université de Paris I (Panthéon-Sorbonne), the Centre Jean Bérard of Naples and the Dipartimento di Scienze del Patrimonio Culturale of the University of Salerno. The investigation was intended to define times and contexts of human occupation of the Lao Valley. The study area is characterized by the presence of a wide coastal alluvial plain in which the Lao River and the Abatemarco stream flow, bounded on the north by Capo Scalea and on the south by Punta Cirella. Landward, spacious marine terraces, along with less extensive surfaces, are affected by erosional phenomena (Fig. 1).

In this area, historical topographic works and field researches have mainly focused on the identification of the Greek presence related to the Achaean sub-colonies of *Skydros* and *Laos*, on contacts with the Oenotrian indigenous element, on the ethnogenetic process of the Lucans, and on territorial and cultural reorganization of the Roman period (Greco, Luppino, Schnapp 1989; Greco, Guzzo 1992; Greco, Gasparri 1995; Greco 1996; La Torre 1999). Based on historiographical criteria, traditional studies have shown little interest in physical and environmental characters, and, in general, with the quantification of archaeological findings. The punctiform distributions usually observed in the archaeological maps of traditional studies tend to smooth out human activities and functions.

1 Methodologies and techniques: multidisciplinarity and GIS analysis

In this research context the project 'Archeologia dei Paesaggi nel contesto territoriale della Valle del Lao' has attempted to overcome the idea of a territory that refers to itself only through its archaeological artefacts, towards a perception of the relationship between man and environment (Santoriello, Amato, Aversa, Cavassa, Duplouy, Filocamo, Munzi, Scelza, Zambon 2010). For this purpose we have adopted the Landscape Archaeology methodology, which considers the territory as a reservoir of environmental and anthropic

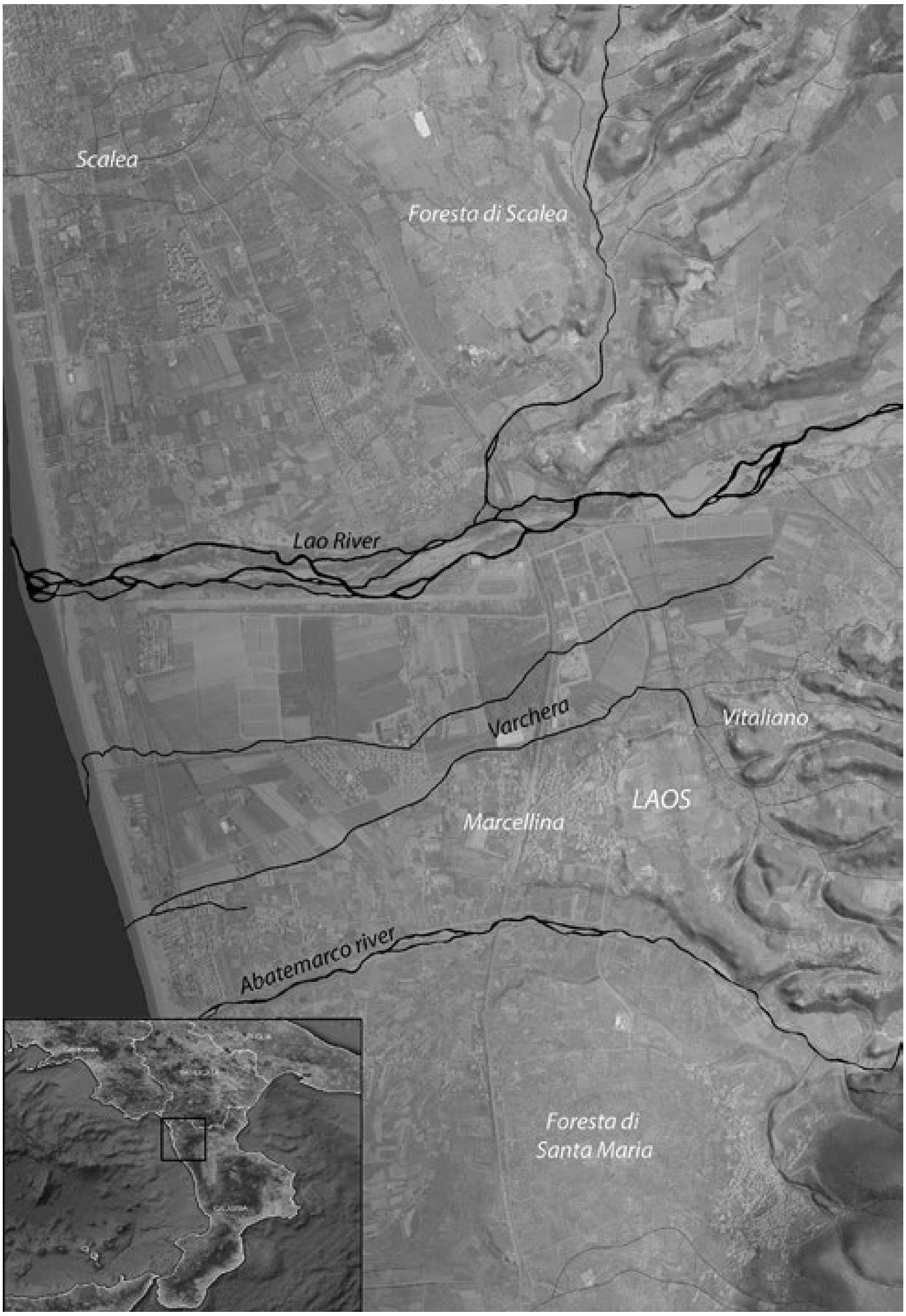

FIG. 1. STUDY AREA.

sources, a system of data resulting from historical, cultural or environmental processes. If on one hand the signs of the landscape cannot be interpreted separately from each other, on the other, they become a source of knowledge even if they are not perceived as being immediately cultural. The system of knowledge is characterized by a multidisciplinary and multitemporal approach, as each part of it follows different rhythms of development, and has a distinct nature. For this reason the landscape has a dynamic character: even if a landscape seems to be mature and completely developed, there are always elements continuously being renewing (Ingold 1993). Therefore to study the structures of landscapes, their genesis and their transformations, means to contextualize a number of processes and to follow their time lines; to understand the organization of a territory does not mean only to identify, describe and distribute the archaeological data in a space but also, and above all, to clarify the structures of the occupation and to specify their roles over time. From a practical point of view, the translation of these assumptions implies the building of a multi-dimensional system. In our research the multidimensionality is constituted by a GIS system from which we have derived archaeo-stratigraphic profiles. These are useful tools that summarize and represent the main factors that have modelled the surface. According to this theoretical framework first of all it was necessary to develop knowledge of the actual landscape and of its trends. We soon noticed that the territory reflects a gradual disintegration of the oldest forms of the landscape to such an extent that the archaeological evidence identified in past decades is disappearing. This is also due to the condition of rural production, directed towards self-consumption. Such a condition is observed mainly along the valleys and plains and on the terraces, where next to small cultivated parcels of land there are vast abandoned areas and no maintenance works. On the contrary the coastal strip is rather affected by seasonal tourism and speculative overbuilding.

The context described has a considerable impact on the research strategy. We decided to divide the territory into homogeneous landscape units from a geological and geomorphological perspective – dunal ridges, back-ridge depressions, alluvial fans, terraces, erosional palaeosurfaces, urbanized areas, etc. These were useful to identify the ancient landscape aspects related to the presence and/or absence of potential populated areas of archaeological interest, to the ancient road network and to the organization of the territory. Within the sample, the work has pursued different surveying techniques, with variable intensity according to the physical and formal characteristics. From the beginning, the research was aimed at an integrated study of every single aspect, such as soil, geomorphology and archaeology. The soil use and the analysis of the structural and infrastructural fabric have resulted in the documentation of the trends of the contemporary economy.

The main purpose is to assess how environmental dynamics and formation processes affect the nature and the conservation of the archaeological record. The method integrates quantitative, qualitative, historical and environmental data. These data have been included in cross sections constructed on a high resolution DEM and used to analyse the archaeo-stratigraphical profiles. This representation shows not only the importance of the physical relationship between stratigraphy, but also their shape and formation, along with their effects on the archaeological record. Spatial analysis has been developed within a GIS platform that allowed the systematization and overlap of several levels of information, used as a basis for the realization of these profiles. The combination of information layers represents uniformly what is summarized in the notion of landscape. In particular, environmental, anthropogenic and archaeological data collected during archaeological and geomorphological surveys have been integrated into a combined reading. Section 4 (below) will show macro groups of data considered the most valuable for the construction of these profiles. The data thus combined were subjected to distribution, density and coherence analysis.

The 3D model created with Encom Discover is built on the basis of the Regional cartography (1:5000 scale); more detailed elevation data have been added thanks to a GPS survey and the integration of maps with greater detail, reaching a resolution of 2m per cell. Finally, archaeological and geomorphological data were added to this support.

2 The natural context: transformation and stability dynamics

The landward plain bordered by hills (Fig. 2), along which a sequence of marine and fluvial terraces, stepping between 240 and 30m.a.s.l. and referred to a time interval falling between the Early Pleistocene and the Middle Pleistocene, is present. In the plain, behind the 20km long and 0.5km wide, modern sandy beach, one or more sandy dunal ridges and back-ridge depression are locally recognizable. These barrier-lagoon systems was formed during the second half of the Holocene, when a strong progradational trend interested the shoreline as result of the decrease of the sea level rise rate and of the increase of the fluvial sediment supplies caused by prehistorical and early historical man-induced impacts. Even more landward stretches of steep slopes, interpretable as palaeocliff relicts, are recognizable. These were probably modelled during the Early Holocene, when the rate of the sea level rise was particularly rapid. Some of it is recognizable in the fluvial valleys and in particular into the Lao River valley, where it goes up to a few kms from the modern shoreline. These were cut into sandy and gravelly deposits of the Pleistocene marine and fluvial terraces. The latter are represented by wide flat surfaces (i.e. Foresta S. Maria and Piano della Suvareta terraces, and by narrow ridges and small strips of lands dissected by a dense river network, which reduced the original width). The valley flanks of the terraces are influenced by several fluvio-gravitational processes (landslides, falls, creeps, rills and gulley erosion), particularly noticeable along the borders of the terraces and on the high part of the slopes. At the base of the slopes, aggradational and colluvial processes are active.

On the wider terraces it is possible to identify more or less preserved soil covers (Fig. 3). The macroscopic features of the soil have been described through the analysis of exposed sections. The thickness of the soil has been estimated approximately at 1-1.5m. The soil horizons are of variable thickness: the upper one (Horizon A) of reddish-brown colour, from 30 to 50cm thick, consists of clayey silt with fine sand component, with occasional gravels and ceramic fragments, rich in organic matter. Horizon B, reddish in colour, has a thickness of between 30 and 70cm, and consists of silty clay; the lower C horizon is of variable thickness and is constituted of gravels of variable size. This soil could be formed in different climate regimes from today, with a very long evolution; it was considered as a pedomarker. This is because the pedogenetic phenomena suggest the stability of the terraces. The ancient material identified in areas with homogeneous soil covers is subjected to dislocation according to dispersion dynamics and gravitational phenomena.

3 Data analysis

The archaeo-stratigraphic profiles used for the analysis are constructed from the cross section on which are arranged the limits of the topographic units (Fig. 4). Each topographic unit is associated with five levels of information: pedology, soil condition, land use, archaeological materials and visibility degree. The first three data are represented by filled or symbolic background; the artefacts through point distributions; the visibility with a colour graduated scale. This information set is combined with the pedogenetic and sedimentological data. To make clear the relationships between human activities, natural phenomena and the stratification of the archaeological record it is necessary to synthesize the amount of data in simplified schemes. The schemes reproduce the basic features recognized on the ground. Each scheme is composed of three levels of information, namely pedology, soil condition and land use. From these data, it is possible to note that with the same

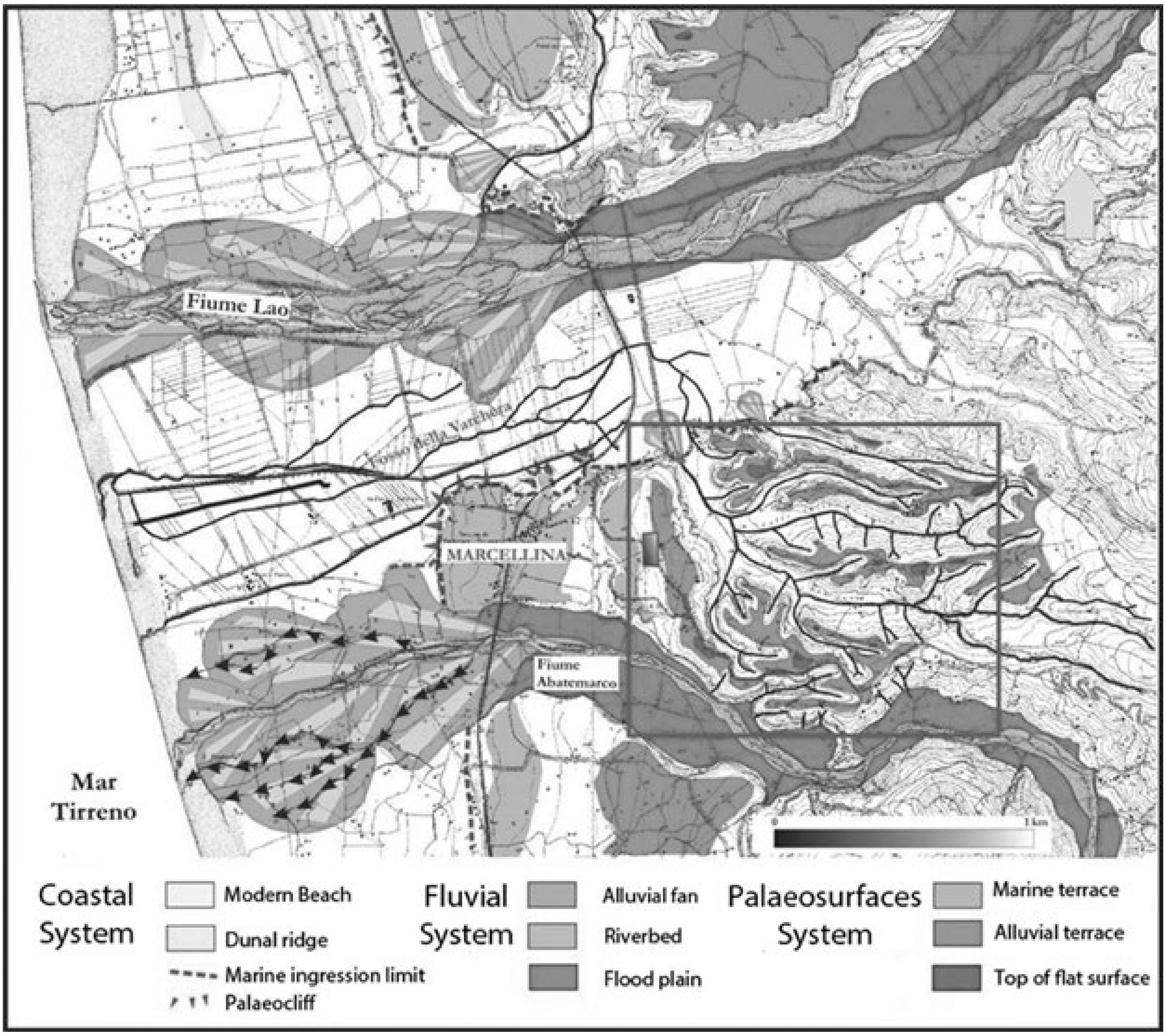

Fig. 2. Geomorphological map of the Laos plain.

pedological and sedimentological characteristics the higher weight in the presence of the surface archaeological evidence is represented by soil working. The presence of the pedomarker is indeed a relevant factor. It indicates stability and the absence of other sedimentological phenomena. The schemes were then compared with the quantitative data of archaeological artefacts.

The data collected in the archaeo-stratigraphic profiles have a different hierarchical value, depending on the basis of the field investigation. The most conditioning in the evaluation of archaeological evidence is related to tillage, which is still tied to the type of cultivation. The presence of palaeosol described above seems to be a relevant factor, which indicates a certain stability of the area and the absence of significant sedimentological phenomena. The schemes thus created were related to each UT and with the quantitative data of fictile fragments. In this way it was possible to define the factors that caused the cancellation of the archaeological evidence, or their location on the surface.

The analysis both archaeo-stratigraphical and topographical has led to some results useful to the evaluation of the archaeological dataset coming from the field survey. Three main geomorphological dynamics were highlighted: they act together with the land use in order to define the presence and the amount of finds and their spatial relationships.

A first dynamic concerns the strong alluvial deposits due to rivers and secondary streams (Fig. 5). The Lao valley is characterized by the presence of a debris layer approximately 1.5m thick, consists of gravelly and sandy deposits of alluvial genesis related to alluvial fans placed behind the dunal ridges of the coastal system. This element is well represented by the excavation of a section of the Varchera canal, where it was possible to identify the Early Medieval ground level, from which several structures of the 4th century BC lie more than 1m deep. Since that directly followed the collapse of some structures of 6th-7th century it is possible to observe dismantling interventions dating from the 15th and 16th centuries, we can assume that between the early Middle Ages

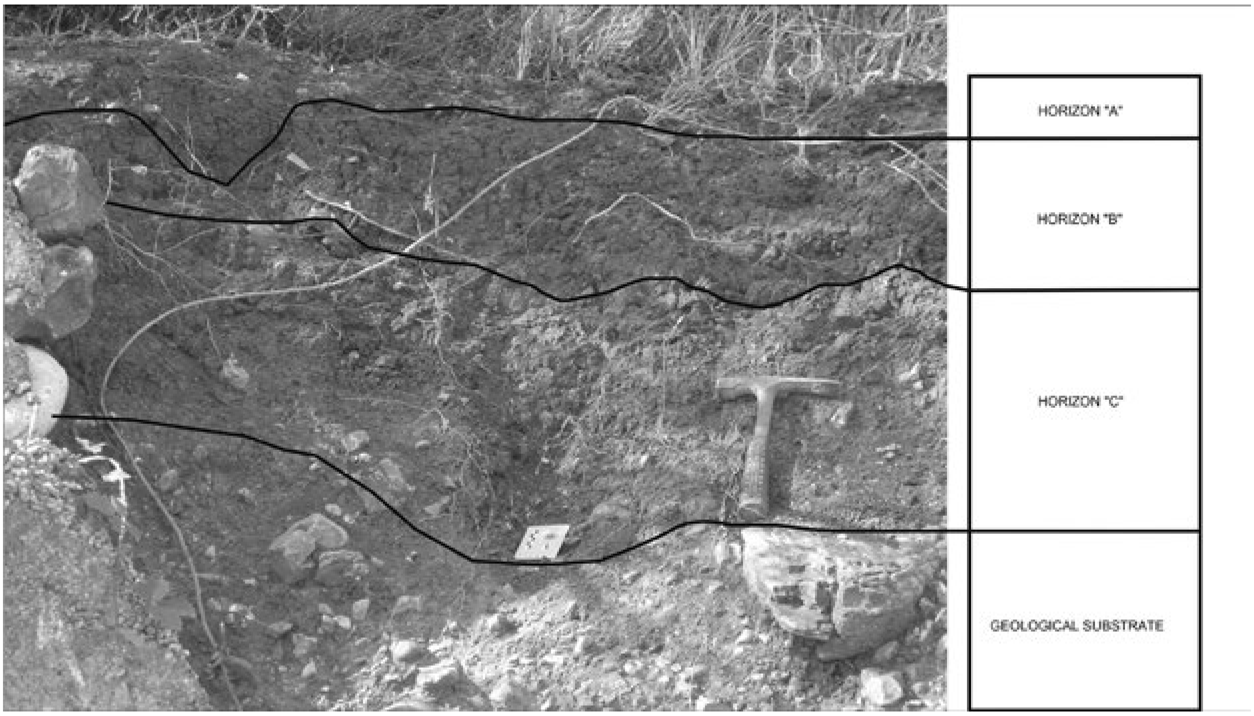

FIG. 3. PEDOLOGICAL STRATIFICATION OF MARINE TERRACES.

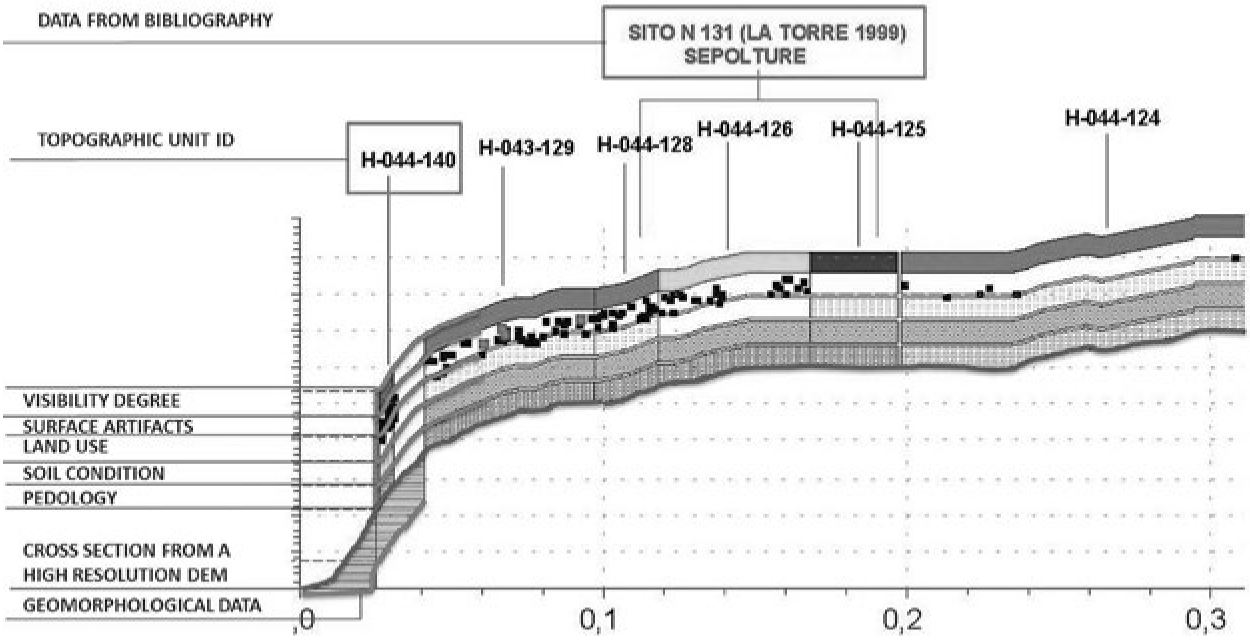

FIG. 4. EXAMPLE OF A MORPHO-STRATIGRAFIC PROFILE.

and Renaissance this area has not suffered huge changes in the height of the ground level. In contrast, the variation between the Hellenistic period and Late Antiquity is stronger.

A second process concerns the relationship between the top and the slopes of the hills (Fig. 6). There are several forms of erosion, which in many places are still active, and large and thick aggradation strips at the base of the slopes. This suggests that the extension of some hills has been considerably reduced with consequences for the shape of the top surfaces. They are affected by erosion due to material detachments, water erosion and quarry activities. In these cases, the only elements of contrast are the terracing work, rarely detected, in particular only along the slopes of San Bartolo, where the Lucan Lao is localized. The hilly surfaces, including that of Lao, are dominated by erosion and solifluction phenomena, which are the main causes

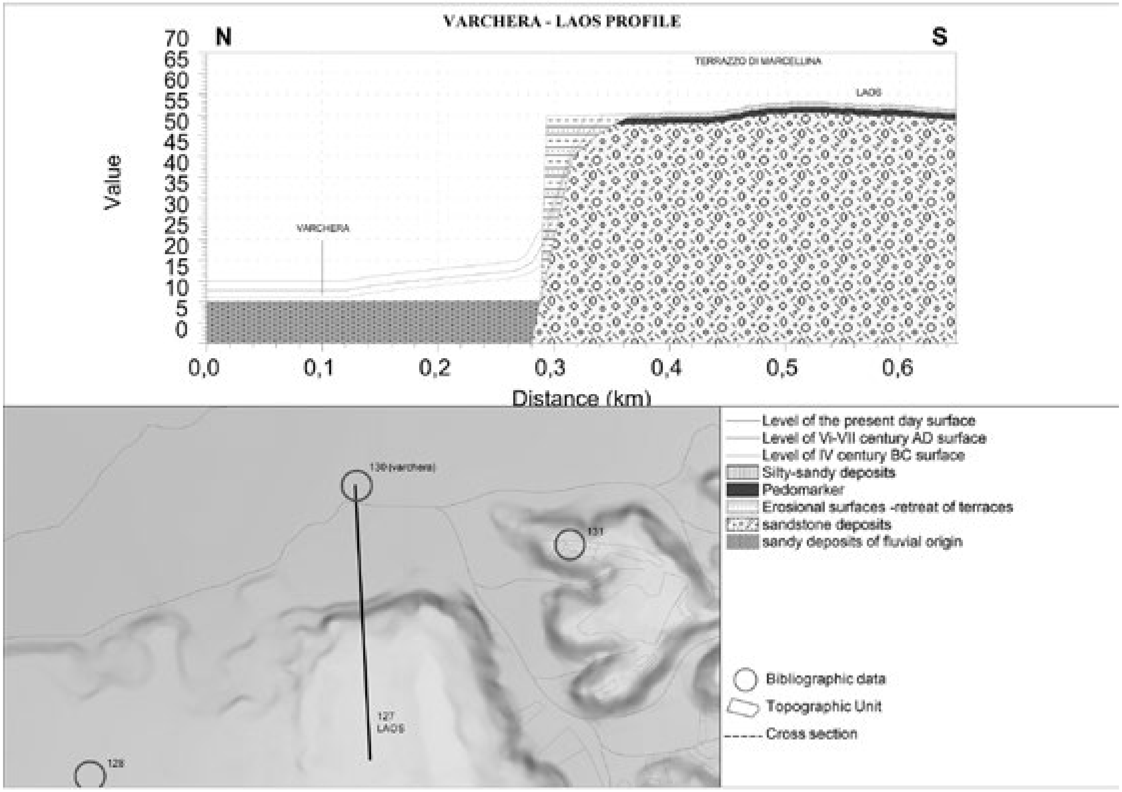

FIG. 5. VARCHERA-LAOS PROFILE.

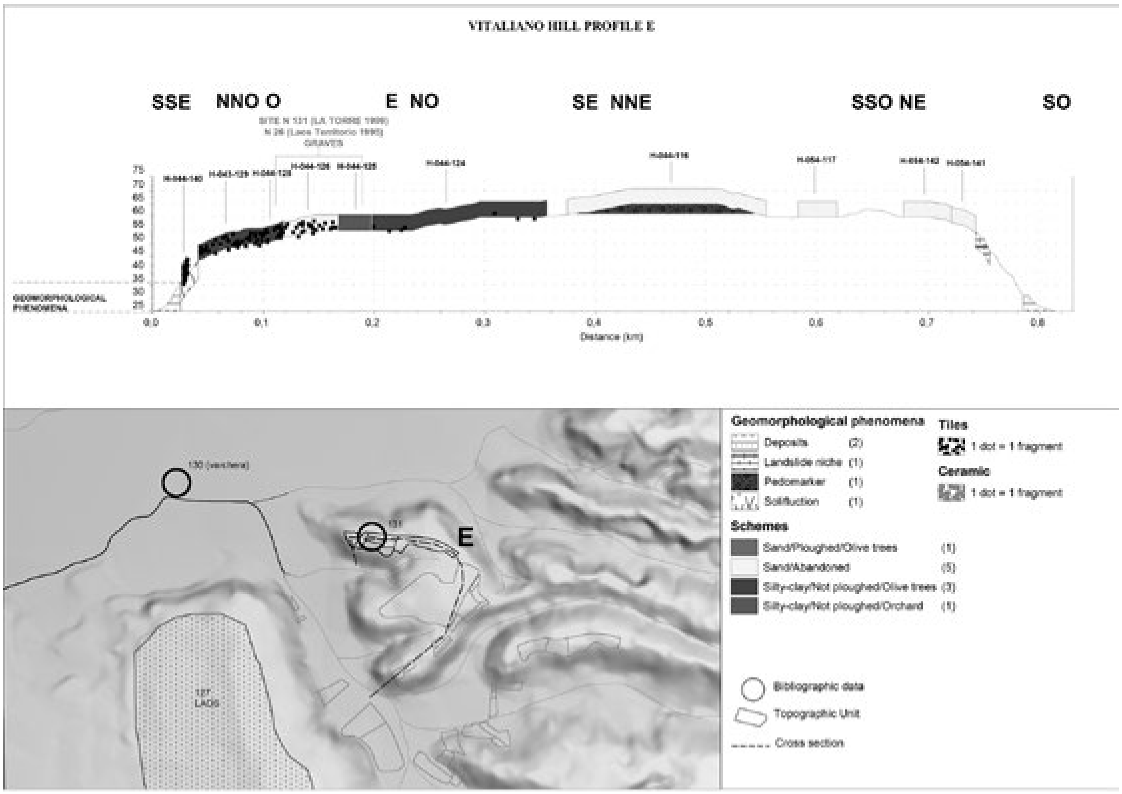

FIG. 6. HILLY AREAS. VITALIANO HILL PROFILE.

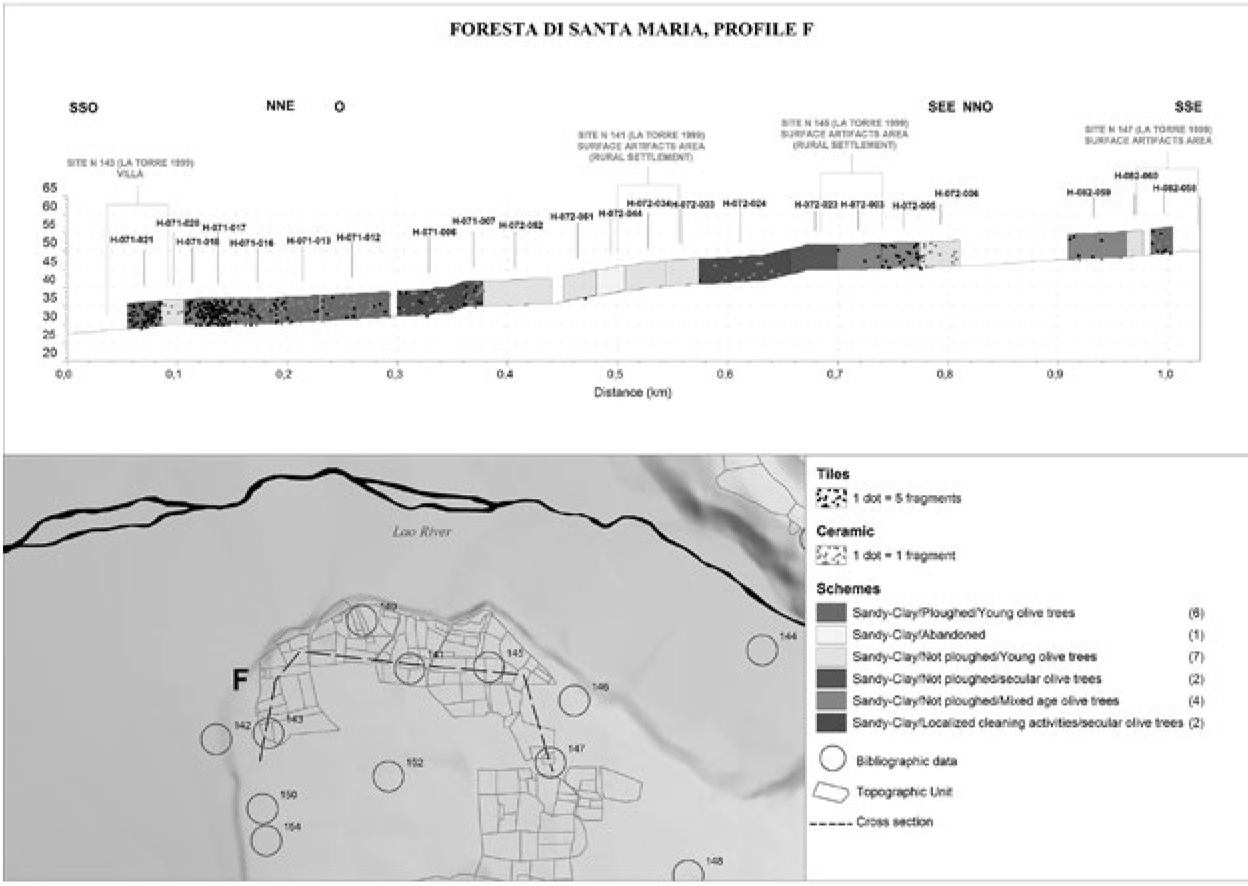

Fig. 7. Marine terraces. Foresta di Santa Maria Profile.

of displacement of archaeological artefacts. This suggests that the presence of human activities is perceivable only through a negative trace and it is extremely difficult to assess the intensity of human intervention in previous periods. For this reason, areas with minimal traces of artefacts could be referred to ancient human activities only in relation to a systematic maintenance of the territory. The data analysis resulting from surveys carried out on the hill of Vitaliano demonstrated a greater extent of the top surfaces and, in general, a greater stability due to the presence of human activities able to organize and exploit the territory. The abandonment of the land and the consequent lack of maintenance have led to a greater impact of erosion, no more opposed by human works.

Finally, the dynamic of marine terraces shows characteristics of stability (Fig. 7). The weak slope reveals little influence of erosion processes, which are more evident only on the outer edges. Moreover, the absence of sedimentological phenomena simplifies the preservation of a thick layer of homogeneous soil. On these stable terraces, on the north and south of the site of Laos-Marcellina, is located the Hellenistic countryside of the Lucan city, through the distribution of a network of individual farms. They are indicted by the presence of several tile sherds, stones and blocks, along with black-glazed and coarse ware fragments, amphorae, as well as Italic and African sigillata. The survey showed a widespread presence on the entire explored surface. It is an average value which changes in correspondence with some concentrations of materials. In this sense, there have been no precise limits helpful for distinguishing clearly differentiated activity cores. The archaeological material is particularly uniform, barely diversified in classes and types.

4 Some conclusions

The effects of dispersion of archaeological materials related to possible sites should be mainly associated with ploughing and land use. Modern agricultural activities are diversified: the permanence of crops or the graft of new plantations impacts in different ways on the possibility of detecting surface artefacts. The cultivation of olive trees is connected to a certain stability of the soil and to localized soil activities, while recent crops involve frequent soil movements. It follows that the discontinuity between the concentrations does not appear to indicate specific limits of activities. The Foresta di Santa Maria Terrace showed a prevalence of anthropogenic processes in the transformation and release of artefacts, able to remove, hide or modify the surface data. The analysis has allowed us to evaluate the behaviour of the archaeological evidence according to different crops, ploughing activities and presence or absence of soil horizons located on terraces.

The framework that emerges emphasizes how the area around Laos is heavily exploited since at least the beginning of the Hellenistic age, with various forms that fit the soil characteristics and the territorial structures (Fig. 8). Some hilly areas could present activities that needed maintenance and regularization. The terraces show a widespread human presence rather than a distribution of specific rural cells in the settlement pattern of

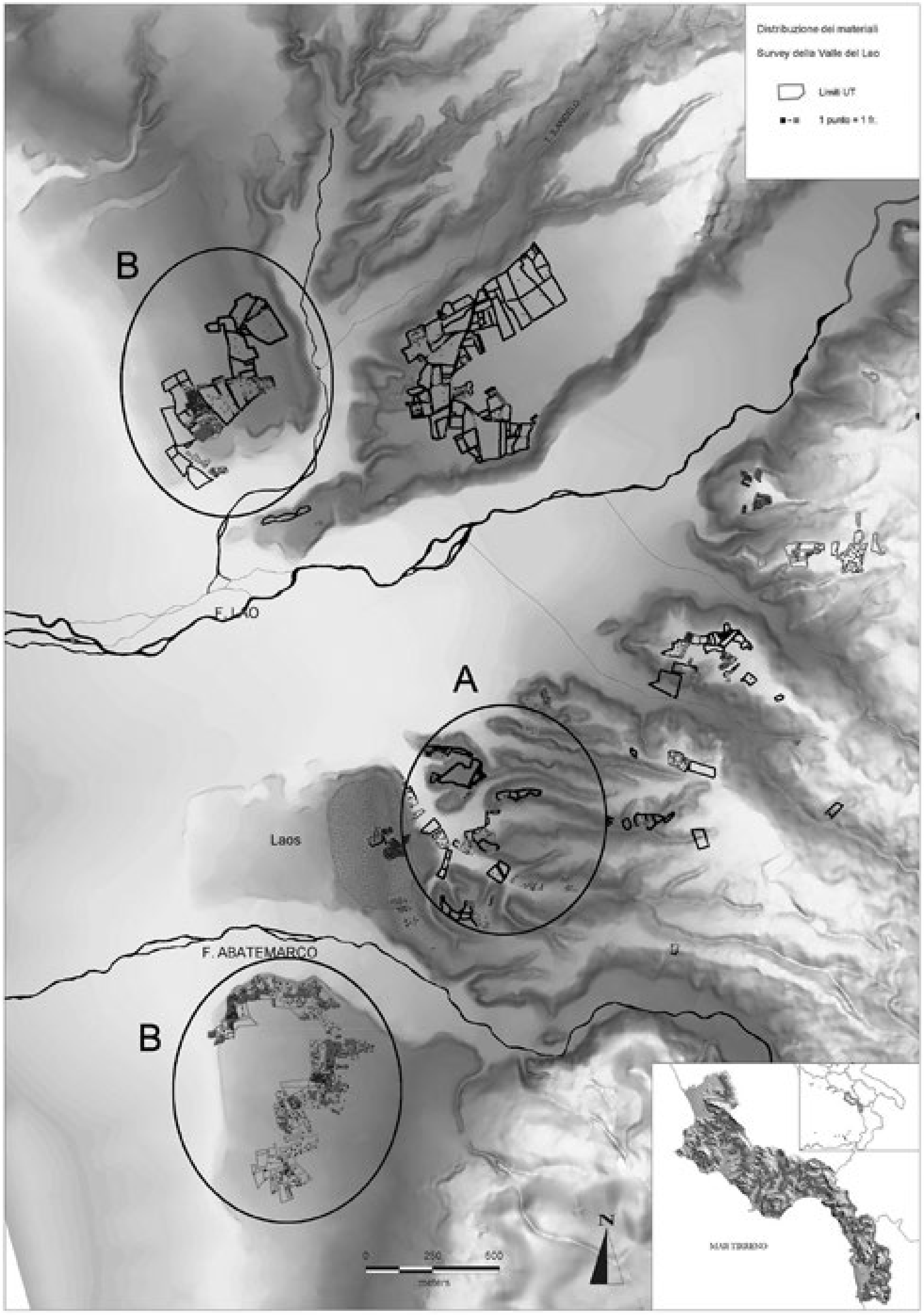

FIG. 8. A DIFFERENTIATED SETTLEMENT TREND OF THE LAOS PLAIN. HILLY AREAS (A) AND MARINE TERRACES (B).

the area. In this case, it is difficult to assume an homogeneous rural landscape that spreads without major changes from north to south. What we see is a differentiated landscape where spaces are selected depending on the intended land use and, maybe, on the juridical charter. The terraced areas arranged along the edges of rivers appear more densely populated and in close relationship with the Lucan Laos, compared to hilly surfaces placed inland, probable sites of permanent presence, where burial finds are witnessed.

Currently, the fragments collected during the survey show at least two chronological levels corresponding approximately to the Hellenistic and Roman Imperial periods. We cannot exclude that some coarse ware sherds, difficult to date, may reflect the oldest occupation. The variety of the dataset suggests the presence of both residential and production areas, apparently merged into the same settlement system. According to this hypothesis, the presence of terraces is also included, often marked only by the existence of anthropic steep slopes: slope cuts and dry stonewalls may well retain traces of an

Fig. 9. Probable agrarian arrangement identified in the Foresta di Scalea terrace.

older system of occupation, since they are not functional to the contemporary landscape. Examples of preservation of the ancient landscape are some orientations identified on the Foresta di Scalea terrace, to the north of the Lao river, characterized by terracing works and partially preserved paths, which reply with dimensions and measures of an agrarian arrangement identified through aerial photographs further north on the Praia a Mare terrace (Fig. 9).

In conclusion, the evaluation of morpho-dynamics and formation processes allowed recognizing stable areas characterized by the absence of on-going phenomena; high erosion areas, defined by clear signs of transformation in contours and extensions of the hills; deposition areas, marked by colluvial debris coming from upstream in ancient times.

A detailed study of soil condition can therefore correct the changes undergone by the archaeological record and assess more precisely the value of surface artefacts.

Bibliography

Greco, E., Luppino, S., Schnapp, A. 1989. *Laos I. Scavi a Marcellina 1973-1985*. Taranto, ISAMG.

Greco, E. and Guzzo, P. G. 1992. *La tomba a camera di Marcellina*. Taranto, ISAMG.

Ingold, T. 1993. The temporality of the landscape, *World Archaeology* 25 (2): 152-74.

Greco, E. and Gasparri, D. 1995. *Laos. Città e territorio nelle colonie greche d'Occidente 2*. Taranto, ISAMG.

Greco, E. 1996. Laos, colonia di Sibari. In D'Andria F., Mannino K. (eds.), *Ricerche sulla casa in Magna Grecia e in Sicilia*, Galatina (LE): 127-32. Congedo Editore.

La Torre, G. F. 1999. *Blanda, Lavinium, Clampetia, Cerillae, Tempsa*, *Forma Italiae* 38. Firenze.

Santoriello, A., Amato, V., Aversa, G., Cavassa, L., Duplouy, A., Filocamo, F., Munzi, P., Scelza, F. U. and Zambon, A., 2010. *Recherches archéologiques à Laos-Marcellina, Mélanges de l'École française de Rome - Antiquité* 123-1: 313-21.

Intrasite Analysis in the Florentine Plain: from Data Integration to Palaeosurfaces Interpretation

Giovanna Pizziolo
giovanna.pizziolo@unisi.it

Nicoletta Volante
nicoletta.volante@unisi.it

Lucia Sarti
lucia.sarti@unisi.it

Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Abstract: This paper presents some intrasite analysis of prehistoric settlement units characterised by multiperiod occupation in the Florentine Plain. The analysis attempts to connect different palaeosurfaces by mean of 3D visualisation and through the integration of ancillary topographic and palaeoenvironmental data. In this way it is possible to compare the stratigraphic sequences spanning from Neolithic to Bronze Age and analyse, in a wider perspective, the formation process of the site and settlement strategies occurred in the area. Erosion processes and post depositional effects have also been considered. Moreover intrasite analysis has been performed using different tools and spatial references in order to get a more comprehensive reading of the use of the space and the organisation of the living-floors. The analysis of palaeosurfaces has been conducted at different levels to increase the understanding of structures, latent structures and functional areas: their integration in a wider context helps in this interpretative process.

Keywords: Intrasite analysis, Prehistory, GIS, Latent structures, 3D perspective

Introduction

This paper illustrates methods and problems related to intrasite analysis performed on prehistoric sites of the Florentine Plain. After a brief presentation on the geomorphological characteristics of the study area we summarise the prehistoric background focusing on the constraints imposed by alluvial settings, urban circumstances and rescue archaeology policy.

We propose to carry on an intrasite analysis developing visual models within the framework of landscape perspective. In other words our elaborations have been developed following a contextual approach which connect together intra site, near site and intersite analysis. The methods and tools adopted by this study have been discussed and their application has been illustrated using Neto - via Verga case study.

1 Geographical and archaeological background

The study area (Fig. 1 a,b) is part of the large system of Firenze-Prato-Pistoia plain originated on a lacustrine basin developed during Villafranchian time. The lacustrine sedimentation has been covered by recent alluvial deposition laid down by the Arno River and other tributaries (Ghinassi and Tangocci 2008). Within the framework of the alluvial plain our research is focused on the Municipality of Sesto Fiorentino which is located on the north western side of the basin. The town is located on the major of the three alluvial fans characterising the foothills and derived by the palaeostream action. Nowadays the watercourses are mostly regularised and transformed into channels especially when they flow in the plain area. Therefore the present day landscape is characterised by the evidence of different reclamation activities undertaken several times in the past to drainage a territory with a naturally wetland predisposition.

The location of prehistoric sites (Fig. 2) suggests possible settlement trends and highlights how the area was increasingly occupied from the end of the 6th to the 2nd millennium BC. The general expansion during this period extended towards the southeast and slightly into the inner part of the plain.

On first analysis we can observe that some zones exerted a major attraction, catalysing in a repeated way the settlement choices. Prehistoric evidence is mainly constituted by artefact scatters located on sub-sunken structure or spatially related to palaeo-streams or palaeo-channels. Very often we find multiperiod prehistoric occupations and dwellings appear in a stratigraphic succession that indicate continuity and a prolonged use of the same layout or the reoccupation of the same area but organised in new structural settings. In other cases the dwellings are in a chronological progression but not strictly insisting on the same stratigraphic sequence, they rather indicate the reoccupation of areas very close by, presenting an ‘horizontal’ stratigraphy or spatial sequence.

2 Archaeological investigations in a urban and peri-urban context: limits and strong constrains

In the alluvial plain the belt zone around Florence has been transformed and progressively occupied by urban and infrastructure activities. In particular, in the last twenty-five years the urban expansion of Sesto Fiorentino has been stretched through the central area Florentine plain. These transformations have been linked to rescue archaeological activities and allowed archaeologists to discover, since the 1980s, a significant

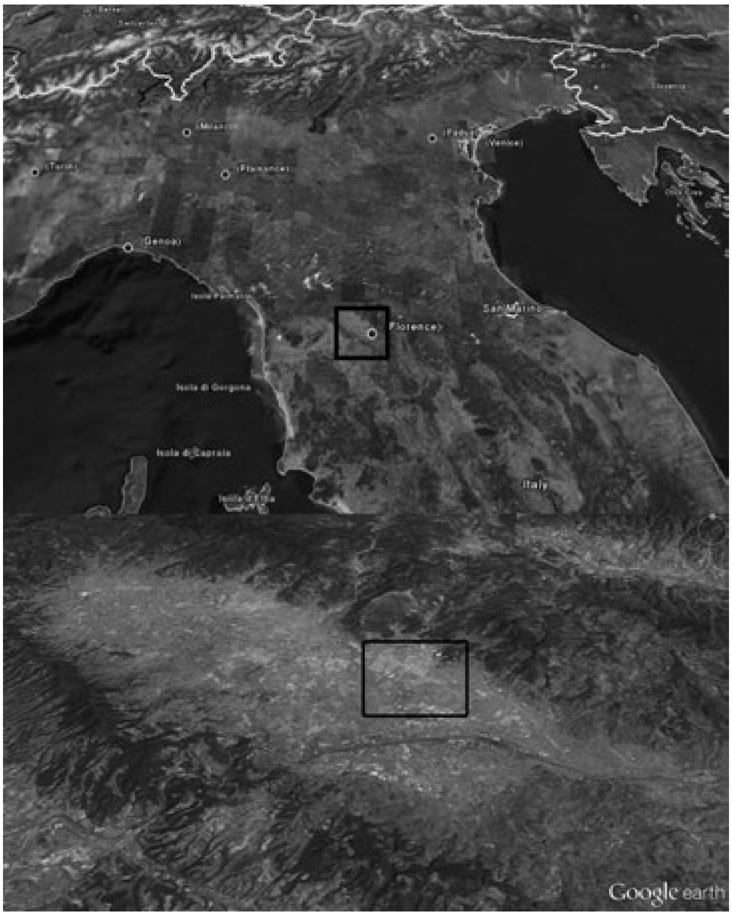

Fig. 1. Location of study areas: A) in Central Italy; B) in the Florentine alluvial Plain.

Fig. 2. Geographical context and prehistoric main evidence in the study area.

Fig. 3. An example of rescue archaeology test pits (in light grey) and excavation areas (in white).

body of prehistoric evidence totally unforeseen before the beginning of this rescue archaeology practice carried on through systematic preliminary archaeological test pits. These specific monitoring conditions have allowed archaeologists to carry out several systematic excavations in the Sesto territory. Due to these existing circumstances, the thick clusters of small trenches (with an average dimension of 1x3x3m) are disseminated irregularly in the study area and have led to more than 500 positive test pits (Fig. 3). In an area of circa 20km, 60 systematic excavations have revealed prehistoric contexts (Sarti *et al*. 2008).

However the rescue field activities are firmly restricted to the extent involved in the building construction. Consequently it is unfeasible for us to investigate the site in continuity with its surroundings and in some cases it is also impossible to determine the complete extension of the site. This constitutes a serious constraint for a general reconstruction of the context, for the investigation of settlement strategies and for the understanding of the characteristic of 'settlement units' (Pizziolo Sarti 2008) of prehistoric territory. Unfortunately it is not feasible for us to investigate the sites in their totality, i.e. in relation to their surroundings, and in most cases it is even impossible to determine their extent. Moreover, urban expansion and the direction it follows, governs the allocation of the excavated areas as well as the authorization to dig test pits and preliminary trenches.

3 Contextual approach: from artefacts distribution to site and near-site analysis

The main aims of this paper are oriented to answer questions on the analysis of palaeosurfaces, in order to understand spatial relationships and formation dynamics of Florentine prehistoric settlements. From a methodological perspective the research has been carried on within a GIS framework which has been considered the best tool to manage and spatially query our data spanning from intra to inter site analysis (De Silva *et al*. 2001).

Due to the high density and complex settings of information gathered through systematic excavations and test pits we believe that an effective way to analyse our corpus of data is to attempt a spatial exploration of them in order to assess anthropic choices and post depositional effect which may have determined the presence of archaeological record. In a landscape archaeology perspective our data are surely biased by the rescue archaeology rules and preventive archaeology policy. Moreover we have to consider that our investigations are strictly related to the opportunity of digging spot trenches, this fact constitutes another constraint which basically limits our research to the plain area.

Furthermore beyond erosion and deposition of the alluvial system we have to take into consideration human action that since the 1st millennium BC might have destroyed or displaced prehistoric artefacts and evidence. Thus the pedogenesis, and in particular the effect of the rise and fall of the water table level, and the anthropic post-depositional events during historic and modern times sometimes have reduced our ability to identify the single layers within stratigraphies.

So, even if we perform an intrasite analysis it is necessary to embrace a contextual view in order to compare different types of data and relate them in a unique palimpsest. This approach needs to work in a dynamic way at different scales spanning from substructures and structures to settlement and landscape views. Moreover, in this analytical framework we judge that the 3D reconstruction is strictly necessary for understanding the formation process of the archaeological record as a result of the interaction of anthropic and natural factors. Furthermore we underline that the specific conditions of the alluvial plain, with multiple erosion and depositional actions, affect the reading of archaeological layers during the field activities. How can we assess the spatial characteristics of archaeological layers? How can we explore the formation process of these prehistoric sites from the analysis of previous documentation? It is therefore necessary that the interpretation undertaken during the excavations could be linked to and supported by the recording of artefact distribution, especially as concern the third dimension.

It is worth noting that dealing with previous excavations, characterised by rescue constraints (see above), the huge quantity of archaeological information has been recorded on paper assigning the Z values to groups of artefacts within a grid reference system. Consequently the 3D management of artefact distributions is a fundamental means to investigate spatial characteristics of archaeological layers.

4 Methodology and tools

The methodology adopted to organise the archaeological information consists of a preliminary data acquisition undertaken within CAD followed by the import of vector layers, artefact databases and other ancillary information within a GIS environment.

The procedure has been set up by the LIARP (Laboratory of Computer Science Applied to Prehistory at University of Siena) (see Aquino *et al*. in this volume) and consists in digitising all the plans and cross section drawings via CAD building up a 3D environment in order to validate the topology of layers (Viti 2004). Most of the validation has been carried out with clipping planes, a CAD tool that allows us to visualise data by means of virtual sections. These are built up through two clipping planes in which material distribution, delimited by the Front and the Back planes is projected in a 3D perspective on the Back plane. The result is a dynamic secant slice that we can move inside our 3D environment observing how material and other XYZ features (i.e. contour lines) are placed in a front view. This tool allows us to explore the relative stratigraphic position of archaeological features within their archaeological context. Through the frontal distribution of the artefacts it is in fact possible to analyse the consistency and texture of archaeological layers and investigate the spatial relationship among each other. Moreover, when available it is possible to compare the shape and volume of layers with the natural morphology on which they are placed.

In this way we can check the position of artefacts and assess if they are in the right layer.

A second test can be performed within GIS once the vector files are imported and linked with archaeological information recorded in artefact databases. Moreover this procedure allows us to create thematic maps and to visualise the distribution of classes and typologies of archaeological finds.

The 3D visual analysis is carried on also within GIS environment using the facilities of 3D viewers (ArcScene© Esri).

Due to the constraints mentioned above which characterise the study area it is particularly important to individuate micro-morphologies or surfaces related to a specific chronological range. We can exploit the great opportunity to link and visualise in a three-dimensional environment features related to different excavated areas and work to highlight and select elements related to the same chronological phase. The 3D views allow us to explore morphologies in their stratigraphic relationships and try to correlate them with other geographical information as the ones derived by remote sensing or geological studies (Pizziolo 2007). In this way we can perform investigations spanning from intra-site to near-site and inter-site scale of analysis.

Through the 3D environment we can contextualise archaeological data and we can address questions related to the analysis of palaeosurfaces, characterised by possible latent structures and/or functional areas, in order to understand spatial relationships and formation dynamics caused by anthropic and/or natural actions. Visual models are a fundamental step of our interpretative process and help us to

clarify problems and formulate questions (Pizziolo, Viti 2011 *cum bibl.*). We illustrate the potentialities of this approach using a case study.

5 Neto-Via Verga: case study

The Neto-Via Verga site, excavated in 1992-93, is located on the foothills of Mt. Morello at the end of trans-Appenine routes. The site (fig. 4) is part of a broad settlement unit which is formed by a group of excavation areas: Neto-via Verga, Neto di Bolasse and Spazzavento (Pizziolo Sarti 2008)

The unit, positioned in the west of Sesto Fiorentino territory, is located on a sort of morphological top formed by depositional accumulations of two alluvial fans related to Rimaggio and Marina streams. Those water courses have a torrential nature with intense seasonal variations.

The Neto-Via Verga areas have been investigated in 5 sectors corresponding to the construction of five buildings.

The sum of the stratigraphic sequences of each sector permits the reading and the re-composition of the complex palimpsest of the settlement. The stratigraphic sequence as a whole covers a wide chronological range which indicates that the area was occupied from the beginning of the 5th millennium (Middle Neolithic) until the Roman period.

Here we propose a synthetic stratigraphic scheme (Fig. 5) which illustrates the general sequence.

The archaeological layers are individuated as follows:

- Layer 2: Roman period (1st c. AD)
- Layer 3: Metal Age subdivided in three phases
    - Bronze Age
    - AOC Bell Beaker (Sarti 1997)
    - pre Bell Beaker Copper Age : characterised by *squame* pottery (in the areas 5; 3340 – 2910 BC cal 2 σ)

Fig. 4. Neto-Via Verga and Spazzavento settlements. Location of excavation sectors.

- Layer 5: Early Copper age characterised by engraved pottery (in the areas 1,4,5; 3708-3486 BC cal. 2 σ).
- Layer 7: Late Neolithic characterised by Chassey ware and pottery of southern Italy (in the areas 1, 3, 4,7; 4114-3906 & 4255-3696 BC cal. 2 σ)
- Layer 10: Middle Neolithic characterised by Square Mouth Pottery (in the areas 1, 5; 5050 - 4515 BC & 4530 – 4320 BC cal. 2σ)

In each phase, but above all in layers 7 and 5, some possible structures have been individuated due to the concentration of archaeological artefacts (latent structures); rarely some sub structures (*sensu* Bagolini-Bagolini *et al.* 1993) e.g. postholes have been found. Sometimes it is possible to individuate thin archaeological layers and isolated sub-structures such as pits, fire places and other evidence which may correspond to open air functional areas.

As we have already mentioned the logistical constraints have impeded the investigation of the site and thus the excavation area is limited to the modern buildings that will be constructed on the spot. The analysis of data in a unique framework helps us to understand the possible settlement unit and to highlight the areas to be explored in the future (Fig. 6).

6 Exploring the Neto-Via Verga settlement

Due to the characteristics of the Neto-Via Verga site our intrasite analysis is oriented to explore the prehistoric settings starting from the spatial connection among different palaeosurfaces discovered in the excavation sectors. We attempted to relate field surfaces that referred to the same cultural and chronological phase that are located at a range distance of a maximum of 150m.

In this context it is necessary to know how to deal with the single stratigraphic sequences selecting and managing the areas which may be related from a chronological point of view. Our plan was to isolate diachronical surfaces in order to investigate their relationship with natural alluvial layers at an intra-site and near-site scale (Fig. 7). These surfaces generally correspond to open air activities, living areas, or to ancient field surfaces with different densities of archaeological material.

Their integration in a unique environment may perhaps help to explain better spatial prehistoric behaviour and we believe

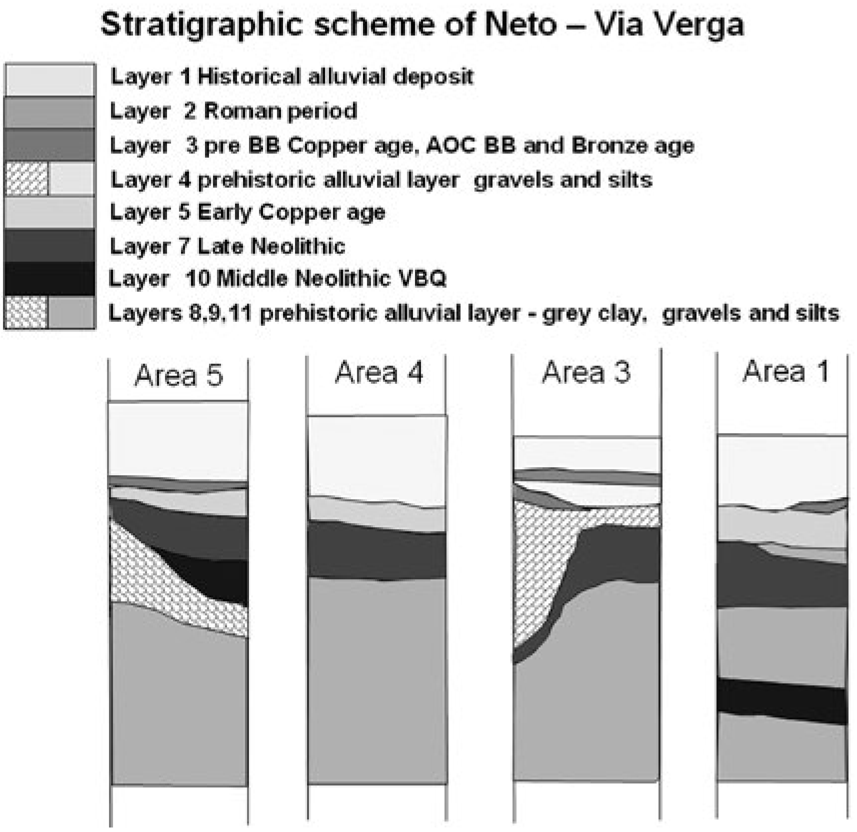

Fig. 5. Neto-Via Verga synthetic stratigraphic scheme.

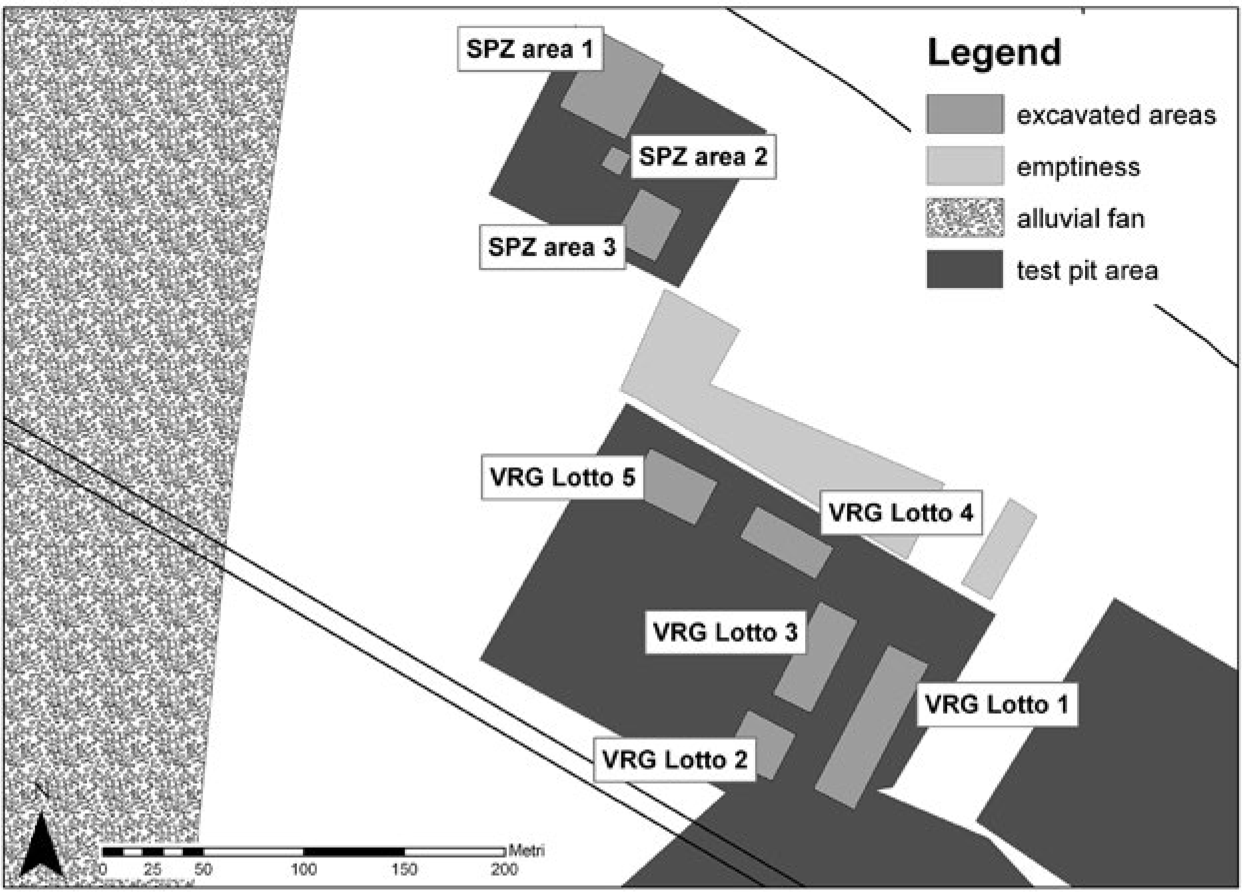

Fig. 6. Settlement unit: assessment of areas to be investigated.

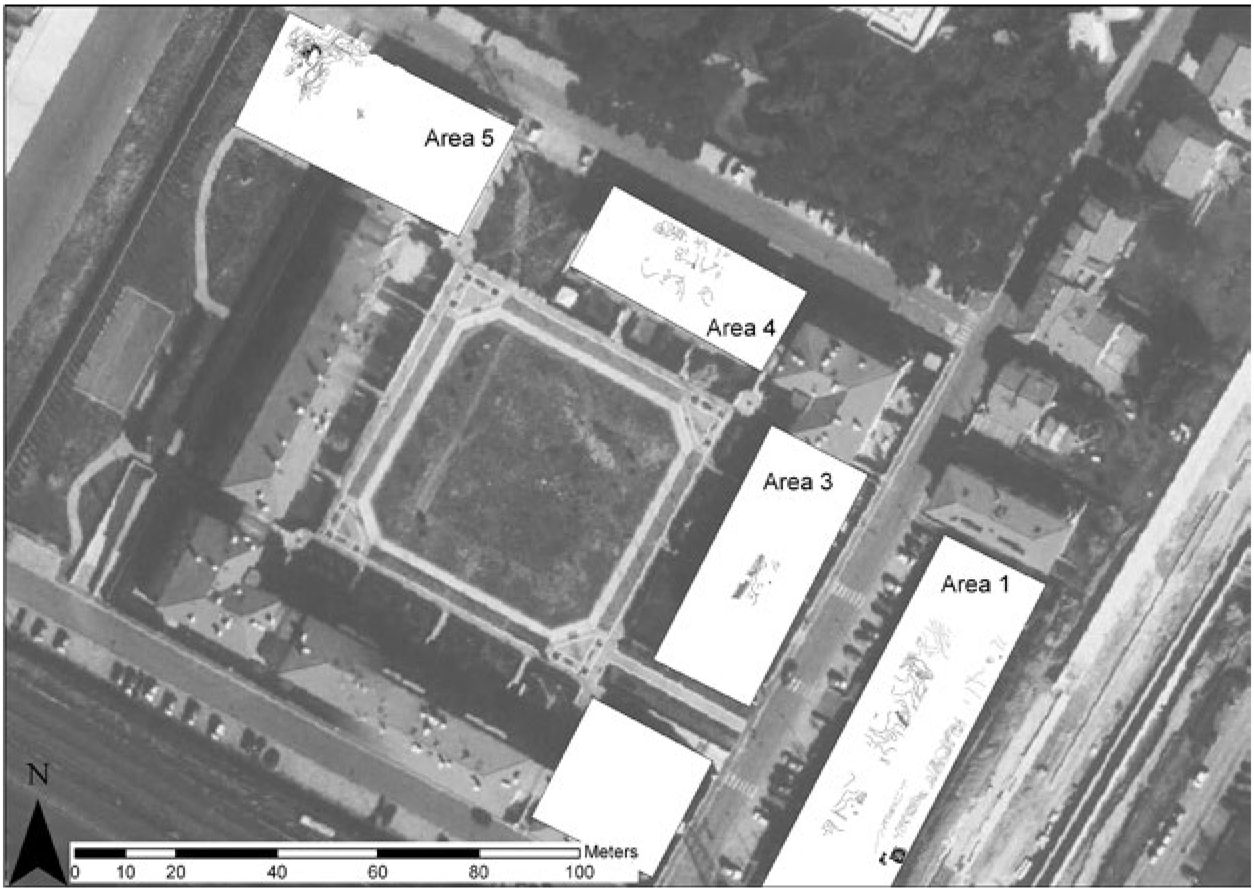

Fig. 7. Settlement unit: identification of features referred to the same chronological range. Features referred to the same phase have the same colour (for colour reference see scheme in Fig. 5).

that significant clues may be obtained through this contextual reading. In order to better perceive these spatial relationship, now completely affected by modern buildings, we have chosen to visualise historical air photographs (Fig. 8).

As a case study we analysed the relationship between layer 7 in sectors 1 and 3. In sector 1 this layer, referred to the Late Neolithic, shows a portion of a possible dwelling structure with an elongated pit which could be used for containing poles. In the external southern side of the elongated pit we have pointed out thin living floors extending out of the structures towards the S and W. Thanks to clipping planes and 3D visual analysis performed within the GIS area we can identify a possible continuity between this surface with the one in sector 3 related to the same phase (Fig. 9).

The Late Neolithic surface of sector 3 can be interpreted as a near-site area close to a deep erosion surface (stream?). On the eastern side of the erosion a dispersion of artefacts, mainly pottery, referred to layer 7 is positioned along the side of the slope. These artefacts show distinct shapes and a good state of preservation, implying that they are in an almost primary deposition; thus they did not move too far along the erosion bank (Fig. 10).

Through remote sensing analysis, which is in progress, we look for evidence of possible palaeoriver crossing the study area and spatially related to sector 3. If this is confirmed we might have identified a stream related to the settlement that could have been an attraction for potential dwellers. In fact in the area in front of the possible riverbank some small pits and burnt clay accumulation – possibly related to small earthen structures or to fire activities – may be related to open air activities undertaken in proximity to the stream. These observations have been developed through visual analysis performed through a dynamic change in scale and perspectives; these spatial relationships could not otherwise be detected.

The challenge is even more interesting when, through using these tools, we are able to connect anthropic and natural layers with the aim of investigating the formation of micromorphologies and settlement dynamics.

7 Eroded surfaces vs stable surfaces: positive and negative opportunities to detect prehistoric latent and evident structures

The Neto-Via Verga settlement unit is characterised by several latent structures which have been analysed also by means of quantitative and statistical analysis (Fenu *et al*. 2002). However in this contribution we want to focus our attention on visual analysis, as we believe that, due to the logistical and palaeoenvironmetal constraints mentioned above, new hints for the interpretation may come from an attempt to interpolate

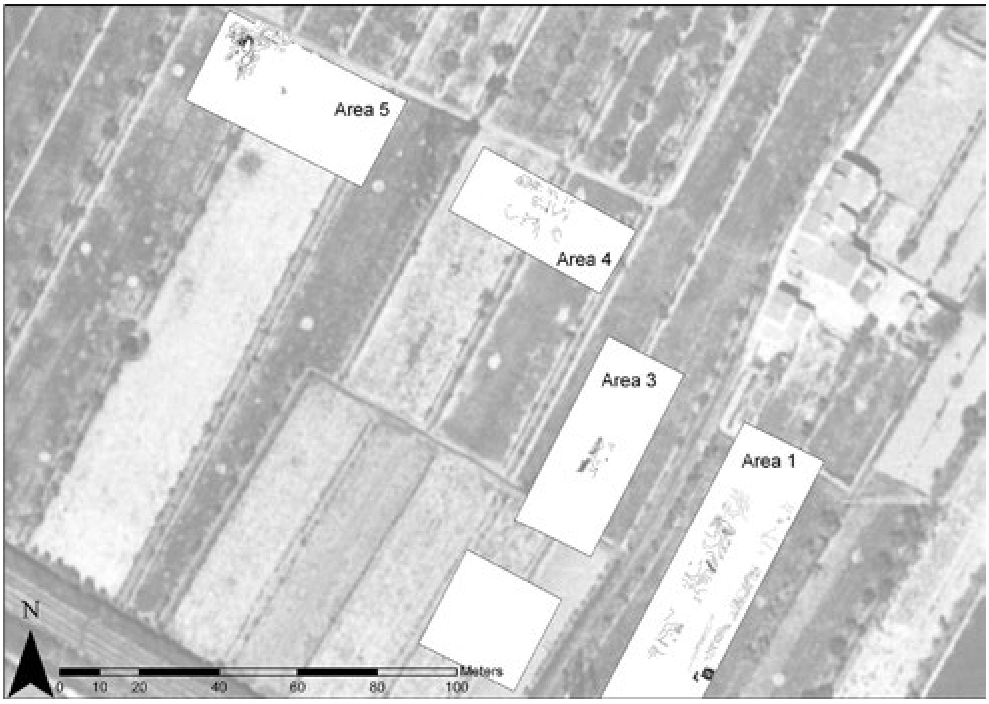

Fig. 8. Diachronic features visualised from historical aerial photographs (for colour reference see scheme in Fig. 5).

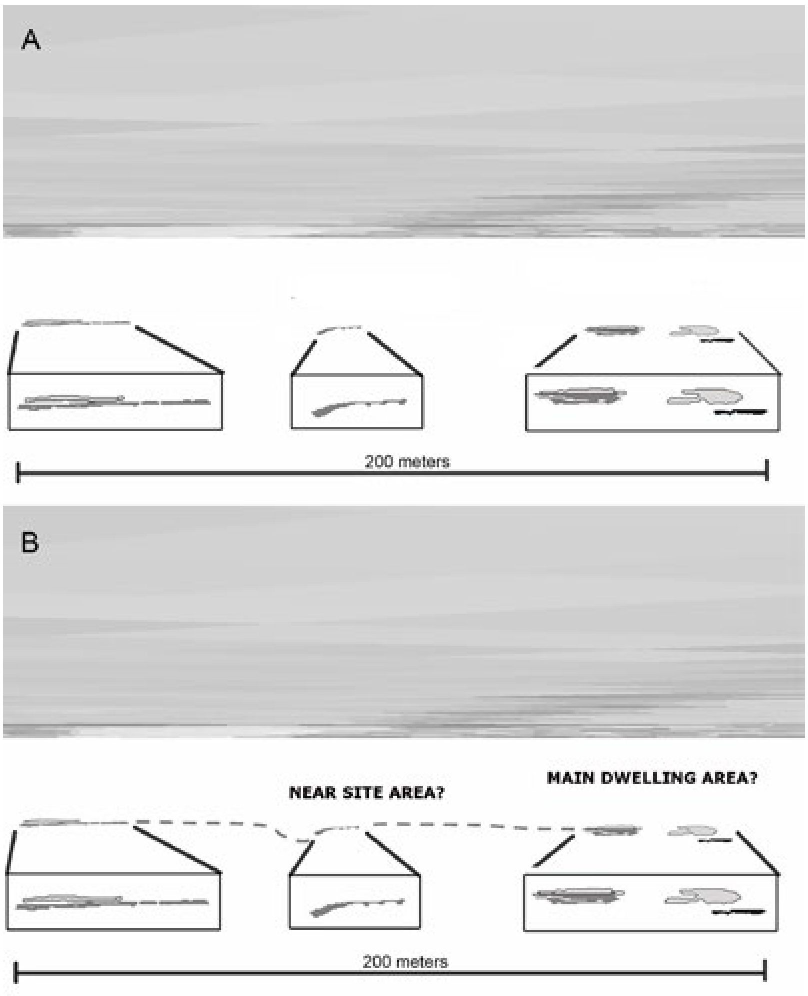

Fig. 9. Front view of Neto-Via Verga settlement unit: synchronic features can be spatially related (9a) and interpreted (9b).

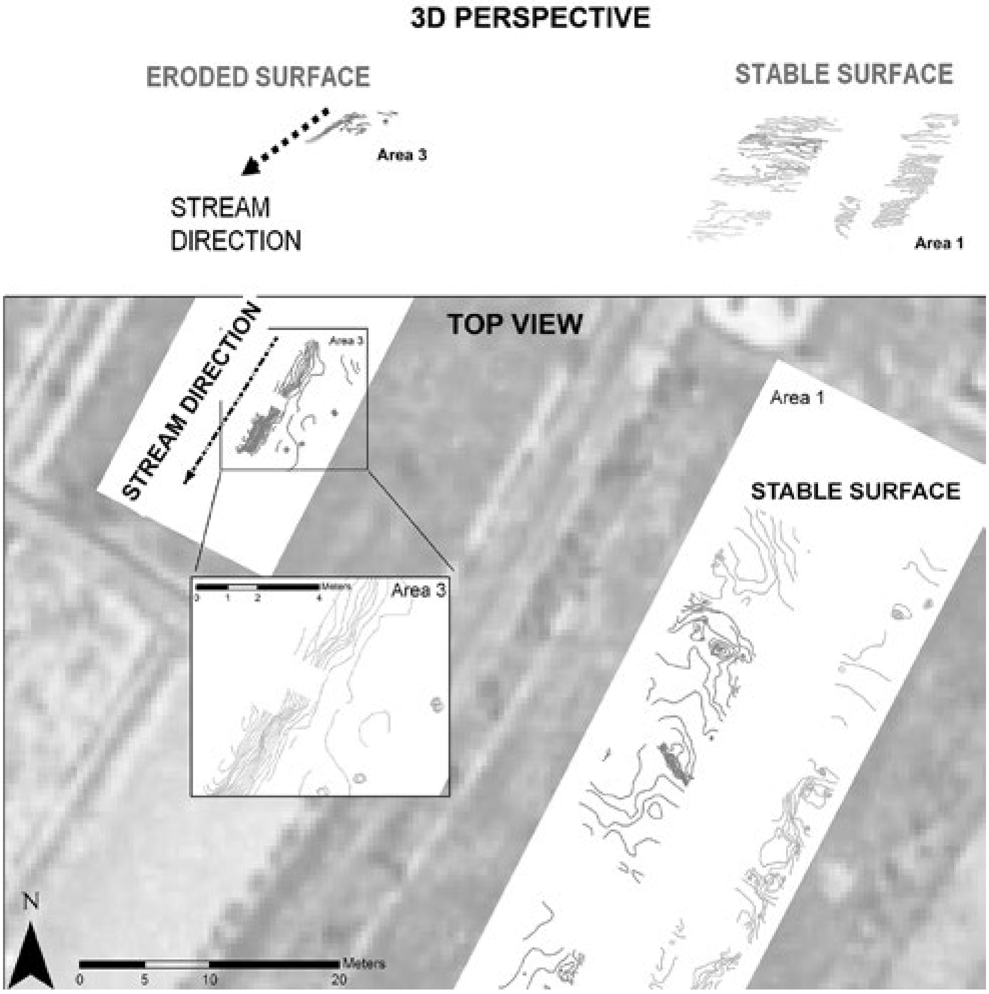

Fig. 10. Top view and 3D perspectives of diachronic features of Neto-Via Verga settlement unit (for colour reference see scheme in Fig. 5).

different excavation sectors. The efficacy of 3D exploration has been tested for this context (Pizziolo, Viti 2011) as well as at other prehistoric sites of Sesto Fiorentino (see Aquino *et al*. in this volume). Here we illustrate some case studies which reveal how clipping planes and artefact analyses may provide new interpretations or confirm archaeological readings recorded during excavation. In Layer 5 (Early Copper Age) and layer 7 (Late Neolithic) of sector 1 we have identified portions of two large structures which are characterised by bases shaped in shallow depressions. These areas are characterised by artefact concentrations c 15cm deep, which we have interpreted as belonging to the bases of huts. However there is no evidence of substructures. The edges of the structures are not sharply defined, and on part of one side the Neolithic structure is overlaid by the Copper Age one (Fig. 11). It was only through an accurate reading of the artefact distribution in the 3D environment that we have been able to distinguish a natural layer that is placed in between the two dwelling structures.

Taking into account this stratigraphic sequence, resulting from the visual analysis compared with other observations, we can define this area as a stable one, even if some light erosion could have occurred. This trend may also be confirmed by the analysis of the whole stratigraphic sequence of sector 1. In fact on the most south-eastern side of the area a well-preserved structure (referring to the Middle Neolithic – layer 10) has been found. This is characterised by a sunken structure covered by a layer of stones (Fig. 12). In that zone of sector 1 a consistent alluvial accumulation separates the Middle Neolithic layers from those of the Copper Age.

An opposite situation has been noticed in sector 5 where the visual analysis (Pizziolo, Viti 2011) identified several erosive factors testified by very thin layers, or by the absence of alluvial layers among the anthropic occupations spanning from the Middle Neolithic to the pre Bell-Beaker Copper Age.

From a contextual perspective we can connect together all the information and identify within the settlement unit the dwelling areas, some productive areas, and other zones that have been disturbed by subsequent erosion. Comparing the erosive and stable surfaces of the different sectors we can surmise where the main erosive actions took place and what might have been the top area of the banks related to erosive faces.

8 Conclusions

This dynamic approach allows us to perceive spatial information (Barcelo 2001) and attempt a reconstruction that can help in the definition of geomorphological and archaeological settings. The possibility to move from the intra-site level may provide useful information for inter-site analysis and help with the investigation of areas near to the site. The research allows us

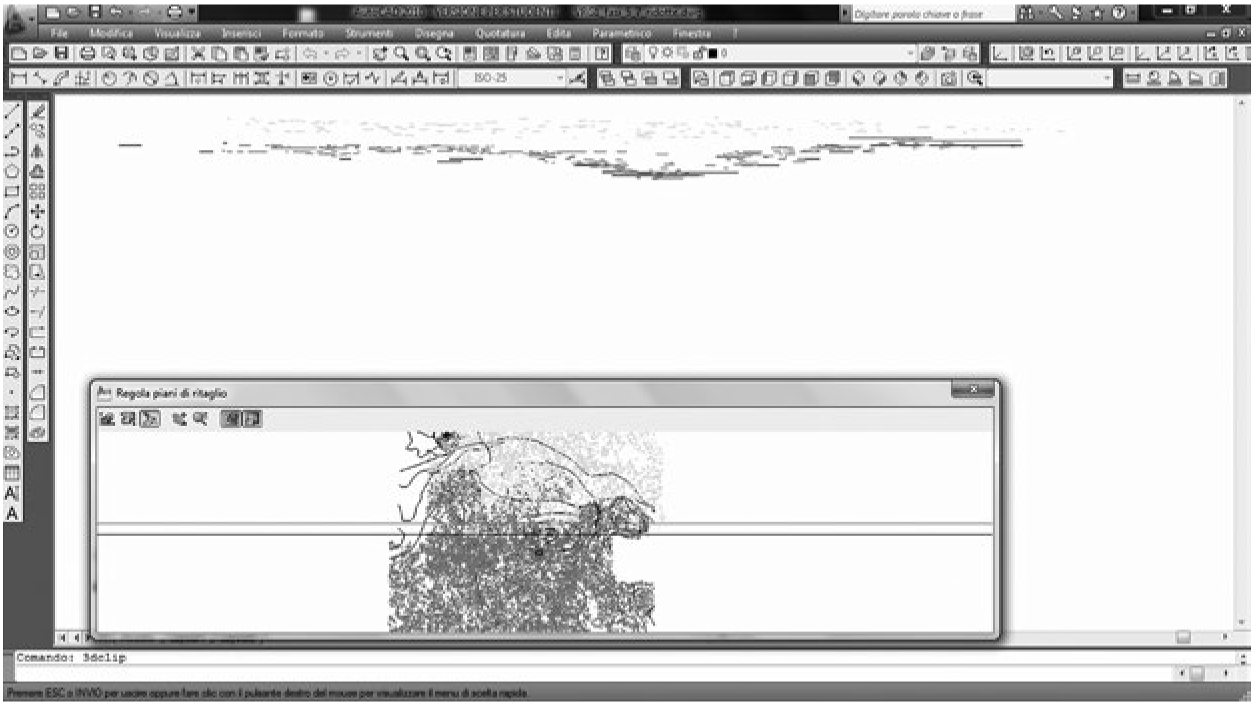

Fig. 11. Neto-Via Verga settlement unit: Layer 5 (Early Copper Age) and layer 7 (Late Neolithic) of sector 1. Overlay of different phases analysed in 3D interactive clipping planes.

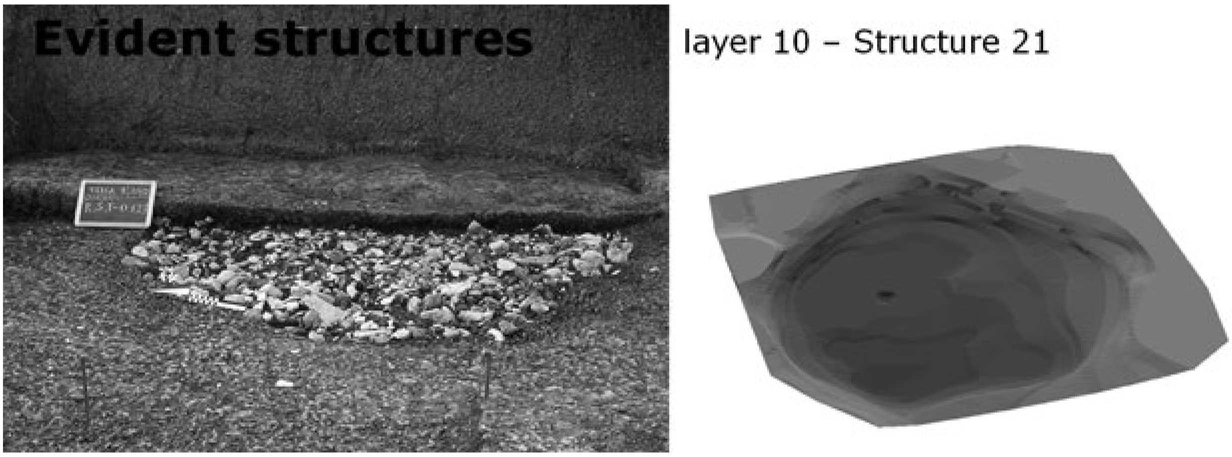

Fig. 12. Neto-Via Verga settlement unit, sector 1. Structure 21 referred to Middle Neolithic (layer 10): photo and 3D elaboration.

also to compare and validate spatial perceptions developed during excavation and virtually explored in the lab.

We need this complex corpus of data in order to investigate social actions and reconstruct the prehistoric palimpsest at different scales of analysis.

Acknowledgements

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Author contributions

The intrasite analysis was conceived by Giovanna Pizziolo and Nicoletta Volante, who contributed equally in this paper. The archaeological records and interpretation of excavation data was provided by Lucia Sarti.

Bibliography

Bagolini, B., Ferrari, A., Pessina, A. 1993. Strutture insediative nel neolitico dell'Italia settentrionale. *Atti del 13° Convegno Nazionale sulla Preistoria, Protostoria e Storia della Daunia, S. Severo 1991*, 2: 33-55.

Barcelò, J. A. 2001. Virtual reality and scientific visualisation. Working with models and

hypotheses. *International Journal of Modern Physics C, 12, 4*: 569–80

Blankholm, H. P. 1991. *Intrasite spatialanalysis in theory and practice*. Aarhus, Aarhus University Press.

De Silva, M., Fenu, P., Pizziolo, G., Sarti, L., Viti, S. 2001. *Verso un sistema informativo geografico per lo studio dei contesti preistorici nell'area di Sesto Fiorentino (Firenze). Lo stato della ricerca*. Rivista di Scienze Preistoriche, LI, 2000-2001: 471-81. Firenze, Istituto Italiano di Preistoria e Protostoria.

Ghinassi, M., Tangocci, F. 2008. Middle-Late Holocene deposits of the Sesto Fiorentino area (Florence, Italy): preliminary data. In M. Baioni,V. Leonini, D. Lo Vetro, F. Martini, R. Poggiani Keller, L. Sarti (eds.), *Bell Beaker in everyday life, Proceedings of the 10th Meeting 'Archéologie et Gobelets' (Florence – Siena – Villanuova sul Clisi), May 12-15, 2006*. Serie Millenni, Studi di Archeologia Preistorica, 6: 33-7. Firenze, Museo Fiorentino di Preistoria 'Paolo Graziosi'.

Leroi-Gourhan, A. 1984. Réflexion terminologique sur « structures ». In H. Berke, J. Hahn, C. J. Kind (eds.), *Jungpaleolithische Siedlungsstrukturen in Europa, Riesenburg/Gunzburg 8-16 mai 1983*. Urgeschichtliche Materialhefte, 6: 266. Tübingen, Verlag Archeologia Venatoria.

Pizziolo, G. 2007. Towards prehistoric landscape interpretation: GIS analysis of stratigraphical and remote sensing data in Sesto Fiorentino plain. In A. Figueiredo and G. Leite Velho (eds.), *The world is in your eyes - Proceedings of the XXXIII Computer Applications in Archaeology Conference: Tomar March 2005, CAA Portugal, Tomar*: 441-6. Tomar.

Pizziolo, G., Sarti, L. 2006. Exploring the archaeological landscape through a local perspective: spaces and places in the prehistory of the Florentine plain. In: Campana, S., Forte, M. (eds.) (2006) *From space to place: 2nd international Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International workshop, CNR, Rome, Italy,4-7 December 2006*. British Archaeological Reports International Series 1568: 261-9. Oxford, Archaeopress.

Pizziolo, G., Sarti, L. 2008. Prehistoric Landscape, Peopling process and Bell Beaker settlements in the Floretine Area. In M. Baioni, V. Leonini, D. Lo Vetro, F. Marini, R. Poggiani Keller, L. Sarti (eds.), *Bell beaker in everyday life, Proceedings of the 10th Meeting 'Archéologie et Gobelets' (Florence - Siena - Villanuova sul Clisi, May 12 - 15, 2006)*. Serie Millenni, Studi di Archeologia Preistorica, 6: 39-58. Firenze, Museo Fiorentino di Preistoria 'Paolo Graziosi'.

Pizziolo, G., Viti, S. 2011. A 3D perspective in the Interpretation of Living-floor Morphologies: Intrasite analysis of Prehistoric Contexts. In E. Jerem, F. Redo, V. Szeverényi (eds.), *On the Road to Reconstructing the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 36th International Conference, April 2-6-2008*: 454-62. Budapest, Archaeolingua.

Sarti, L. 1997. *Campaniforme di Neto-Vìa Verga (Sesto Fiorentino),* Rivista di Scienze Preistoriche, XL, 48: 367-98.

Sarti, L., Martini, F. 1993. *Costruire la Memoria. Archeologia preistorica a Sesto Fiorentino (1982-1992).* Montelupo Fiorentino.

Volante, N. 2003. La produzione vascolare dell'insediamento di Neto-Via Verga a Sesto Fiorentino tra la fine del Neolitico e la prima Età dei metalli, Rivista di Scienze Preistoriche, LIII: 375-504.

Viti, S. 2004. Between Recostruction and Reproduction: the role of Virtual Model in archeological research. In K. Fischer-Ausserer, W. Börner, M. Goriany, L. Karlhuber-Vöckl (eds.), *Enter the Past. The E-way into the four Dimensions of Cultural Heritage. CAA 2003. Computer Applications and Quantitative Methods in Archaeology*, British Archaeological Reports Series 1227: 525-8. Oxford, ArchaeoPress.

Viti, S. 2006. *Modalità insediative nella piana fi orentina nel Neolitico: analisi informatizzata e trattamento dei dati delle aree di frequentazione e delle strutture*. Unpublished Phd thesis, University of Pisa.

Living in a Palaeoriverbed: Intra-site Analysis of Two Prehistoric Sites in the Florentine Alluvial Plain

Rosalba Aquino
aquino@student.unisi.it

Matteo Faraoni
faraoni.matteo86@gmail.com

Laura Morabito
lauramorabito@hotmail.com

Giovanna Pizziolo
pizziolo@unisi.it

Lucia Sarti
lucia.sarti@unisi.it

Laboratory of Computer Science applied to Prehistory (LIARP), Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Abstract: This paper focuses on the intra-site analysis of two case studies from the area of Sesto Fiorentino (Florence): S. Antonio and Bulimacco Cilea. The sites, constituted by complex stratigraphies, are located in an alluvial plain affected by severe erosion/ accumulation processes. The two settlement areas are both positioned inside palaeoriverbeds but are characterised by some chronological and structural differences.

The study concerns the analysis, performed through the CAD and GIS applications, of the distribution of archaeological materials compared with the morphological settings and palaeoriverbed characteristics.

Visual analysis, spatial analysis and 3D reconstruction of micro morphologies and structures help us to test interpretations and hypotheses as well as to identify possible 'latent structures'.

Keywords: Intra-site analysis, Visual analysis, Palaeoriverbed, Bronze Age, Florentine plain.

Introduction

This paper[1] aims to provide some considerations on the intra-site analysis undertaken in the Florentine plain (Florence, Italy) on two prehistoric sites, Cilea and S. Antonio. This work is part of a broader project carried out since 1982 by the University of Siena and University of Florence with the Soprintendenza ai Beni Archeologici della Toscana, called 'Progetto Sesto' (Sarti and Martini 1993; De Silva *et al.* 2001; Pizziolo and Sarti 2008; Pizziolo and Sarti 2011).

Our study has been undertaken on a visual basis and it represents an initial stage of a more detailed analysis. After a brief presentation of the archaeological context the paper illustrates the peculiar characteristics of these two case studies referred to the Bronze Age. In particular, using the CAD and GIS applications we explore the settlement strategies which consist in settling inside palaeoriverbeds.

1 The study area and the archaeological contexts

The Sesto Fiorentino territory is located in the NW area of the broad geographical context of the Florence–Prato–Pistoia plain in which prehistoric evidence is placed in the complex alluvial plain system (Ghinassi and Tangocci 2008). The Pliocene lacustrine sedimentation related to the formation of the plain was covered by recent alluvial deposits which may affect the conservation and the visibility of prehistoric evidence. These have been mainly found and investigated within the policy framework of rescue excavation activities.

The location of prehistoric sites (Pizziolo and Sarti 2008; Pizziolo and Sarti 2011) suggests possible settlement trends spatially related to the presence of palaeoriverbeds and highlights how the area was increasingly occupied from the end of the 6th to the 2nd mill. BC (Martini and Sarti 2015). A peculiar settlement strategy has been individuated for the Bell Beaker sites which are widely testified in this part of the alluvial plain. The Bell Beaker settlements are located inside the paleoriverbeds exploiting the drainage 'facilities' provided by the bottom gravel deposits of the abandoned river bed. This

[1] Authors' contribution: archaeological data L.S., project and methodology G.P., Bulimacco Cilea R.A., S. Antonio M.F., supervision of case studies L.M.

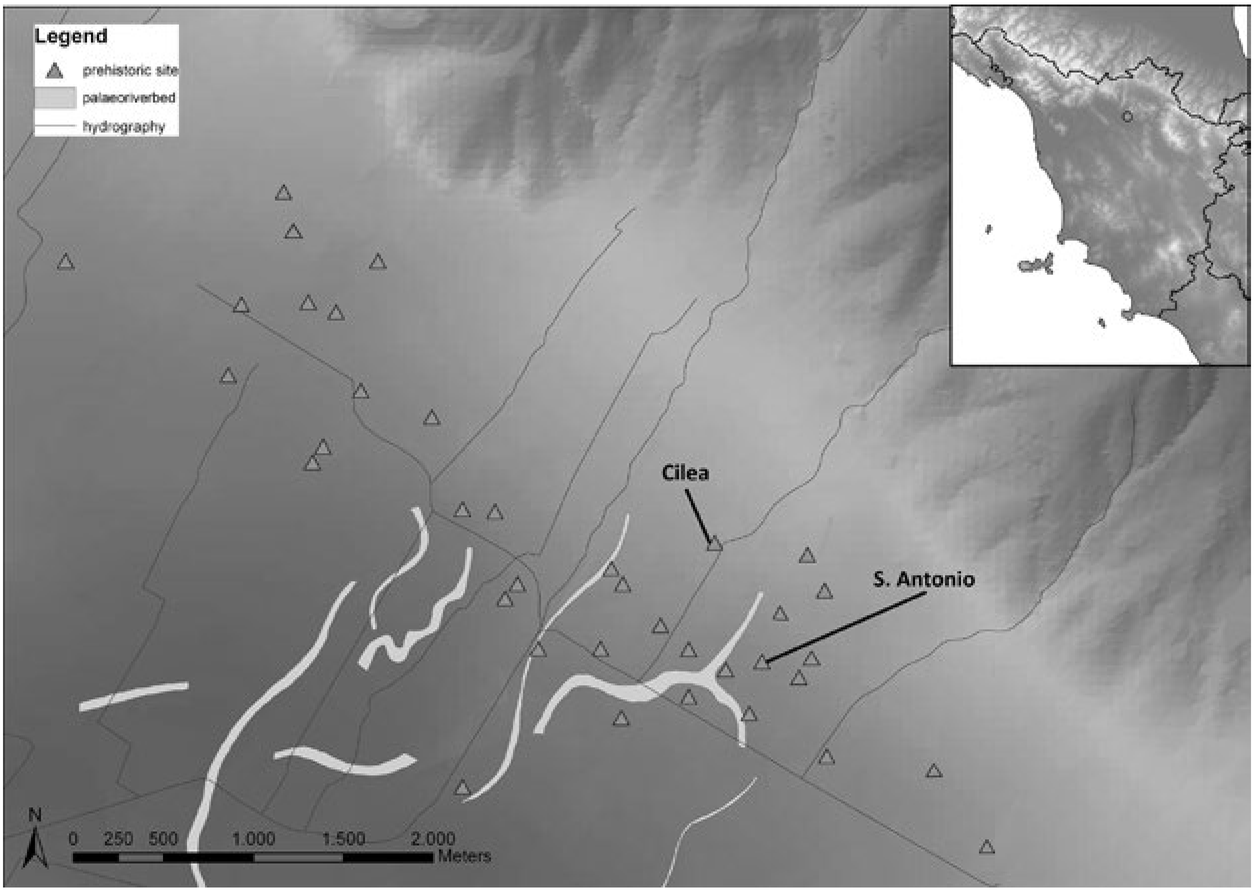

Fig. 1. Archaeological site location in the Sesto Fiorentino area. Prehistoric sites and location of the main palaeoriverbeds derived by photointerpretation.

specific settlement strategy has been well attested (Martini and Sarti 1993; Pizziolo and Sarti, 2008). However the two Bronze Age sites of Bulimacco Cilea and S. Antonio (Fig. 1) are also located on palaeoriverbed morphology, suggesting new issues for these Bronze Age dwelling choices. It is worth noting that in the Florentine plain the sites, from Middle to Late Bronze Age, are generally characterised by dwelling structures located in shallow depressions but not inside the abandoned beds of palaeorivers. Consequently through this intra-site analysis we attempt to explore if this peculiar settlement strategy of Bell Beaker sites was adopted also during the Bronze Age phases.

2 Methods

The rescue excavations carried out since the 1980 in the Sesto Fiorentino territory produced a large number of detailed data in traditional paper formats and which did not envisage any digital elaboration at that time. A process to convert this precious information into a GIS system in order to manage and analyse excavation data started in 2001 (De Silva *et al.* 2001) and has been developed following various strategies. The procedure was set up by the LIARP (Laboratory of Computer Science Applied to Prehistory at University of Siena) and consists in digitising all the plans (at different scales from 1:10 to 1:100) and cross section drawings through CAD in a vector format, building up a 3D environment to validate the topology of layers and palaeosurfaces. Plans and sections are integrated in a unique environment in order to have a first 3D visualization with the 'Orbit Tool' and to validate the spatial consistency of documentation.

Once the vector files are imported into GIS a second phase of validation is also carried on linking together also the information related to artefacts which are recorded into databases: this procedure allows us to create thematic maps and to visualise the distribution of classes and typologies of archaeological finds.

In general our study followed these main procedures:

CAD

- Digital acquisition of paper documentation
- Creation of an unique environment of analysis
- 3D data validation of different type of sources
- Visual analysis with clipping planes

GIS

- Data import in GIS environment
- Layer organisation and digital database management

- Visual analysis
- Spatial analysis
- Quantitative analysis

As for the management of information in a 3D environment the 'Interactive 3D orbit' and *ad hoc* clipping planes help us to get a clearer reading of the archaeological vertical distribution. These tools have been effective for our case studies to perform the analysis of the relationship between the displacement of archaeological materials and the morphology of the palaeoriverbeds.

3D orbit allows an interactive rotation around a target in any direction. This means that after digitizing every feature of the archaeological deposit it is possible to navigate interactively the stratigraphy as it was before the excavation.

Clipping planes are useful visual tools which 'create' virtual sections of the material distribution in a 3D perspective through secant planes. Thus we create a sort of slice – delimited by the two clipping planes, the Front and the Back ones – which cut the palaeoriverbed orthogonally along its main orientation. All the features included in the slice are projected on the background plane which results in a virtual cross section.

Our front view cutting features the front side of the palaeoriverbed in order to visualise the vertical distribution of materials in their third dimension and to identify their position in relation to the palaeoriverbed morphology. In other words we can explore the relative stratigraphic position of archaeological features in a dynamic and virtual way.

In the second stage, digital data were imported in GIS and then georeferenced. This is a fundamental procedure that allows us to spatially relate the different excavation sectors together. Often the policy of rescue activities rarely permits us to merge the different sectors in a unique excavation area. The combination of different sectors helps us to recognise the presence of 'settlement units' (see Pizziolo *et al.* in this volume).

The interaction between the CAD and GIS systems has been of primary importance for the integration of archaeological and morphological data. For the study of the Bulimacco Cilea and S. Antonio sites the visual analysis, spatial analysis and 3D reconstruction of micro morphologies and structures helped us to test interpretations and hypotheses that have been suggested during the excavation, as well as to identify possible 'latent structures' (*sensu* Leroi-Gourhan, Leroi-Gourhan 1984; Cavulli 2008).

How can we infer dwelling activities and settlement strategies by using the analysis of artefact distribution? If we assume that 'the area where spatial density values are more continuous is the most likely place where a social action was performed' (Barcelo and Maximiano 2007: p. 6), we may focus our attention on identifying artefact concentration. Moreover the spatial distribution of pottery fragments, charcoal (Tasca 1998) and stones which are part of the palaeosurfaces is hard to examine through a simple visual observation of such a mix of vector features. Our aim is therefore to use the spatial tools available in GIS in order to better explore artefact concentrations. At this stage of the research a first application of density analysis has been performed using the Kernel algorithm. The Kernel Density tool calculates the density of features in a neighbourhood and produces isonumeric curves. For our case studies we applied this algorithm to different classes of archaeological material (ceramic, lithic, charcoal, etc.) belonging to palaeosurfaces by setting fixed parameters which made the different densities comparable. In the next phase, when the artefact information is completely available and uploaded to the GIS, we will apply quantitative and geostatistical analysis (Blankholm 1991).

For the Bulimacco Cilea and S. Antonio sites we are investigating spatial relationships among palaeosurfaces and palaeoriver morphologies. For this reason we have produced Digital Elevation Models of the bed morphologies, and created Slope and Flow Direction maps. These operations allow a better view and analysis of the natural and anthropic morphologies. A 3D reconstruction of micro morphologies has been carried out in order to help structure interpretation (Fig. 2a, 2b, 2c) and to identify the natural or artificial origin of some layers (Fig. 3). We also applied flow direction analysis to derive the hydrologic characteristics of a surface so as to calculate the direction of flow from every cell in the raster.

3 Bulimacco Cilea

The multi-stratified settlement unit of Bulimacco-Cilea (Pizziolo and Sarti 2008) is constituted of five areas at Cilea (A, B, C, D, E) and by the site of Bulimacco. The archaeological rescue excavation (1991-92) was carried out in different intervals without having at that time the possibility to merge the different sectors in a unique excavation area.

We focused our intra-site analysis on Cilea areas C, D and E, which cover 740m^2. These areas show a prehistoric occupation spanning from Copper Age to Final Bronze Age with some interruptions (Fig. 4).

Due to rescue constraints the site is characterised by some critical conditions which affected the archaeological analysis:

- stratigraphic complexity
- fragmented documentation
- difficulties in mapping single palaeosurfaces
- 'overlap' and direct contact of different chronological layers in certain zones

Throughout the intra-site study we have tried to:

- organize different types of documentation in a unique environment
- analyse the palaeosurfaces and individuate functional areas
- interpret functional characteristics of the structural elements
- identify possible latent structures (*sensu* Leroi-Gouran)
- analyse the natural and anthropic changes of the palaeoriverbed

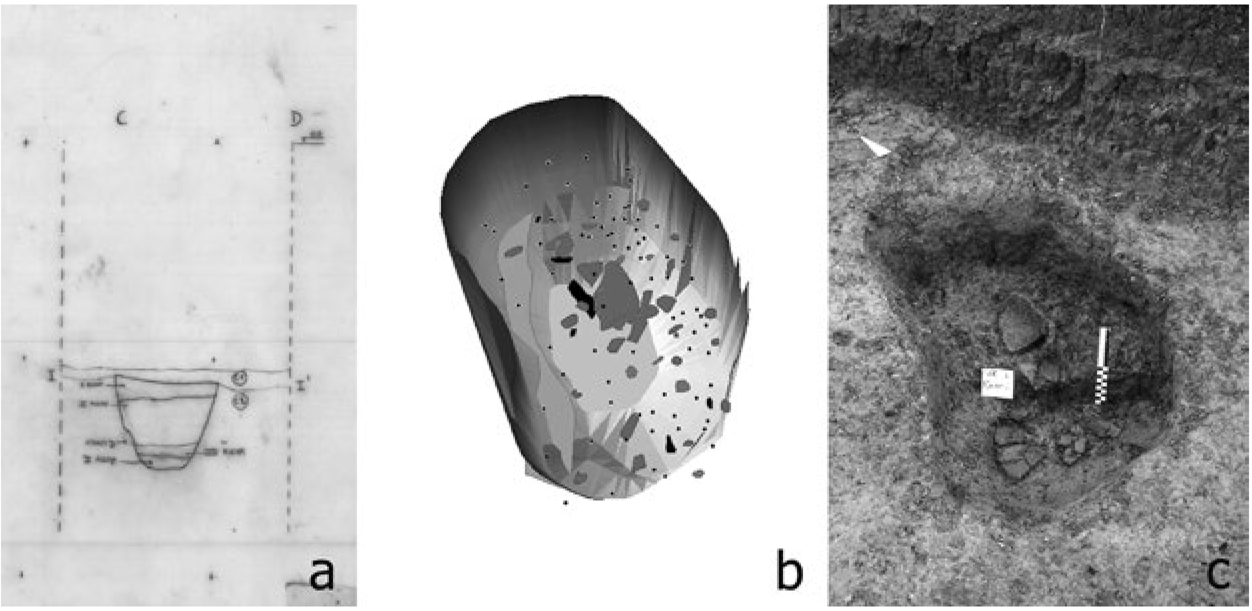

Fig. 2. A) Cross section drawing of structure 1 in S. Antonio. B) 3D reconstruction of micro morphologies carried out in order to perform structures interpretation: structure 1 S. Antonio. C. Photography of structure 1 of S. Antonio.

Fig. 3. 3D representation (ArcScene) of artefact distribution and palaeoriverbed of S. Antonio.

- identify settlement strategies

Among our goals we would like to study the spatial relationships among palaeosurfaces, dwelling strategies and natural morphology.

As far as the management of data is concerned, we adopted the consolidated procedures developed by the LIARP (see above).

Due to the rescue nature of the archaeological dig, the palaeosurfaces have been documented following artificial boundaries according to the limits of the excavation grid. Consequently the first step was focused on individuating the limits of the prehistoric palaeosurfaces. This goal was achieved by applying clipping planes (see above). The clipping planes have been moved orthogonally to the palaeoriverbed direction in order to read the vertical distribution of archaeological materials in their third dimension and to locate their positions related to the palaeoriverbed morphology.

This procedure is very effective for studying complex stratigraphies such as the ones of our case studies. For instance when we set the clipping planes orthogonal to the river direction it is possible to notice a particular overlay of Copper and Bronze Age materials without any clear spatial separation. Then in order to better investigate this phenomenon we have changed the clipping planes direction: the front view was set parallel to the palaeoriver direction, so an intermediate layer was clearly visible, without any archaeological materials, between the distribution of the Bronze Age finds and the Copper Age ones. This reconstruction of the virtual position of the artefacts was possible only through clipping planes. By applying these 3Dclip tools it has been possible to highlight the relationships among archaeological surfaces, settlement strategies and natural morphologies.

In this case the new visual perspective provides an interesting hint that we therefore investigated through other spatial analysis.

As already mentioned, in this study the integration of CAD and GIS analysis has been of fundamental importance. In fact GIS thematic distribution related to specific diagnostic artefacts validates the visual analysis performed through CAD (Fig. 5).

Through the density analysis it has been possible to focus on a specific area that may be interpreted as being related to peculiar functions: for instance a hypothetical fire place it has been identified corresponding to the maximum density of pottery, burnt clay and charcoal in a Final Bronze Age layer (Fig. 6, yellow area).

A quantitative approach has been tested for a specific material class, such as 'cooking stands' (Scheffer 1981), which have been mapped on a square metre grid base (Pizziolo and Viti 2011). The typological information related to the cooking stands was imported into the GIS in order to visualise the distribution of these materials. Then a map algebra calculation

Fig. 4. DEM of the palaeoriverbed of the site of Cilea.

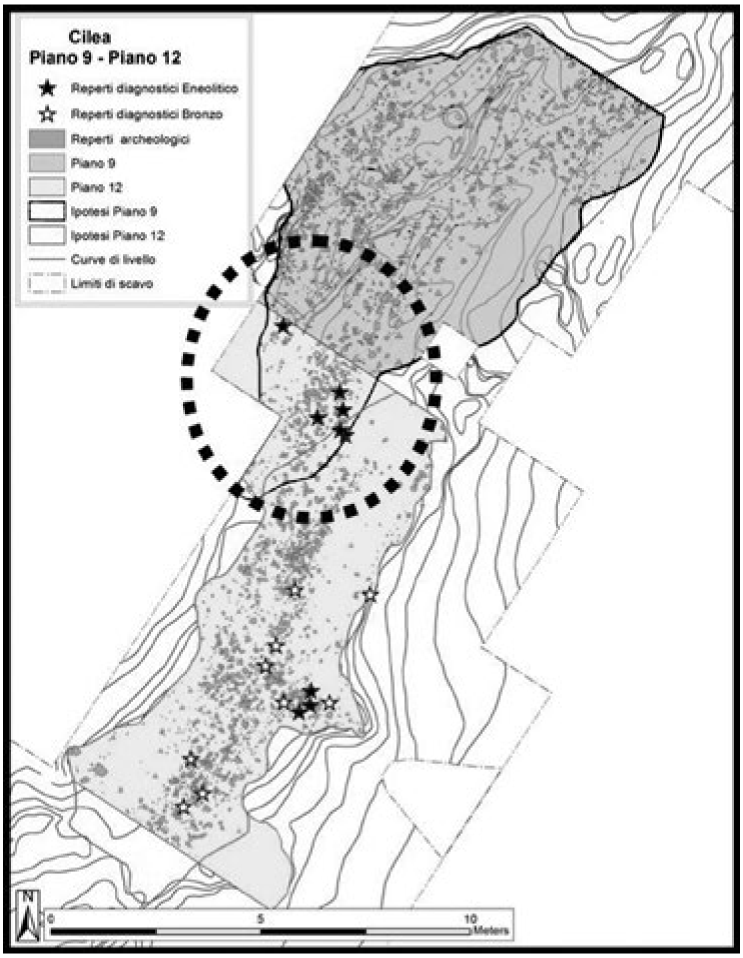

Fig. 5. Thematic distribution related to specific diagnostic artefacts which validates the visual analysis obtained through CAD in Cilea.

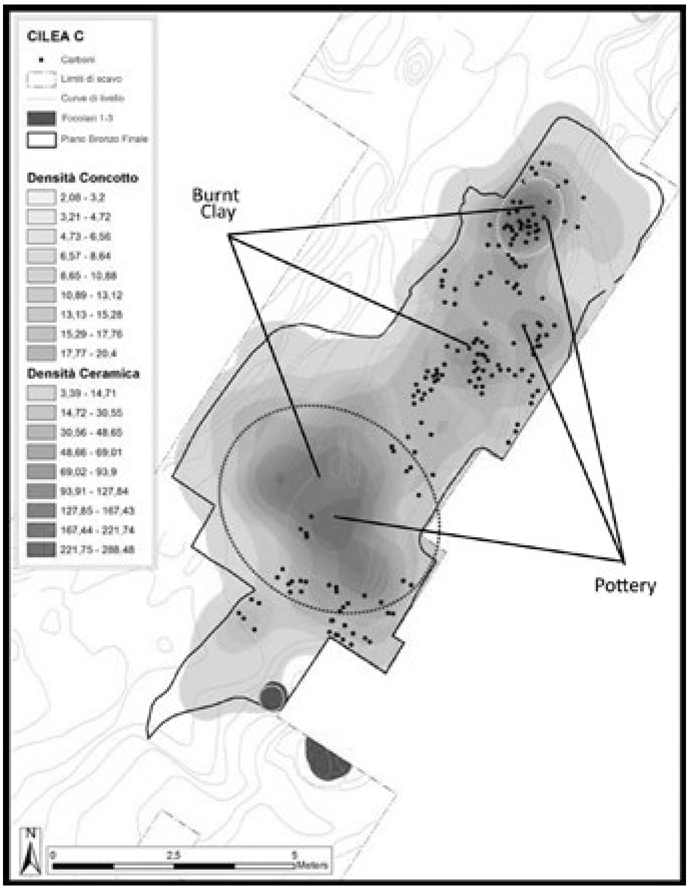

Fig. 6. Example of spatial analysis of the Final Bronze Age layer. The area in the smallest circle was interpreted as an hypothetical fireplace corresponding to the maximum density of pottery, burnt clay and charcoal in Cilea.

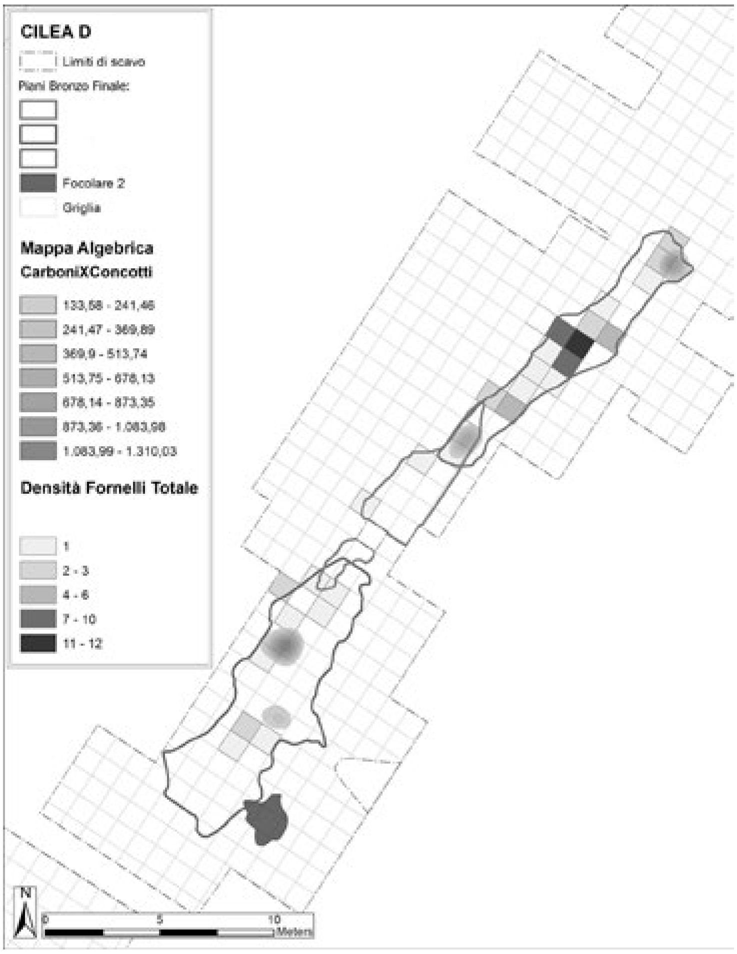

Fig. 7. Example of a map algebra calculation of Cilea. Burnt clay density multiplied by charcoal density and overlaid on cooking stands.

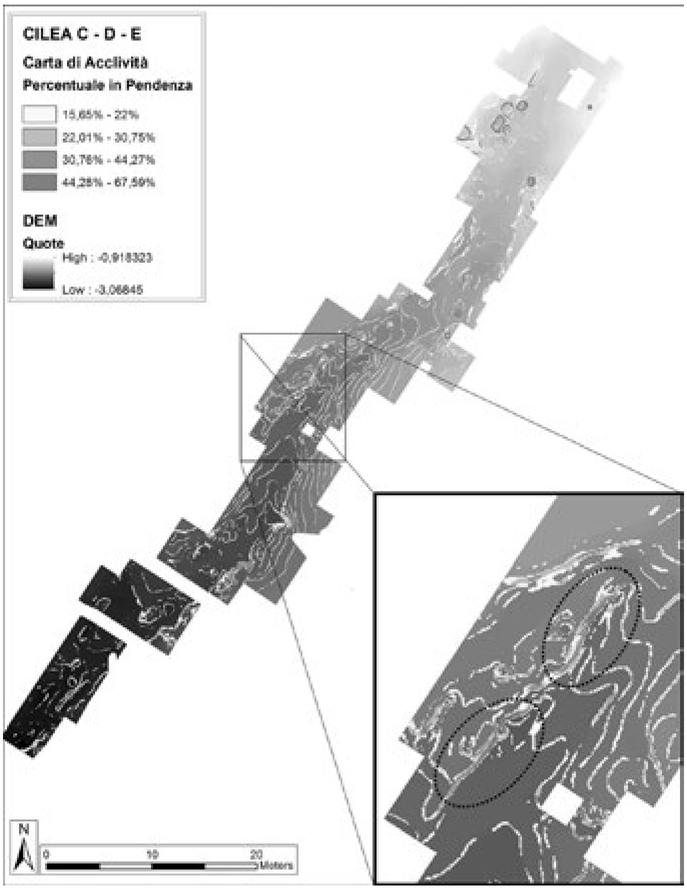

Fig. 8. Slope analysis combined with DEM of Cilea: in proximity of a higher percentage the slope could be referred to anthropic action.

was performed by multiplying the burnt clay distribution by the charcoal distribution (Fig. 7).

Furthermore the DEM has been used to analyse the morphology of the palaeoriverbed and to visualize the flow direction of the river when it was active.

The micro morphology study of the palaeoriverbed was useful for distinguishing natural from anthropic actions through the help of slope analysis. In proximity of a higher percentage of acclivity a form of human action has been hypothesized (Fig. 8).

Through spatial analysis in GIS a definition of the different extent of layers was achieved (Fig. 9).

Outcomes:

- Use of a partially 'filled' and eroded palaeoriverbed banks which can be compared to the other cases of Final Bronze Age dwelling structures in slight depressions.

- Opportunistic exploitation of Copper Age layers for drainage facilities.

- Identification of different kinds of relationships between occupation layers and palaeoriverbed morphology.

The visual analysis in a 3D environment proved/demonstrated the exploitation of slight depressions, typical of Middle and Final Bronze Age, and the banks of the paleaoriverbed were partially covered with Copper Age layers. We suggest a possible opportunistic use of the Copper Age layers as functional elements for drainage.

4 S. Antonio

The S. Antonio settlement unit (Fig. 10) is divided into four areas and our study focused on the A4 area, which shows a continuous occupation during the Middle Bronze Age, spaced by several phases of erosion/abandonment. A first occupation of the site, referred to as Middle Bronze Age, is positioned on the palaeoriverbed morphology. This is followed by layers in which alluvial and erosion actions have been individuated. A second occupation of the Middle Bronze Age covers this natural deposit and is followed by other erosive phenomena. The last occupation of this area is referred to the late phases of the Middle Bronze Age, which was then covered by modern natural deposits.

S. Antonio has been investigated through rescue excavation in 2001-2002. The archaeological documentation was recorded in the traditional way and drawn on paper. Consequently the data for the intra-site analysis have been acquired following LIARP procedures (see above).

This kind of analysis allows us to investigate some problems and suggestions we encounter during the excavation phases and the study of the site.

At this stage of the research our analysis is focused on these issues:

Fig. 9. Definition of the different extent of layers through spatial analysis in Cilea.

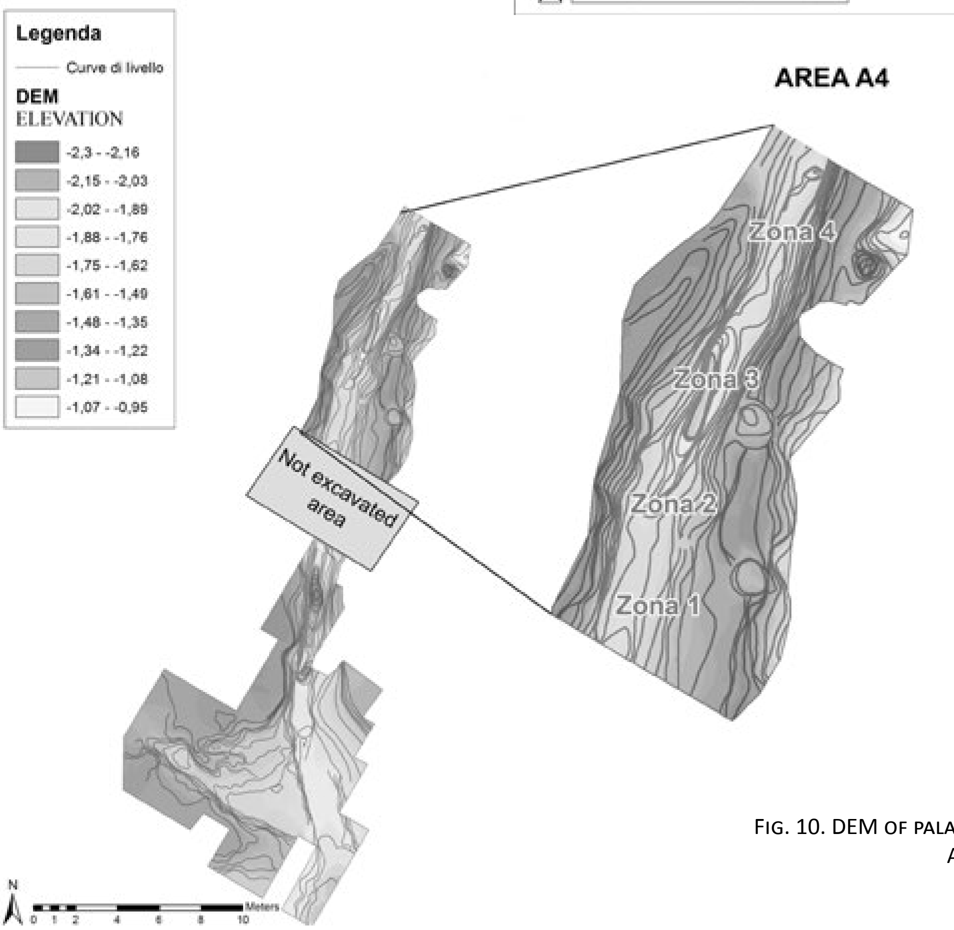

Fig. 10. DEM of palaeoriverbed of the site of S. Antonio.

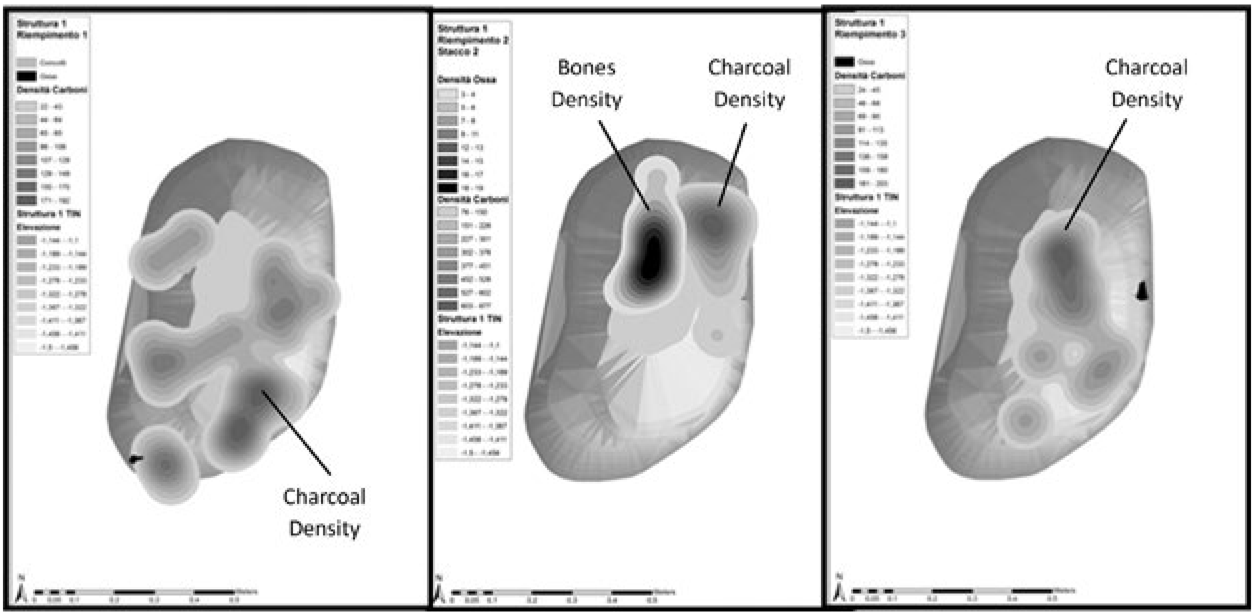

FIG. 11. DENSITY ANALYSIS: OVERLAY OF DENSITIES INSIDE THE STRUCTURE 1 OF S. ANTONIO.

- correlation of archaeological structures with the artefacts' distributions
- morphological and functional interpretation of structural features
- recognition of anthropic adaptation of the palaeoriverbed morphologies
- individuation of functional areas
- interpretation of functional areas
- interpretation of the Bronze Age settlement strategy compared with the Copper Age one testified in the Florentine plain

The correlation of archaeological structures with the artefact distribution has been studied through the application of clipping planes tool. This procedure allows us to individuate and propose stratigraphical relationships between structures and anthropic layers, setting up a chronology for the formerly undefined structures.

The morphological and functional interpretation of structural features has been developed throughout the analysis of the structures (for example structure 1) with the use of density tools available in the GIS software. The observation of the densities allows us to explore the structures in a better way. For example the overlay of these densities inside structure 1 shows the spatial trend of the artefacts, probably thrown into the structure, which we propose to interpret as a dump pit (Fig. 11).

The recognition of anthropic action on the palaeoriver morphology has been carried out through DEM analysis. This elaboration highlights the particular shape of an elongated pit located on the base of the palaeoriver. This elongated pit could be possibly interpreted as a pit for the installation of a light cover. The slope analysis also shows the presence of a small horizontal surface between structures 5 and 2 (Fig. 12).

The density tool has been used to investigate the presence of functional areas. We therefore have applied density analysis to the artefacts distribution included in the second layer of occupation, i.e. charcoal, burnt clay and plaster (Fig. 13). The overlap of these data reveals a singular concentration of these materials in a specific area, allowing us to suppose here the presence of a light cover structure.

The charcoal inside the second layer of occupation has been analyzed in its volumetric distribution, and the uppermost and lowest features have been selected in order to create two surfaces. So we have interpolated the upper and the lower features with the tool available in GIS and generated the upper and lower surface of this charcoal layer. After this operation the two surfaces have been cut in order to create a virtual cross section visible in 3D GIS environment (ArcScene): this reveals that the upper surface has the shape of a lens where it intersects the palaeoriver morphologies (Fig. 14).

The site, despite its chronology, shows the typical settlement strategy of dwelling which exploits the palaeoriverbed morphologies already testified in the Florentine area during the Bell Beaker period and Ancient Bronze Age.

5 Final remarks

The integrated methodology and tools we used led us to propose new hypotheses for the reading of the stratigraphic sequence and for the chronological interpretation of some palaeosurfaces.

Through the application of intra-site analysis and micro-morphological analysis it has been possible to recognize with more precision the anthropic action on the palaeoriver

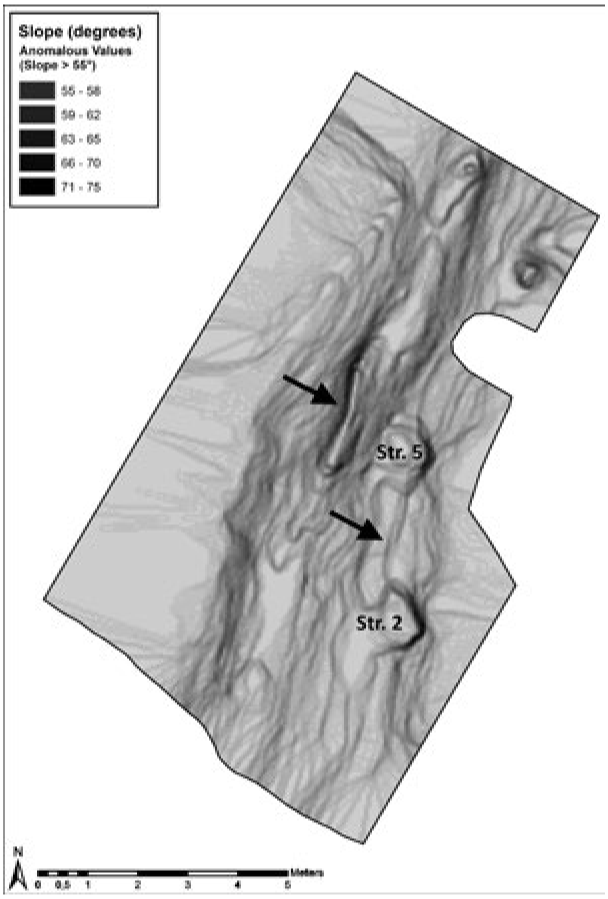

Fig. 12. Slope analysis of S. Antonio, in particular the shape of a pit located on the base of the palaeoriverbed and the small horizontal surface between structures 5 and 2 st S. Antonio.

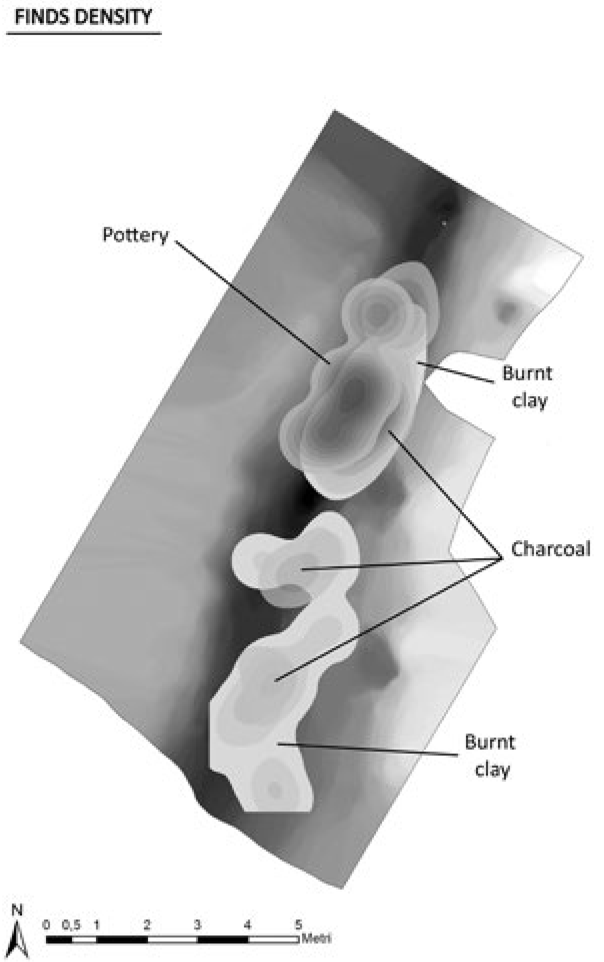

Fig. 13. Overlay of density analysis of charcoal, burnt clay and plaster for layers relating to the second occupation of Middle Bronze Age of S. Antonio.

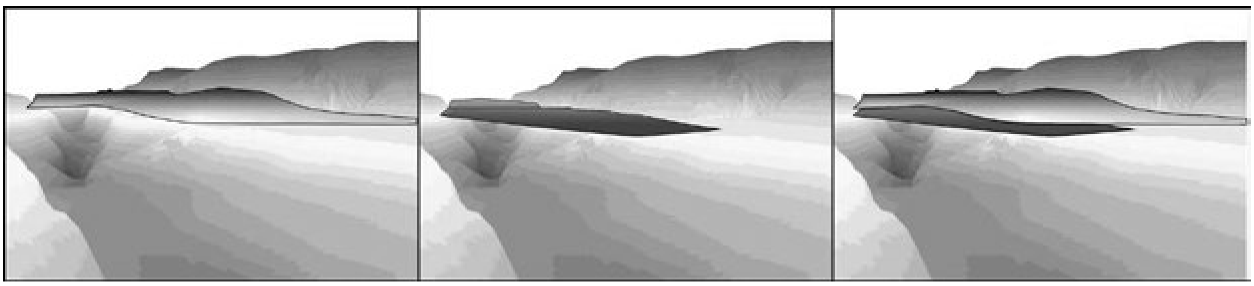

Fig. 14. 3D perspective of the upper and lower surface of the charcoal lens inside the layer related to the second occupation of Middle Bronze Age of S. Antonio.

morphologies and their opportunistic exploitation with more precision. The comparison between the two sites enabled us to emphasize differences and similarities of the palaeoriver occupation through time. In the next phase, when artefact information will be completely available via the GIS, we will apply geostatistical analysis to integrate and validate our interpretations with statistics analysis and further quantitative elaborations.

Once the study of the artefact classes is completed it will be possible to integrate these data into our system and so we will propose further intra-site analysis and eventually new interpretations.

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Bibliography

Aquino, R. 2013. *Il sito di Cilea a Sesto Fiorentino (FI). Analisi intrasite delle fasi dell'Età del Bronzo*. Unpublished MA Thesis (Laurea Specialistica in Archeologia), University of Siena.

Balducci, C., Cuda, M. T., Sarti, L. 2008. La transizione bronzo antico - medio nell'Italia centrale tirrenica: problematiche interregionali e tematiche locali attraverso alcuni casi studio toscani. In A. Manfredini (ed.), *Origini. Preistoria e protostoria delle civiltà antiche*, XXIX: 33-74. Roma, Gangemi Editore s.p.a.

Barceló, J. A, Maximiano, A. 2007. The mathematics of domestic spaces. Paper presented at the Archaeology of the Household Workshop. Barcelona, April 2006. Universitat Autonoma de Barcelona. Published by the Centro de Investigaciones Científicas. [On line] Available from: http://prehistoria.uab.es/barcelo/publication/mathdomspaces.pdf [Accessed: 23 June 2015].

Blankholm, H. P. 1991. *Intrasite spatialanalysis in theory and practice*. Aarhus, Aarhus University Press.

Cavulli, F. 2008. *Abitare il Neolitico. Le più antiche strutture antropiche del Neolitico in Italia Settentrionale*. Preistoria Alpina, 43, Supplemento 1. Trento, Museo Tridentino di Scienze Naturali.

De Silva, M., Fenu, P., Pizziolo, G., Sarti, L., Viti, S. 2001. *Verso un sistema informativo geografico per lo studio dei contesti preistorici nell'area di Sesto Fiorentino (Firenze). Lo stato della ricerca*. Rivista di Scienze Preistoriche, LI, 2000-2001: 471-81. Firenze, Istituto Italiano di Preistoria e Protostoria.

Faraoni, M. 2013. *Indagine intrasite del sito dell'Età del Bronzo di S. Antonio Area A4 (Sesto Fiorentino-Firenze)*. Unpublished BA Thesis (Laurea Triennale in Scienze dei Beni Archeologici), University of Siena.

Fenu, P., Pizziolo, G., Sarti, L., Viti, S., Volante, N. 2002. Elaborazioni e analisi distributive del sito di Neto Via Verga: problemi e prospettive di ricerca di un contesto insediativo complesso. In C. Peretto (ed.), *Analisi informatizzata e trattamento dati delle strutture di abitato di età preistorica e protostorica in Italia*. Collaga Origines, serie Progetti 1: 159-171. Firenze, Istituto Italiano di Preistoria e Protostoria.

Ghinassi, M., Tangocci, F. 2008. Middle-Late Holocene deposits of the Sesto Fiorentino area (Florence, Italy): preliminary data. In M. Baioni, V. Leonini, D. Lo Vetro, F. Martini, R. Poggiani Keller, L. Sarti (eds.), *Bell Beaker in everyday life, Proceedings of the 10th Meeting 'Archéologie et Gobelets' (Florence – Siena – Villanuova sul Clisi), May 12-15, 2006*: 33-7. Serie Millenni, Studi di Archeologia Preistorica, 6. Firenze, Museo Fiorentino di Preistoria 'Paolo Graziosi'.

Leroi-Gourhan, A. 1984. Réflexion terminologique sur « structures ». In Berke, H., Hahn, J., Kind C. J. (eds.). *Jungpaleolithische Siedlungsstrukturen in Europa, Riesenburg/Gunzburg 8-16 mai 1983*: 266. Urgeschichtliche Materialhefte 6. Tübingen, Verlag Archeologia Venatoria.

Martini, F., Pizziolo, G., Sarti, L. 2007. Paesaggi nell'antichità: Uomo e ambiente in area fiorentina nella preistoria. In Conti, S., Scardigli, B., Torchio, M. C. (eds.), *Geografia e viaggi nell'antichità*, *Atti del Convegno Internazionale di studi Certosa di Pontignano*: 123-47. Ancona, Affinità Elettive.

Martini, F., Poggesi, G., Sarti, L. 1999. *Lunga memoria della piana. L'area fiorentina dalla preistoria alla romanizzazione. Guida alla mostra.* Firenze e Pontassieve, Centro Stampa 2P s.r.l.

Martini, F., Sarti, L. 2015. Prima di Firenze: dal Paleolitico all'Età del Bronzo. In V. D'aquino, G. Guarducci, S. Nencetti, S. Valentini (eds.), *Archeologia a Firenze: città e territorio. Atti del workshop, Firenze. 12-13 aprile 2013*: 3-38. Oxford, Archaeopress Archaeology.

Peretto, C. 2002. *Analisi informatizzata e trattamento dati delle strutture di abitato di età preistorica e protostorica in Italia*. Collaga Origines, serie Progetti 1. Firenze, Istituto Italiano di Preistoria e Protostoria.

Pizziolo, G., Sarti, L. 2006. Exploring the archaeological landscape through a local perspective: spaces and places in the prehistory of the Florentine plain. In S. Campana, M. Forte (eds.), *From space to place: 2nd international Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International workshop, CNR, Rome, Italy, December 4-7, 2006*: 261-9. British Archaeological Reports International Series 1568. Oxford, Archaeopress.

Pizziolo, G., Sarti, L. 2008. Prehistoric Landscape, Peopling process and Bell Beaker settlements in the Floretine Area. In M. Baioni, V. Leonini, D. Lo Vetro, F. Marini, R. Poggiani Keller, L. Sarti (eds.), *Bell beaker in everyday life, Proceedings of the 10th Meeting 'Archéologie et Gobelets', Florence - Siena - Villanuova sul Clisi, May 12 - 15, 2006*: 39-58. Serie Millenni, Studi di Archeologia Preistorica 6. Firenze, Museo Fiorentino di Preistoria 'Paolo Graziosi'.

Pizziolo, G., Sarti, L. 2011. Fotografia aerea e paesaggi preistorici: alcune riflessioni sull'analisi di 'elementi latenti'. In Ceraudo, G. (ed.), *100 di Archeologia aerea in Italia, Atti del Convegno Nazionale di Archeologia Aerea, Roma, 15-16 aprile 2009, Archeologia Aerea 4/10, Studi di Aerotopografia Archeologica*: 101-6. Foggia, Claudio Grenzi Editore.

Pizziolo, G., Viti, S. 2011. A 3D perspective in the Interpretation of Living-floor Morphologies: Intrasite analysis of Prehistoric Contexts. In E. Jerem, F. Redo, V. Szeverényi (eds.), *On the Road to Reconstructing the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 36th International Conference, April 2-6-2008*: 454-62. Budapest, Archaeolingua.

Poesini, S. 2011. *Dal Bronzo Recente al Bronzo Finale: la formazione di culture regionali in Toscana. Elaborazioni locali, elementi interregionali e produzioni specializzate in complessi artigianali dell'area fiorentina e grossetana*. Unpublished PhD thesis, University of Siena.

Sarti, L., Martini, F. 1993. *Costruire la memoria. Archeologia preistorica a Sesto Fiorentino (1982 - 1992)*. Firenze, Garlatti e Razzai Editori.

Sarti, L., Martini, F. 2000. *Insediamenti e artigianati dell'età del Bronzo in area fiorentina: le ricerche archeologiche nei cantieri Consiag (1996-1998)*. Serie Millenni, Studi di archeologia preistorica, 2. Firenze, CONSIAG, Museo Fiorentino di Preistoria 'Paolo Graziosi'.

Scheffer, C. 1981. Cooking stands and some possibly related objects from Acquarossa. A preliminary report. In *Acta Instituti Romani regni Sueciae, Series IN 4, XXXV, Opula Romana XI*: 39-52. Stockholm, Distributor Paul Åströms Förlag.

Tasca, G. 1998. Intonaci e concotti nella preistoria: tecniche di rilevamento e problemi interpretativi. In Castelletti, L., Pessina, A. (eds.), *Introduzione all'archeologia degli spazi domestici. Atti del seminario - Como, 4-5 novembre 1995*. Archeologia dell'Italia Settentrionale, 7: 77-87. Como, Museo Civico Archeologico 'Giovio' Edizioni New Press.

Viti, S. 2004. Between Recostruction and Reproduction: the role of Virtual Model in archeological research. In Magistrat der Stadt Wien Referat Kulturelles Erbe-Stadtarcaologie Wien (eds.), *Enter the Past CAA2003, Processing of the 31th Conference, Wien*, Austria, April 2003. BAR International Series 1227: 525-8. Oxford, Archaeopress.

Exploring Scenarios for the First Farming Expansion in the Balkans Via an Agent-based Model

Andrea Zanotti[(1,2)]
andrea.zanotti@outlook.com

Richard Moussa[(1)]
richard.moussa@gmail.com

Jérôme Dubouloz[(3)]
jerome.dubouloz@mae.cnrs.fr

Jean-Pierre Bocquet-Appel[(1,2)]
jean-pierre.bocquet-appel@cnrs.fr

[1] CNRS, UPR 2147, Paris, France
[2] Ecole Pratique des Hautes Etudes (EPHE), Paris, France
[3] CNRS, UMR 8215 Trajectoires, Nanterre, France

Abstract: An agent-based model was built in order to simulate the spread of the first Neolithic farmers through the Balkan region. This comprehensive approach is based on various sources of data: archaeological records are combined with ethnographic, anthropological and palaeodemographic data in order to create partial intermediate models that simulate the functioning of a Neolithic farming society. Our work has produced a regional adaptation of the OBRESOC model, which simulates the spread of the LBK culture in central Europe. With this agent-based modelling approach it is possible to explore demo-economic structures that cannot be observed in the archaeological record.

Keywords: Balkan Neolithic, Farming system, Agent-based model, Anthropological partial models, Ethno-historical partial models, Demo-economics

Introduction

Recent developments in research on the spread of the farming system to the Balkans from Anatolia suggest that it was a complex process that involved many different trajectories rather than developing from a single migratory wave (Özdoğan 2012, 2011, 2008).

Three main recent approaches were followed to reconstruct the spread of the early farming system through the Balkans: analysis of i) inter-site cultural similarities with Anatolia (Özdoğan 2008); ii) spatio-temporal traces of the expansion of early farming, represented by directional derivatives from the distribution of radiocarbon dates on a grid (Bocquet-Appel *et al*. 2009); graphic representation of the geographical and chronological distribution of those dates (Brami 2014) or analysis of the spatio-temporal coherence of those dates (Reingruber and Thissen 2009); iii) use of diffusion equations adapted to testable scenarios (Fort 2015).

The approach proposed by Özdoğan (2008) is based on archaeological similarities among different types of Neolithic 'packages': each package is defined by a set including cultivated plants, domesticated animals, stone tools and pottery, as well as the architectural structure of the settlement and the way of life inferred from it. The comparison of similarities provides indications as to the common geographical origins and gradual differentiation of the Neolithic as it advanced westwards (Özdoğan 2008).

The approach based on spatio-temporal traces expressed by radiocarbon dating provides indications about the timing and direction of the spread of the farming system. But, while these approaches can describe the system's diffusion, the explanatory processes only relate to very broad qualitative categories. Current models of the diffusion equation type are purely deterministic. They do not take stochasticity into account, particularly climatic. They work with a very small number of causal variables, usually 2-3, beyond which this type of modelling becomes mathematically intractable. An approximation of reality would be able to go into more depth than with only a small number of variables, and would allow the agent to react to different hazards; in turn, this reactiveness potentially modifies the spread of the farming system in terms of trajectory, pace, direction, demography and social structure.

In order to answer the question of the nature and trajectories of the spread of farming through the Balkans in space and time, we used an archaeological agent-based model. The main reason for doing so is that this type of modelling is comprehensive by nature, because it integrates unidirectional effects of meteorological variables on landscape, socio-economics and demography, as well as interactions between the latter two. In order to reduce the impact of stochasticity on this historical type of modelling, the model is centred on the economic superstructure through the long duration of the first farming societies. All this is developed through the OBRESOC computer program, which models the expansion of the LBK culture (Bocquet-Appel *et al*. 2015; Bocquet-Appel *et al*. 2014).

This paper describes the main changes, in terms of anthropological modelling, that were made to the OBRESOC program, in order to develop a version suited to exploring the question of the spread of farming through the Balkans. This version is called OBRESOC BEAN (Bridging the European and Anatolian Neolithic).

Does the OBRESOC BEAN model, for which the parameter values are deduced from ethno-archaeological inferences or specialized literature and initiated from archaeologically identified source regions, populate the zones archaeologically known to have been colonized by farming – referred to as test zones – within the expected timeframe? The geographical coincidence between the timing of the simulation and that of the test zones represents a first validation test of the model. Did meteorological variations have any impact on the timing? Did colonization proceed in a steady or irregular pattern across the different regions? What was the regional demographic structure by the end of the Balkan expansion in terms of the distribution of hamlets/villages and inhabitants?

The aim of this paper is to describe the structure and functioning of the OBRESOC BEAN model, which has been refined to answer the above questions. The simulations, as well as their analysis, are still in progress and will be presented at a later date.

1 The archaeological data

1.1 The Balkan archaeological context

The decision to model the expansion of the Neolithic farming system specifically in the Balkans was based on ethno-archaeological inferences from Balkan archaeological data, which are briefly reviewed below.

Household: Archaeological evidence for Western Anatolia and the Balkans shows standardized dwellings, generally made up of a single room and ranging from 3x3m to 7x7m (although there are exceptions: see Brami and Horejs, to be published). This suggests that, for reasons of space, the dwellings could host only a nuclear family. A second room has sometimes been found, but is assumed to have been used for food storage and preparation (Perlès 2001).

This architectural pattern is quite different, in terms of size and internal layout, to the LBK long houses modelled with OBRESOC.

Farming system: Specific studies have suggested that Neolithic farmers in the region had an intensive farming system: the cultivated area was not large, but the input of labour was substantial (Bogaard *et al*. 2013, 2005, 2004).

The diet, as shown by isotopic analysis (Papathanasiou 2003) was largely based on cereals (wheat, barley) and pulses.

As regards domesticated animals, three major species are found in the site assemblages: cattle, sheep/goats and pigs. In an intensive farming system, animals were not only exploited for food and milk, but also had an important role in the farming system as a whole, especially for the production and use of manure (Bogaard 2004).

The presence of wild animals and wild plants is attested to in the archaeological sites, but always in very limited quantities (Perlès 2001). This suggests that hunting/gathering only took place in order to supplement the diet with the necessary amount of kilo-calories. Fishing was marginal, even in coastal areas despite their abundance of marine resources (Powell 1996).

Demography: Because of the almost complete absence of human skeletons, no hypothesis can be formulated as to the age structure of the living population. In OBRESOC, the demography of the LBK population, located mainly in Central Europe, is expressed by forces that are sampled in that region, using mortality and fertility tables for rural pre-industrial populations of the 18th century.

Regarding OBRESOC-BEAN, despite an exhaustive bibliographic search to reconstruct the demographic structure of preindustrial populations in the region, there is no evidence that population registers were kept. Byzantine (Laiou 1977) and Ottoman (Behar 1998; Kavas and Thornton 2013) archives do not have full information about the population as they are mainly tax registers. The values for the demographic parameters are therefore taken from the same pre-industrial population tables as those used in OBRESOC (Bocquet-Appel *et al*. 2015).

Mesolithic/Neolithic Interactions: Because of the very small number of Mesolithic sites discovered (Perlès 2001; Demoule in press), it is considered that very few hunter-gatherers were present at the regional scale. It is likely that the first farmers found themselves in a geographical area that was virtually devoid of human occupation. Their possible interactions with hunter-gatherers are therefore not taken into account in the OBRESOC-BEAN model.

Concerning the Danube Gorges, these are a special case in the Balkan Neolithic. In this region, which is unique in the Balkan context, there is evidence of occupation since the Mesolithic, which produced numerous Mesolithic/Neolithic interactions (Boric 2007). However, there is no evidence in the archaeological remains of any development of a farming system in the Danube Gorges sites. Even if the settlers adopted some Neolithic practices, such as household structure, funerary practices and pottery, they still relied for their subsistence on resources available from the natural environment, and particularly on fishing (Dinu 2010). For this reason, Mesolithic sites in the Danube Gorges were not taken into account in the OBRESOC-BEAN model of the farming expansion.

Starting region: While OBRESOC identified the origin of the LBK culture in a specific region, near Lake Balaton in present-day Hungary, the arrival of the farming system in the Balkans is less easily defined. As seen in the introduction, the Neolithic migration routes from Anatolia arrived in the Balkans at several different points and the first Balkan farmers subsequently followed different geographical trajectories.

Because it is currently impossible to locate a single point of first arrival of farmers on the European continent, the Aegean region as a whole was initially chosen as the starting point. In the OBRESOC model, a settler-farmer preferentially chooses pixels that are most favourable to agriculture. Consequently, even if the starting zone is much larger, *a priori*, than in the OBRESOC model, the initial placement of the agents is in fact

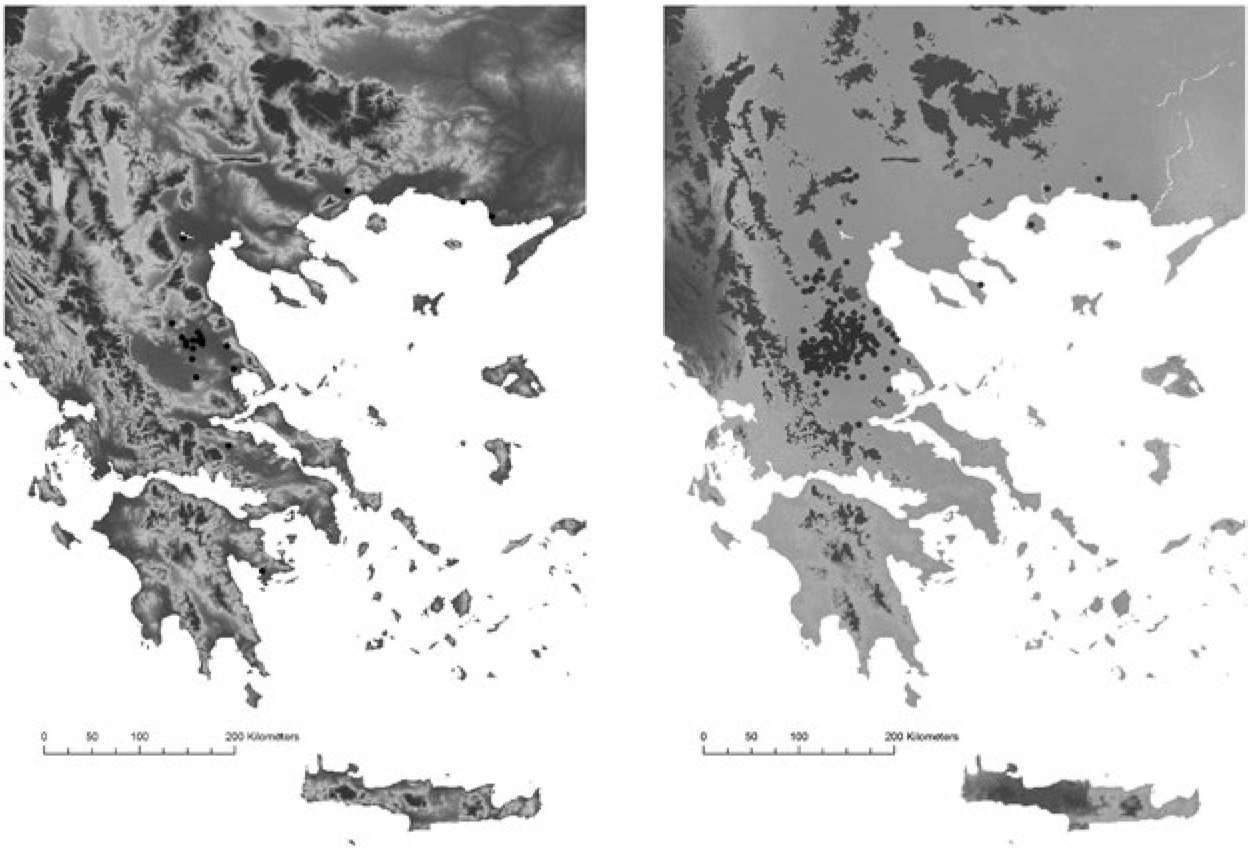

Fig. 1. On the left, the Early Neolithic archaeological sites. On the right, the initial location of the hamlets-pixels according to the best patch rule.

limited to the specific areas most favourable to agriculture, which are themselves geographically limited to the three starting regions of Thessaly, Macedonia and Thrace (Fig. 1).

1.2 A transnational Balkan database

The data used to model the farming expansion represent all of the Early Neolithic sites published up to 2013 in the specialized literature on the Balkans in Greece, Bulgaria, Romania, Macedonia, Serbia, Hungary and Albania, as well as in European Turkey (Eastern Thrace). Altogether, 1114 sites/sequences are listed for the Early Neolithic; 108 of these have at least one radiocarbon date, with a total of 341 dates. Other databases have already been published: the Central Anatolian e-Workshop CANeW database (Reingruber and Thissen 2005); the Near Eastern radiocarbon CONTEXT database (Böhner and Schyle 2008); and the 14C backbone database (Brami 2014). The main difference between these databases and the one compiled for this study is that the latter does not include sites with radiocarbon dates only, but all published sites including those represented only by surface findings. On the basis of seriation sequences, this allowed us to establish a period of occupation for sites that do not have a radiocarbon date.

The database was audited to exclude obsolete dating techniques (< 1980), unsuitable charred wood samples, or cases where the standard deviation was considered too high (> 100 years). If there were different sources for the same sequence, priority was given to the dates obtained with the AMS technique and from bone or seed samples.

These archaeological data were necessary to the model design and construction phases and will also be used to validate the simulations once these have been run.

The validation criteria will be: i) the simulated hamlets-pixels occupy the areas where there is archaeological evidence of their presence within the correct time frame; ii) the density of the archaeologically observed sites in a well-prospected sample zone corresponds to the density generated by the model for the same area; iii) the configuration of the simulated hamlets-pixels (the inter-hamlet distances as well as their relative geographic positions) and of the observed archaeological sites are similar (Procrustes analysis).

2 The Agent-based Model

This agent-based model is designed to represent the first farming societies that appeared in the Balkans, as well as their expansion through the region. The model simulates the functioning of a farming system, focusing on the mechanisms of its demo-economic expansion, in order to understand how it might have spread.

As indicated above, the model is built up from ethno-archaeological inferences and estimations of the

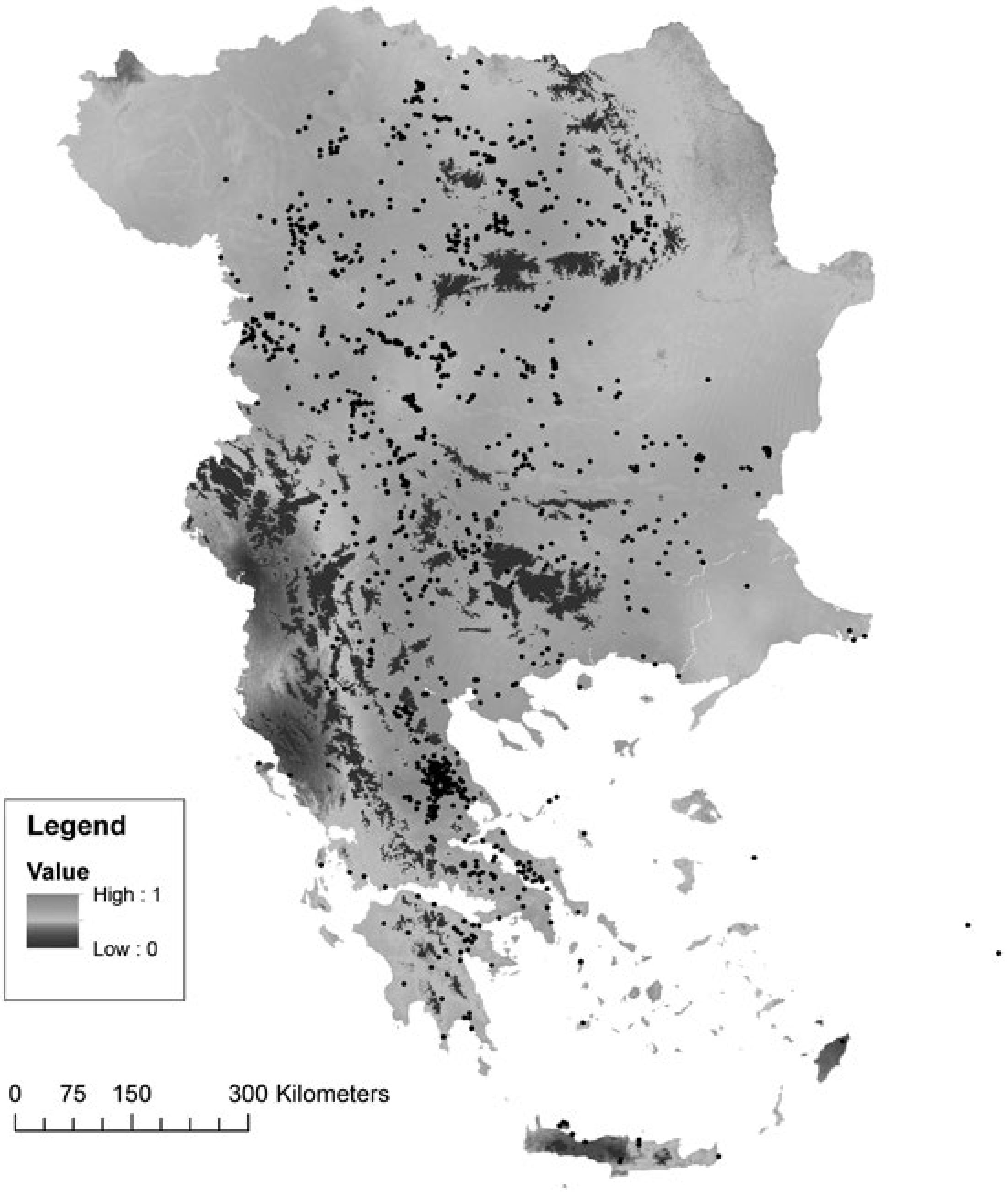

Fig. 2. The *best patch* map with the archaeologically observed sites.

palaeoenvironment, together with partial intermediate anthropological and ethno-historical models.

This agent-based model works at different levels, using partial intermediate sub-models.

A description of the characteristics and functioning of the model is given below. This description draws on the ODD protocol (Grimm *et al*. 2010), but does not follow it strictly.

2.1 The agents

Each agent is at once a household and a nuclear family, the latter typically composed of two parents and their children. The information about kinship between the individuals within the households and between the households themselves is kept for reasons related to the patterns of geographic colonization and solidarity during food crises.

Several agents situated on the same pixel make up a village.

Each agent/household owns a mini-herd, each one made up of sheep/goats, cattle and pigs, that is to say 3 mini-herds whose meat and possibly milk are consumed. These mini-herds follow set patterns of birth, death and reproduction.

2.2 The Environment

The spatial environment is reconstructed through the creation of a best patch map (Fig. 2). The entire area, of 749.576km², is divided into pixels of 1km² each. Each pixel has a value representing its attractiveness for Neolithic farmers. These values are deduced from different palaeo-environmental and palaeo-meteorological variables that can influence settlement choices, such as precipitation, temperature, soil fertility and altitude. All these values are regressed on the dummy presence/absence variable (1/0), where the first consists of the sites actually discovered while the second is a sample of non-colonized pixels. The result is a map where every pixel has a standardized value ranging from 0 to 1. The higher the value, the greater the *a priori* probability of occupation by farmers.

Climate estimates: An estimation of Early Neolithic meteorology (monthly average temperature T, monthly cumulated value of precipitation P) and its variations was made using the estimation procedure developed with OBRESOC (Bocquet-Appel *et al*. 2015).

The source of information for the Balkans is the high-resolution pollen sequence obtained from Tenaghi Philippon in north-eastern Greece (Peyron *et al*. 2011). Briefly, the OBRESOC procedure simulates the climate (T, P) of the period as follows: the Balkans are subdivided into a regional grid and the mean and variance of the seasonal climate variables (variance of the monthly means during the season) are obtained for each grid square using the values for the last 50 years (WorldClim climate database http://www.worldclim.org). The OBRESOC estimation takes millennial climate variations into account, on the assumption that the standard local variance has not changed. The OBRESOC procedure estimates the seasonal climate values by taking into account the difference between the Neolithic mean estimated from the Tenaghi Philippon pollens and the current mean for the last 50 years at the same geographical location. The difference between the two means, which represents the positive or negative fraction due to climate change, is then added to the current seasonal climatic mean for each grid square. Finally, a fraction representing random climatic variation is added; this is obtained from a random sampling of the distribution of local monthly seasonal means. These values, calibrated to the Tenaghi Philippon reconstructions, provide an estimation of the climate variables during the Neolithic as well as their variations for each pixel in the region. Values for the climate thresholds determining impacts on agriculture were also estimated, based on climate observations for Larissa (Thessaly) from 1955 to 2004, published by the National Center for Environmental Information (http://www.ncdc.noaa.gov/). As no benchmark agro-climatic data is available on impact thresholds in the region's agriculture, these were set when the 3-monthly values for a season were systematically below (cold, dry) or above (hot, humid) the 3 seasonal monthly values.

Soil fertility estimates: Soil fertility is of primary importance for farming societies, since it determines the productivity of the farming system and the survival of individuals. Soil fertility influences the behaviour of individuals, especially in terms of their dispersal during a colonization phase. Soil fertility is determined by geology as well as climate. As for the climate estimations, the OBRESOC procedure was used to estimate soil fertility during the Balkan Neolithic.

The geological composition of the soils was obtained from the European Soil Portal (http://eusoils.jrc.ec.europa.eu/), divided into 11 fertility classes based on the WRB-Full classification. A standardized value (ranging from 0 to 1) for soil fertility per pixel/km² was assigned to each pixel, according to an estimation of the relative fertility of each kind of soil.

2.3 Rules of interaction

In order to survive through each season, the agent/household needs a certain quantity of calories, depending on its demographic structure. These are supplied by farming and herding and by supplementary hunting and gathering. The partial intermediate economic model simulates the functioning of the intensive farming system.

In each simulation step, corresponding to a calendar season, the agents perform farming activities. These consist of preparing fields, sowing, weeding, picking and also herding tasks. Hunting and gathering are additional activities undertaken only in order to reach the calorie count required for survival if agricultural production and herding are not sufficient.

Another partial intermediate sub-model concerns demography. The individuals within households are born, marry, reproduce and die.

In OBRESOC BEAN, marriage coincides with the creation of a new household: because these are nuclear households, the formation of a new family causes the individual who marries to leave the household and form a new household. This differs from the OBRESOC model, which, in accordance with the Eastern European family type, incorporates nuclear families into an extended family.

The new household can either result in local densification of a hamlet or in the foundation of a new settlement, depending on regional density. Because there is plenty of agricultural land at the outset, local density depends on what is known as scalar stress (Bandy 2004; Johnson 1982), which expresses the loss of consensus within communities due to the growing population: once the population in a village reaches a certain size, social tensions increase. Unlike the OBRESOC model (Bocquet-Appel *et al*. 2015), this approach does not directly integrate Chayanov's scalar stress at the household level, which stems from the tensions arising from the altered producer/consumer ratio.

The new rule whereby married children split directly away from the nuclear family, without cohabiting with the parents, raises questions in terms of modelling and colonization. Some rare sources on European colonial settlers from the 1930s (Pelzer 1945) suggest that there would only be a low frequency of young couples in a colonization process because young children and the lack of a family workforce would be a handicap. A pioneer front composed demographically of young couples only is very unlikely. In OBRESOC BEAN, when a settler role is attributed to a new young married couple, the couple moves to a new pixel in the best patch together with the nuclear family of the parents of the husband or bride (depending on whether the model is patrilineal or matrilineal).

When a village exceeds, probabilistically, a density threshold for agents/households, it becomes a Big Man hamlet, which has storage privileges for any unused surplus from the harvest and is demographically attractive to other households in the local area.

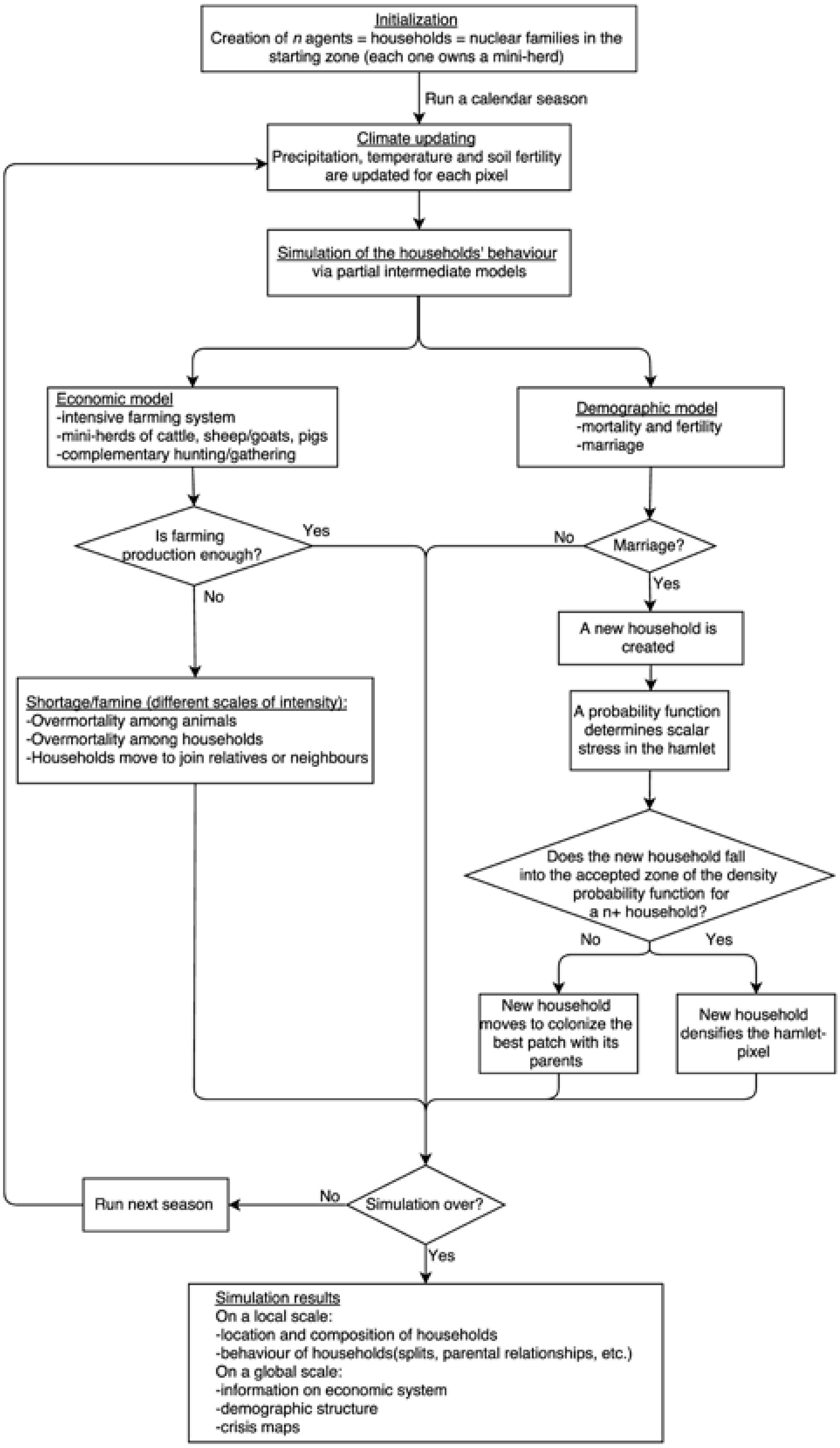

Fig. 3. Sequential diagram of the model dynamics.

2.4 Scheduling

A sequential diagram outlining the structure of the model is given in Fig. 3. Every simulation step represents one calendar season in the farming year (autumn, winter, spring and summer) and the information is updated in each season.

Initialization: The agents are initialized in the geographical starting zone, following the 'best patch' rules of occupation. The number of initial agents and the duration of the initialization are chosen as parameters.

Climate update: At the beginning of each season, the climate is simulated according to the rules previously described. The agricultural fertility of each pixel is updated according to the temperatures and precipitation simulated on the map.

Modelling dynamics: The agents are responsible for the economic production needed to satisfy their calorific requirements. If production is inadequate, this may trigger shortages and famines, which may in turn cause the disappearance of households and their animals and force the agents to react in consequence, for example through kinship solidarity networks.

The individuals within each agent/household follow the demographic cycles of entry into and exit from the population, as well as ensuring reproduction through marriage. In the event of a marriage, when the new household wants to settle in the hamlet-pixel, a random draw expressing the scalar stress determines whether the agent is accepted into the village or whether it has to leave for somewhere else.

Output: Information about demographic events, economic production and herds is stored for each farming year. These data, which are both aggregated chronologically over the years in question and georeferenced for the agent/household (x, y, t), allow numerous socio-natural issues to be taken into account and represented on the map. It is also possible to visualize where meteorological events occurred regionally, as well as to see their impacts on the agriculture and demography of the corresponding households.

3 Concluding Remarks

This paper describes the structure and the main features of the model. OBRESOC BEAN is a regional adaptation of the OBRESOC model, which required several modifications.

The economic systems are identical, characterized by an intensive farming system based on the same crops, and with herds of the same kinds of animals; the main differences concern the anthropological structure of the model.

The simulated agent is different: the long OBRESOC houses, occupied by extended families, are replaced by small dwellings that house nuclear families. This had an impact on the scalar stress, the main mechanism driving population expansion, and thus required a change to the model for household splitting and colonization.

These modifications, in addition to the possibilities for choosing among a large number of parameters and for injecting Balkan climatic and environmental data, made it possible to customize the OBRESOC model. For future studies, this model could be applied to other regions, thus offering an additional means of investigation to understand the expansion of farming systems.

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Bibliography

Bandy, M. (2004) Fissioning, Scalar Stress, and Social Evolution in Early Village Societies. *American Anthropologist* 106 (2). p. 322-333.

Behar, C., (1998) Sources pour la démographie historique de l'empire ottoman: Les tahrirs (dénombrements) de 1885 et 1907. *Population (French edition) 53 (1/2)*. p. 161-177.

Bocquet-Appel, J.-P., Moussa, R. And Dubouloz, J., (2015) Multi-Agent Modelling of the Neolithic LBK. In Giligny, F., Djindjian, L., Costa, L., Moscati, P. and Robert, S., *CAA 2014 21st Century Archaeology. Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*: 611-22. Oxford, Archaeopress.

Bocquet-Appel, J.-P., Dubouloz, J., Moussa, R., Berger, J.-F., Tresset, A., Ortu, E., Vigne, J.-D., Bendrey, R., Bréhard, S., Schwartz, D., Salavert, A., Sanchez-Goñi, M.F., Ertlen, D., Gauvry, Y., Davtian, G., Vander Linden, M., Lenneis, E., Noiret, L., Guillaumont, A., O'connor, M. 2014. Multi-agent Modelling of the Trajectory of the LBK Neolithic: A Study in Progress. In A. Whittle and P. Bickle (eds.), *Early Farmers: The View from Archaeology and Science. Proceedings of the British Academy*. Oxford, Oxford University Press.

Bocquet-Appel, J.-P., Naji, S., Vander Linden, M., Kozlowki, J. 2009. Detection of diffusion and contact zones of early farming in Europe from the space-time distribution of 14C dates. *Journal of Archaeological Science* 36: 807-20.

Böhner, U. and Schyle, D. 2008. Radiocarbon CONTEXT Database 2002–2006. doi:10.1594/GFZ.CONTEXT.Ed1

Boogard, A. 2005. 'Garden Agriculture' and the Nature of Early Farming in Europe and the near East. *World Archaeolo*gy 37 (2): 177-96.

Boogard, A. (2004) The nature of early farming in Central and South-east Europe. *Documenta Praehistorica XXXI*: 49-58.

Boogard, A., Fraser, R., Heaton, T. H., Wallace, M.,Vaiglova, P., Charles, M., Jones, G., Evershed, R. P., Styring, A. K., Andersen, N. H., Arbogast, R. M., Bartosiewicz, L., Gardeisen, A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schafer, M., Stephan, E. 2013. Crop manuring and intensive land management by Europe's first farmers. *Proceedings of the National Academy of Siences of United States of America* 110 (31). Available from: www.pnas.org/content/110/31/12589 [Accessed: 1 June 2015].

Boric, D. 2007. Mesolithic-Neolithic interaction in the Danube Gorges. In J. Kozlowskiand and M. Nowak (eds.), *Mesolithic/Neolithic Interactions in the Balkans and in the Middle Danube Basin. Proceedings of the XV World*

Congress of the International Union for Prehistoric and Protohistoric Sciences, Lisbon, 4-9 September 2006. British Archaeological Reports International Series 1726: 31-45. Oxford, Archaeopress.

Brami, M. 2014. A graphical simulation of the 2,000-year lag in Neolithic occupation between Central Anatolia and the Aegean basin. *Archaeological and Anthropological Science* Available at: doi: 10.1007/s12520-014-0193-4.

Brami, M. and Horejs, B. (forthcoming), *Upscaling the Neolithic House. Trends in House Size and Function in Anatolia and the Balkans*.

Demoule, J.-P. (in press). Archaeological Manipulations and Manipulation of History, or How to Build an Identity. In A. Coudart *et al*. (ed.), *Constructing Identity*. Tucson, Arizona University Press.

Dinu, A. 2010. Mesolithic fish and fisherman of the Lower Danube (Iron Gates). *Documenta Praehistorica XXXVII*: 299-310.

Fort, J. 2015. Demic and cultural diffusion propagated the Neolithic transition across different regions of Europe. *Journal of the Royal Society Interface* 12 (106). Available at: http://rsif.royalsocietypublishing.org/content/12/106/20150166 [Accessed: 9 July 201].

Grimm, V., Berger, U., De Angelis., D. L., Polhill, G., Giske, J. And Railsback S. F. 2010. The ODD protocol: A review and first update. *Ecological modelling* 221 (23): 2760-8.

Johnson, G. 1982. Organizational Structure and Scalar Stress. In C. Renfrew, M. Rowlands, B. Seagraves (eds.), *Theory and Explanation in Archaeology*: 389-421. New York, Academic Press.

Kavas, S. and Thornton, A. 2013. Adjustment and Hybridity in Turkish Family Change: Perspectives from Developmental Idealism. *Journal of Family History 38 (2):* 223-41.

Laiou, A. 1977. *Peasant society in the Late Byzantine Empire. A social and demographic study*. Princeton, Princeton University Press.

Özdoğan, M. (2012) An Anatolian Perspective on the Neolithization Process in the Balkans. New Questions, New Prospects. In: Krauß, R. (ed.) Beginnings - New Research in the Appearance of the Neolithic between Northwest Anatolia and the Carpathian Basin, Istanbul, 8-9 april 2009, Rahden/Westf : Verlag Marie Leidorf Gmb.

Özdoğan, M. 2011. Archaeological Evidence on the Westward Expansion of Farming Communities from Eastern Anatolia to the Aegean and the Balkans. *Current Anthropology 52 (4)*: 415-30.

Özdoğan, M. 2008. An alternative approach in tracing changes in Demographic composition. The Westward expansion of the Neolithic Way of Life. In J.-P. Bocquet-Appel and O. Bar-Yosef (eds), *The Neolithic Demographic Transition and its Consequences*. New York; Springer Verlaag.

Papathanasiou, A. 2003. Stable Isotope Analysis in Neolithic Greece and Possible Implications on Human Health. *International Journal of Osteoarchaeology* 13: 314-324.

Pelzer, K. J. 1945. *Pioneer settlement*. New York, International Secretariat Institute of Pacific Relations Publication Office.

Perlès, C. 2001 *The Early Neolithic in Greece. The first farming communities in Europe*. Cambridge, Cambridge University Press.

Peyron, O., Goring, S., Dormoy, I., Kotthoff, U., Pross, J., De Beaulieu, J. L., Drescher-Schneider, R., Vanniere, B., Magny, M. 2011. Holocene seasonality changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece). *The Holocene* 21 (1): 131-146.

Powell, J. 1996. *Fishing in the Prehistoric Aegean.* Jonsered, Paul Åströms Förlag.

Reingruber, A. and Thissen, L. 2009. Depending on 14C data: Chronological Frameworks in the Neolithic and Chalcolithic of Southeast Europe. *Radicarbon* 51 (2): 751-70.

Reingruber, A. and Thissen, L. 2005. 14C database for the Aegean Catchment (Eastern Greece, Southern Balkans and Western Turkey). In C. Lichter (ed.), *How Did Farming Reach Europe? Anatolian-Europaean Relations from the Second Half of the 7th through the First Half of the 6th Millenium Cal BC. Proceedings of the Internat. Workshop Istanbul, 20–22 May 2004*. Ankara, Byzas 2.

CHAPTER 10
Spatial Analysis: Data, Patterns and Process Interpretation

Strontium Isotope Analysis and Human Mobility from Late Neolithic to Early Bronze Age in the Central Plain of China

Chunyan Zhao
zhaocy@cass.org.cn
Institute of Archaeology, Chinese Academy of Social Sciences, Beijing, China

Abstract: Archaeological surveys of a series of late Neolithic to early Bronze Age settlements in the central plain of China provided useful data for understanding a prehistoric period of increasing local social complexity. A combination of the modelling functions offered by Geographic Information Systems (GIS) and the data of strontium isotope ratios in Human teeth from archaeological sites allow us to explore possible relationships between human mobility and the natural environment. The results reveal complexities that in conjunction with other archaeological data can be correlated to social, political, or economic inequality in ancient sites.

Keywords: Strontium isotope analysis, Human mobility, Geographic Information Systems, China

Introduction

Over the last two decades, the measurement of strontium isotopes in archaeological skeletons has matured into an established method for characterizing prehistoric human migration, the methods were introduced in archaeology for the research of residential change among prehistoric humans by Ericson (Ericson 1985). Prior to this, whether domestic or foreign, traditional archaeological methods were to speculate that the migration of populations may exist by the circulation of artefacts. But we all know the evidence obtained by this method is only indirect evidence of population migration – to find direct evidence of population migration we have to proceed from man himself. Strontium isotope analysis involves the determination of strontium isotope ratios from skeletons and human bones and teeth, and the differences between the strontium isotope ratios can determine directly ancient population movements between different geographical regions.

In this paper we will only briefly represent the strontium isotope technique, which has been discussed in detail (Bentley *et al*. 2004). Strontium has a geological origin and four naturally occurring isotopes: non-radiogenic ^{84}Sr, ^{86}Sr and ^{88}Sr, and radiogenic ^{87}Sr. Different rocks are characterized by distinct ratios of two isotopes of strontium: ^{87}Sr and ^{86}Sr. As rocks are weathered into soils, Strontium in rock moves into soil and groundwater, the plants growing in those soils acquire the ^{87}Sr/^{86}Sr ratio. Animals that eat the plants incorporate strontium into their body, as do the humans who eat those animals and plants and as strontium passes from weathered rocks up the food chain into the human skeleton (Price *et al*. 2002). Measured strontium ratios in human bones and teeth can serve as tracers of the geology of the areas in which the individuals grew up and in which they died, respectively, because consumed strontium is incorporated into the mineral portion of the human skeleton, were strontium substitutes for calcium. Bone undergoes continual replacement of its inorganic phase, so that measurements of bone strontium reflect the later years of the life of the individual. Tooth enamel, on the other hand, forms during childhood and undergoes relatively little change. Differences in strontium isotope ratios between bone and tooth enamel in a single individual thus reflect changes in the residence history of that person (Knudson *et al*. 2012; Kennedy *et al*. 1997; Ericson 1985).

Especially in recent years the international use of strontium isotope analysis in the study of ancient human migration has increased year by year, while domestic research has just started (Ruochun, Juzhong, Xiaoyong 2008; Chunyan, Jing, Nu 2011; Chunyan *et al*. 2012; Zhao, Peng 2012), however the population movements at the ancient capital sites of China have not been studied.

This paper seeks to fill this gap: it draws its data from an archaeological survey project in China's central plain, the sites of Taosi and Erlitou, that was designed to explore the relationship between changing environments and the emergence of a more complex society over the crucial period from the late Neolithic to early Bronze Age (ca. 4000-1500 BC). Despite the project only being able to collect samples from a relatively small number of sites, the results have revealed interesting and recurrent trends in human mobility and subsistence strategies in the region. Moreover, this preliminary analysis has suggested that some of the variability in observed archaeological patterns might be explained by their spatial correlation with particular environmental variables, or their temporal correlation with particular cultural changes. This paper therefore considers these correlations more formally, taking advantage of the exploratory and confirmatory potential offered both by Geographic Information Systems (GIS) and Strontium isotope analysis.

1 Materials and methods

1.1 Selection of samples

In this study, 39 tooth enamel and bone samples from 23 individuals at Etlitou site (3800-3500 aBP) and 21 tooth enamel samples from 21 individuals at Taosi site (4300-3900 aBP) were selected. These samples came from the excavated pits within the settlement. Tooth samples were taken from the first molar whenever possible. The tooth enamel sample is not random: samples were taken from those skeletons with adequate tooth preservation.

1.2 Sample preparation and analysis

Samples for this study were prepared at the Institute of Archaeology, Chinese Academy of Social Sciences. The measurements were made at the Beijing Geological Research Institute, CNNC. The methods for sampling and analyzing Sr isotopes from teeth have been described in detail elsewhere and are therefore not repeated here (Price *et al*. 2010; Price *et al*. 2011; Sjögren, Price, Ahlström 2009). $^{87}Sr/^{86}Sr$ ratios were corrected for mass fractionation in the instrument, using the exponential mass fractionation law and $^{86}Sr/^{88}Sr = 0.1194$. Measured values for the NBS 987 standard were $^{87}Sr/^{86}Sr = 0.710250 \pm 0.000007$.

2 The site at Taosi

2.1 Archaeological contexts at Taosi

The Taosi site is located in Xiangfen County, the Linfen Basin of the southwestern Shanxi Province. This site is large settlement site of Longshan culture, and it dated to 4300-3900 aBP (Dongxiafeng 1983). Based on settlement distribution, hydrographic and topographic data, the present paper researches into the features of ancient settlement distribution in the Linfen Basin of southwestern Shanxi Province by means of GIS, which includes the techniques of spatial overlay analysis. The study aims at revealing the relationship of ancient settlements distribution with the natural environments in this region from the late Neolithic to early Bronze Age and inquiring into man's dependence on natural settings and the ability for their transformation (Fig. 1 and Fig. 2). Settlements evolved from the late Neolithic period began rapid development to reach peak in the Longshan Culture period (4350-3950 aBP); there are many large and medium-sized settlements, among the largest of which is Taosi site (Fig. 1). The number of settlements begins to decrease during the Shang culture period (3600-3060 aBP) for uncertain reasons (Fig. 2) (Jianguo, Lin 2007).

The period from 4300-3900 aBP in the China plain spans the transition from small communities to the beginning of complex societies and state formation. Archaeologists have focused on the Taosi site partly due to the visibility of its 'city sites', and partly because of the hypothesized influence of such communities on the later development of the Xia and Shang Dynasties: associated with the palaces, tombs, bronze, and observatory (Nu 2007). Material culture studies suggest considerable acculturation between non-local groups. It remains unclear how migration affected this population increase and the increase of social complexity in the region. Human migration has been suggested, but not conclusively, as, of course, ideas, material culture and technologies can spread without the permanent migration of people. Physical anthropology and human bone DNA studies cannot determine the existence of human migration (Yajun, Nu, Fan 2009).

Measurement of strontium isotopes in archaeological skeletons is an effective technique for characterizing prehistoric human migration. The capital's population growth is an important opportunity for social complexity and, therefore, human migration and its sources have special significance.

2.2 Strontium isotope ratio determination results

Tooth enamel samples from 21 individuals were analyzed for strontium isotope ratios ($^{87}Sr/^{86}Sr$) by thermal ionization mass spectrometry. The human remains at Taosi were unearthed from two cultural layers: middle Taosi (4100-4000 aBP) and

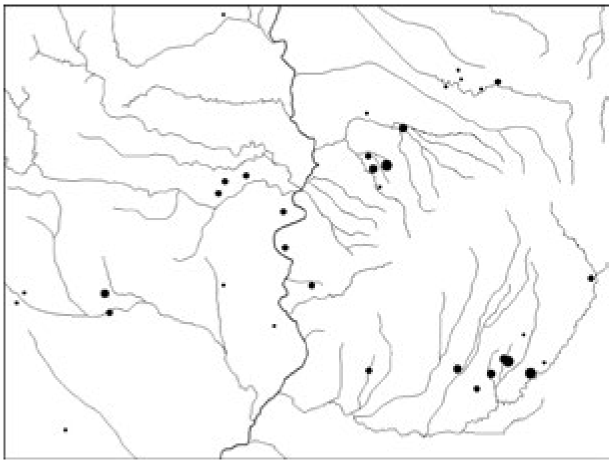

Fig. 1. Settlements of Longshan culture (4350-3950 aBP) and distribution in the Linfen Basin.

Fig. 2. Settlements of Shang culture (3600-3060 aBP) and distribution in the Linfen Basin.

late Taosi (4000-3900 aBP). These samples are listed in Table 1.

2.3 Human mobility atTaosi

We have measured $^{87}Sr/^{86}Sr$ in enamel samples from different species of domestic animals at Taosi. From the results the pig was identified as a suitable local species. Five pig samples were obtained in order to provide an independent measure of the local ratio of strontium isotopes at Taosi. Analyses of these produced an average strontium isotope ratio of 0.711179, defined as within 2σ of the mean $^{87}Sr/^{86}Sr$ in the archaeological pig enamel, the local range at Taosi is 0.711314-0.711044 (Chunyan, Jing, Nu 2011).

Results of the strontium isotope analysis are presented in Fig. 3. The tooth enamel samples in this bar graph are arranged in the same order as in Table 1 and the discussion below will follow this order. Values are grouped by time of burial. The horizontal

Tab. 1. Strontium isotope ratios from archaeological human tooth enamel from Taosi site.

Sample ID	Unit	Dates	Sex	Age	Material	$^{87}Sr/^{86}Sr$	2σs
1	02JX||ST7254M14	late Taosi	-	15-17	M3	0.711232	0.000013
2	02JX||ST7254M22	middle Taosi	Male	Adult	M2	0.711143	0.000012
3	02JX||ST7254M22-4	middle Taosi	Male	Adult	M2	0.711627	0.000010
4	02JX||ST7254M22-e	middle Taosi	Male	Adult	M2	0.710183	0.000009
5	T7404H16M22	middle Taosi	Male	Adult	front teeth	0.711254	0.000012
6	IHT5026HG8⊖B	late Taosi	-	-	M1	0.711456	0.000012
7	IHT5026HG8⊖C	late Taosi	Male	Adult	M1	0.711445	0.000014
8	IHT5026HG8⊖E	late Taosi	Male	Adult	M1	0.711127	0.000014
9	IHT5026HG8⊖D	late Taosi	Male	Adult	M3	0.711534	0.000014
10	IHT5026HG8⊖	late Taosi	-	-	M1	0.711455	0.000011
11	02JXTIHT5126H36⊖-⊜	late Taosi	Male	35±	M1	0.711570	0.000011
12	IHT5026HG8⊜	late Taosi	-	-	M3	0.711191	0.000009
13	IHT5026HG8⊜6号	late Taosi	-	-	M3	0.711351	0.000012
14	02JXTIHT5126H34⑤	late Taosi	-	-	M3	0.712037	0.000012
15	IHT5026 HG8⊜-1	late Taosi	-	> 45	M3	0.711603	0.000010
16	02JXTT5126H35 M4	late Taosi	Male	Adult	M2	0.711422	0.000014
17	IHT5026 HG8⊖	late Taosi	-	-	M3	0.711393	0.000013
18	02JXTST7254 M4（4B）	late Taosi	-	-	M2	0.711428	0.000012
19	T5216 HG8⊛	late Taosi	Female	35±	front teeth	0.711302	0.000008
20	T5026 HG8⊖-4	late Taosi	-	-	M3	0.711520	0.000011
21	02JXTT5126H36	late Taosi	-	-	M1	0.711578	0.000011

line on the side of the graph and marked local average shows the mean for the enamel of the five pigs.

Through radiogenic strontium isotope analyses we investigated the origins of the individuals who lived and died in the middle and later periods at Taosi. Mean archaeological human enamel isotope values from Taosi are 87Sr/86Sr = 0.711374 (2σ=0.000680, n=21). Comparing these data with archaeological faunal data from the local strontium isotopes ratio range from Taosi we find that 15 individuals from Taosi fell well outside the local strontium isotopes ratio range and were considered to be non-local. The extreme distribution of the outliers suggests they came from different geographical locations. 'Non-local' individuals accounted for 71.4% of the total number of residents. There is a higher proportion of immigrants at the Taosi site.

3 The Erlitou site

3.1 Archaeological contexts at Erlitou

The Erlitou site is located in Henan province, in the Luoyang basin to the northwest, within China's central plain (Fig. 4). It is in this region that China's earliest state-level society developed in the early 19th century BC (Liu, Chen 2003). Most prehistoric sites (Longshan culture and Erlitou culture) are found at locations in this region (Fig. 5) and, from the 1950s onwards, this was one of the first areas where Chinese archaeologists looked for the origins of Chinese civilization. Since then, many sites dating from late Neolithic to early Bronze Age have been discovered (Liu, Chen 2003; Luoyang Basin 2005).

Erlitou was the earliest and largest city in the Early Bronze Age, occupied primarily between 3800-3500 aBP. There are many distinctive areas within the city limits, including major ceremonial precincts, a large palace building, residential areas, Bronze casting workshop and other handicraft workshops, and thousands of residential compounds. To date it is still thought of as the site for the earliest capital of kingdom (Luoyang Basin 2005, Xu 3009). It was one of the most complex, urban developments in prehistoric China. The city grew very quickly in the periods of Erlitou culture and this rapid increase must have involved immigration into the city.

Some of these residential compounds contain non-local artefacts, known from other areas. The identity of the residents

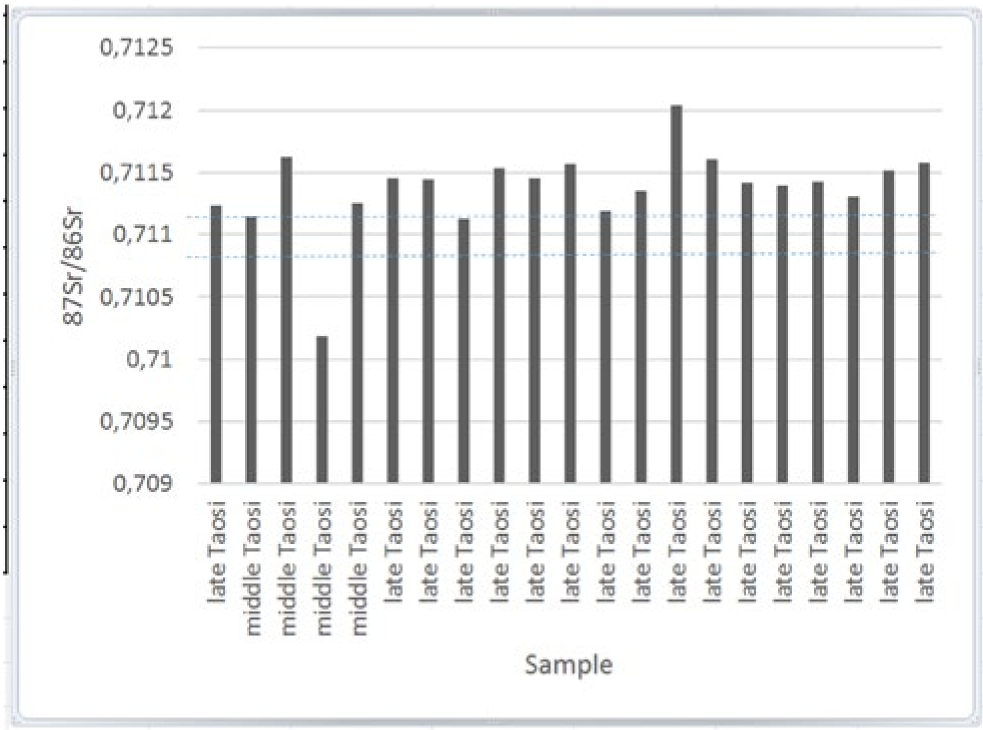

Fig. 3. Bar graph of strontium isotope ratios in tooth enamels from the Taosi site.

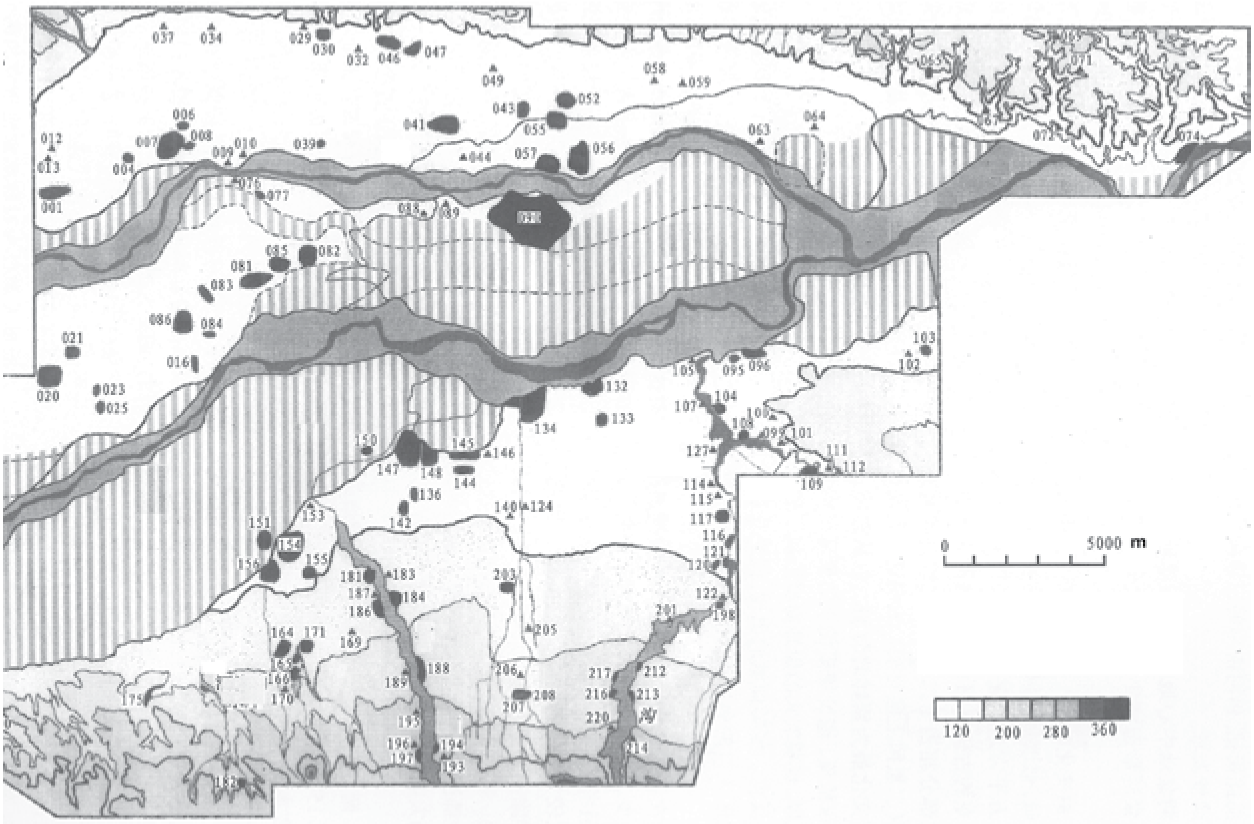

Fig. 4. Settlements of Erlitou culture (3800-3500 aBP) and distribution in the Luoyang Basin.

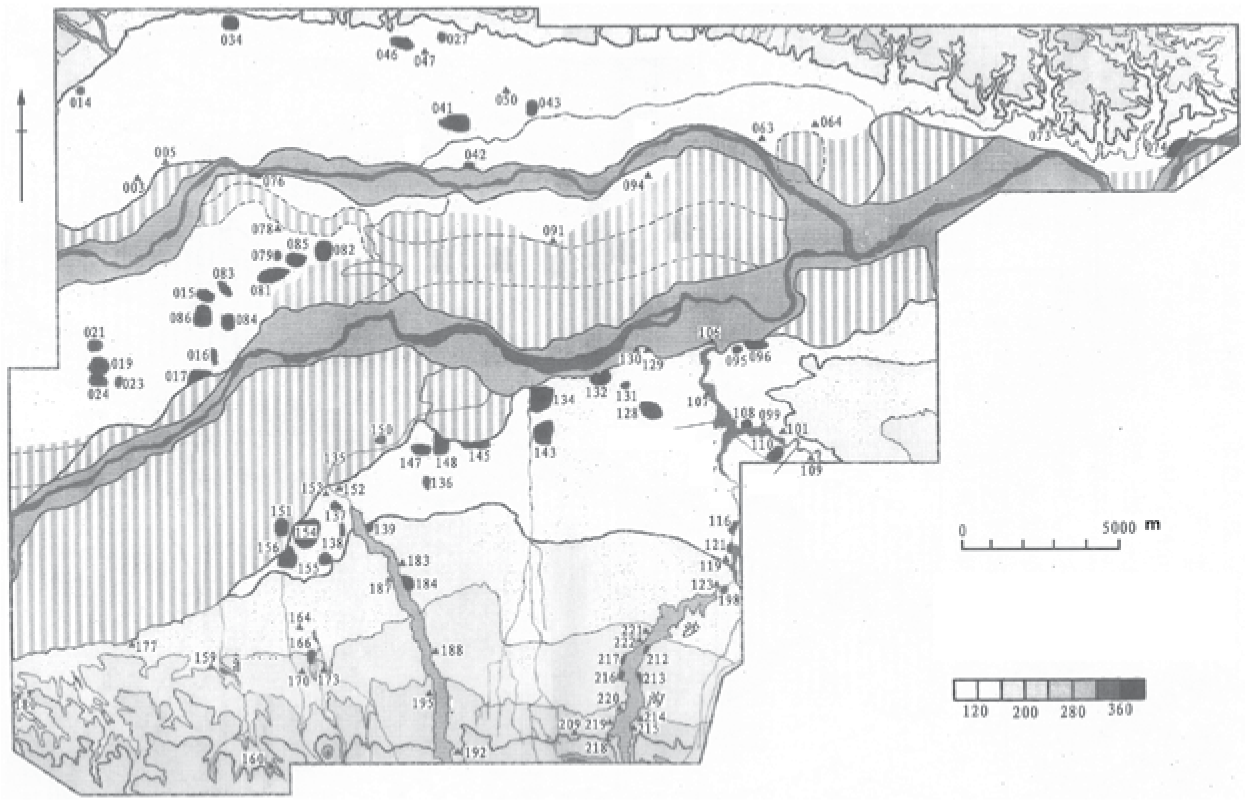

Fig. 5. Settlements of Longshan culture (4350-3950 aBP) and distribution in the Luoyang Basin.

of these ‘foreign’ compounds is uncertain. Were these local individuals adopting foreign culture, or a mix of locals and outsiders? After the fall of Erlitou, people with Erligang culture associations came to the city. For this paper, the primary research deals with questions about the origins of some of the inhabitants of Erlitou: (1) How many people were buried in the ‘palace’ were migrants to Erlitou? (2) How many people buried in the palace during the periods of Erligang culture were also migrants to the city? Strontium isotope analysis of human bone and tooth enamel was used to investigate these questions.

3.2 Strontium isotope ratio determination results

A total of 39 samples from the Erlitou site have been analysed for this study. There are a total of 16 individuals represented by paired samples of bone and enamel. There are 7 individuals represented by samples of bone. These samples are listed in Table 2.

3.3 Human migration in Erlitou

In this study we have measured $^{87}Sr/^{86}Sr$ in enamel samples from different species of domestic animals at Erlitou. From the results the pig was identified as a suitable local species. The ten pig samples were obtained in order to provide an independent measure of the local ratio of strontium isotopes at Erlitou. The analyses produced an average strontium isotope ratio of 0.712078, with a standard deviation of 0.000089, defined as within 2σ of the mean $^{87}Sr/^{86}Sr$ in the archaeological pig enamel: the local range at Erlitou is 0.712256 – 0.711900 (Chunyan *et al*. 2012).

Results of the strontium isotope analysis are presented in Fig. 6. The samples in this bar graph are arranged in the same order as in Table 2 and the discussion below will follow this order. Bone and tooth bars from the same individual are connected in the graph. Values are grouped by time of burials. The horizontal line on the side of the graph and marked local average shows the mean for the enamel from the ten pigs.

The mean value for enamel samples from 16 individuals buried at Erlitou was 0.711943± 0.000092, with a minimum value of 0.711805 and a maximum value of 0.712185. The average value of bone samples from 23 individuals buried at the same area was 0.711949± 0.000077. The high standard deviation points to a variable population and suggests a number of non-local individuals.

We would expect individuals who were long-term residents of Erlitou to have strontium isotope ratios similar to the pig values. Using this local range, there are a total of eight individuals represented by paired samples of bone and enamel. They have values for both bone and enamel that are in the local ratio range, suggesting that they were life-long residents. In addition there are seven individuals for bone that are very similar to the local ratio – they may be local residents. A 45-50 year-old middle-aged men has values for enamel that are very similar to the local Erlitou ratio; he had bone values below the local range, suggesting he was a recent immigrant. ‘Local’ individuals accounted for 65.2% of the total number of residents.

Comparing the local range to the $^{87}Sr/^{86}Sr$ ratios in the human teeth, five non-locals were found overall out of 23 sampled

TAB. 2. STRONTIUM ISOTOPE RATIOS FROM ARCHAEOLOGICAL HUMAN TOOTH ENAMEL AND BONE FROM ERLITOU SITE

Sample ID	Unit	Dates	Sex	Age	Material	$^{87}Sr/^{86}Sr$	2σ
1	2001YLVM1	ErlitouII	Male	Adult	limb	0.712013	0.000010
2	2002YLVM3	ErlitouII	Male	30-35	limb	0.711945	0.000011
3	2004YLVM19	ErlitouII	Male	45-50	limb	0.711835	0.000015
4	2004YLVM19	ErlitouII	Male	45-50	enamel	0.711900	0.000014
5	1972YVM55	ErlitouIII	Male	Adult	limb	0.711831	0.000009
6	2003YLVT35④A	ErlitouIV	?	Adult	limb	0.711997	0.000010
7	2003YLVM13	ErlitouIV	Female	35	limb	0.711982	0.000013
8	2003 YLVM13	ErlitouIV	Female	35	enamel	0.711836	0.000013
9	2003YLVM12	ErlitouIV	Female	30	enamel	0.712112	0.000014
10	2003YLVM12	ErlitouIV	Female	30	limb	0.711994	0.000011
11	2004YLVM17	ErlitouIV	Male	45	limb	0.711830	0.000011
12	2004YLVM17	ErlitouIV	Male	45	enamel	0.711810	0.000008
13	2004YLVM18	ErlitouIV	?	6	limb	0.711931	0.000012
14	2004YLVM18	ErlitouIV	?	6	enamel	0.711977	0.000011
15	2004YLVM16	ErlitouIV	?	7、8	limb	0.712048	0.000011
16	2003YLVM8	ErlitouIV	Male	>45	limb	0.712029	0.000011
17	2003YLVM8	ErlitouIV	Male	>45	enamel	0.712019	0.000010
18	2004YLVH305M2	ErlitouIV	Male	20-25	limb	0.711803	0.000009
19	2004YLVH305M2	ErlitouIV	Male	20-25	enamel	0.711825	0.000011
20	2004YLVH305M1	ErlitouIV	Female	25-30	limb	0.711874	0.000010
21	2004YLVH305M1	ErlitouIV	Female	25-30	enamel	0.711805	0.000002
22	2004YLVH305M3	ErlitouIV	Male	25-30	Skull	0.711835	0.000007
23	2004YLVH305M3	ErlitouIV	Male	25-30	enamel	0.711869	0.000013
24	2002YLVH112	ErlitouIV	Male?	17-18	limb	0.711966	0.000010
25	2004YLVH267	ErlitouIV	Female	>45	enamel	0.712100	0.000008
26	2004YLVH267	ErlitouIV	Female	>45	limb	0.711998	0.000002
27	2004YLVH262	ErlitouIV	?	2	enamel	0.711978	0.000011
28	2004YLVH262	ErlitouIV	?	2	limb	0.712098	0.000012
29	2003YLVM8	ErlitouIV	Male	>45	limb	0.711892	0.000009
30	2003YLVM8	ErlitouIV	Male	>45	enamel	0.711884	0.000010
31	2001YLVH17	Erligang upper	Female	25-30	limb	0.711928	0.000014
32	2001YLVH17	Erligang upper	Female	25-30	enamel	0.711950	0.000010
33	2002YLVM6	Erligang upper	?	<1	limb	0.712125	0.000008
34	2005 YLVG23	Erligang upper	Female	10-12	enamel	0.711958	0.000010
35	2005 YLVG23	Erligang upper	Female	10-12	limb	0.711975	0.000010
36	2005 YLVG23	Erligang upper	Female	25-30	enamel	0.711884	0.000010

Sample ID	Unit	Dates	Sex	Age	Material	$^{87}Sr/^{86}Sr$	2σ
37	2005 YLVG23	Erligang upper	Female	25-30	Skull	0.711981	0.000007
38	2002YLVH160	Erligang upper	Female	>50	limb	0.711915	0.000011
39	2002YLVH160	Erligang upper	Female	>50	enamel	0.712185	0.000001

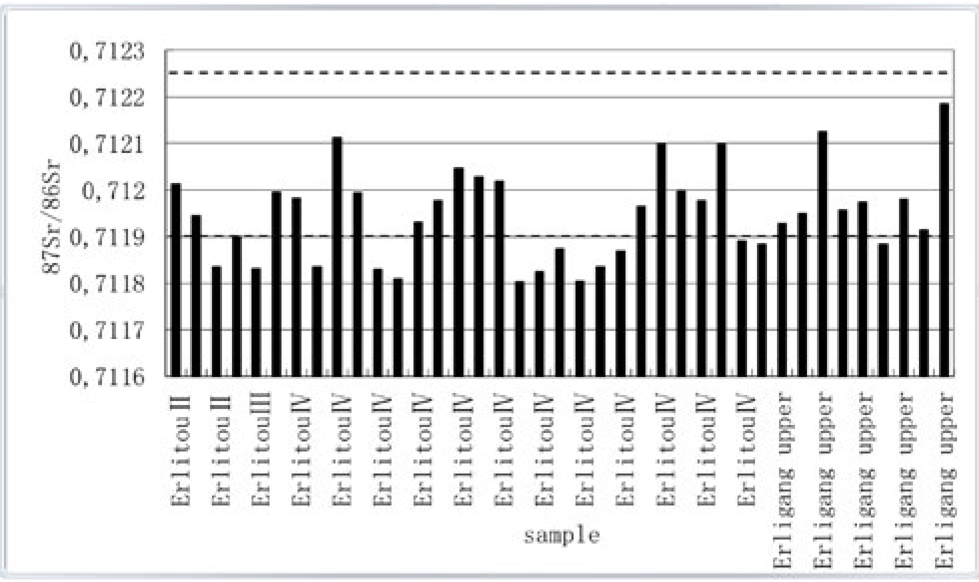

Fig. 6. Bar graph of strontium isotope ratios in tooth enamels from the Erlitou site.

individuals (tooth enamel) at Erlitou (Fig. 6). One of these had bone values in the local range. There are two individuals for bone that are outside the local ratio and they may be non-local residents. There are now 8 non-locals from the Erlitou site. In addition there are five children among the local individuals. Subtracting them from the total of 23 individuals, the number of adult individuals is 18 and thus the proportion of immigrants will increase to about 40%. Overall, the test results show that at the Erlitou site, the home of our ancestors, the native population is in the majority, but there is also a higher proportion of immigrants.

4 Conclusions

The Taosi site is the largest settlement site in the Linfen Basin in the Longshan period (4350-3950 BP) by GIS data analysis. Through strontium isotope analyses we investigated the origins of the individuals who lived and died in middle and late periods at the Taosi site. 'Non-local' individuals accounted for 71.4% of the total number of residents. There is higher proportion of immigrants at the Taosi site.

Erlitou is also the largest settlement site in the Luoyang basin of the Erlitou culture period (3800-3500 aBP) by GIS data analysis. The strontium isotope ratios ($^{87}Sr/^{86}Sr$) in human bone and tooth enamel from individuals buried in Erlitou have been measured. Results show that the proportion of population migration was 34.8%; the uniformity of Strontium ratios in skeleton suggests that most of these individuals had spent their whole lives at the site.

Data analysis showed that the proportion of population migration at Erlitou is far below that of Taosi. The results reveal complexities that, in conjunction with other archaeological data, can be correlated to social, political, or economic inequalities in ancient sites.

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Bibliography

Ericson, J. E. 1985. Strontium isotope characterization in the study of prehistoric human ecology. *Journal of Human Evolution* 14: 503-14.

Bentley, R. A., Price, T. D., Stephan, E. 2004. Determining the 'local' $^{87}Sr/^{86}Sr$ rang for Archaeological skeletons: a case study from Neolithic Europe. *Journal of Archaeological Science* 31: 365-75.

Price, T. D., Burton, J. H., Bentley, R. A. 2002. The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry* 44 (1): 117–35.

Knudson, K. J., O'Donnabhain, B., Carver, C., *et al*. 2012. Migration and Viking Dublin: paleomobility and paleodiet through isotopic analyses. *Journal of Archaeological Science* 39: 308－20.

Kennedy, B. P., Folt, C. L., Blum, J. D. *et al*. 1997. Natural isotope markers in salmon. *Nature* 387: 766-7.

Bentley, R. A. 2006. Strontium isotopes from the earth to the archaeological skeleton: a review. *Journal of Archaeological Method and Theory* 13: 135-87.

Yin Ruochun, Zhang Juzhong, Yang Xiaoyong 2008. Preliminary study of prehistoric human migration based on Sr isotope analysis from Jiahu relics (in Chinese). *Quaternary Sciences* 28(1): 50-7.

Zhao Chunyan, Yuan Jing, He Nu 2011. Strontium isotope analysis of archaeological fauna from the Taosi site (in Chinese). *Quaternary Sciences* 31(1): 22-8.

Zhao Chunyan, Yang Jie, Yuan Jing, *et al*. Strontium isotope analysis of archaeological fauna at the Erlitou site. *Science China, Earth Sciences* 55: 1255-9.

ChunYan Zhao, Lv Peng, 2102. Strontium Isotope Analysis of Archaeological Fauna from the Wadian Site. In Zhou Mingquan, I. Romanowska, Zhongke Wu, Pengfei Xu, P. Verhagen (eds.), *Revive the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 39th International Conference, Beijing, 12-16 April 2011*: 357-63. Amsterdam, Pallas Publications.

Price, T.D., Burton, J.H., Sharer, R., Buikstra, J., Wright, L., Moore, K. 2010. Kings and commoners at Copán: isotopic evidence for origins and movement in the Classic Maya period. *Journal of Anthropological Archaeology* 29: 15-32.

Price, T. D., Frei, K. M., Dobat, A., Lynnerup, N., Bennike, P. 2011. Who was in Harold Bluetooth's army? Strontium isotope investigation of the cemetery at the Viking Age fortress at Trelleborg, Denmark. *Antiquity* 85: 476-89.

Sjögren, K. G., Price, T. D., Ahlström, T. 2009. Megaliths and mobility in south-western Sweden. Investigating relations between a local society and its neighbors using strontium isotopes. *Journal of Anthropological Archaeology* 28: 85-101.

The Dongxiafeng Archaeological Team of Institute of Archaeology. 1983. Chinese Academy of Social Sciences. Linfen Cultural Bureau. Excavation of the cemetery at the Taosi site in Shanxi from 1978-1980 (in Chinese). *Archaeology* 1: 30-42.

Liu Jianguo, Wang Lin, 2007. The Study of Settlements Archaeology in the Linfen Basin Supported by GIS (in Chinese). *Archaeology* 7: 64-70.

He Nu, 2007. The Taosi site: An important milestone in the early urbanization of China. In Xie Xigong (ed.), *Study of the Taosi cite at the Xiangfen*: 695-7. Beijing, Science Press.

Zhang Yajun, He Nu, Zhang Fan, 2009. The racial type of the middle later phases of the Taosi Culture of Shanxi. *Acta Antheropologica Sinica* 28 (4): 363-71.

Liu, L., Chen, X., 2003. *State Formation in Early China*. Duckworth, London.

Team of Erlitou 2005. Institute of Archaeology of the Chinese Academy of Social Sciences. Archaeological Surveys in Luoyang Basin, Henan Province 2001-2003, (in Chinese), *Archaeology* 5: 18-37.

Xu H. 2009. *The Earliest Chinese* (in Chinese): 14-8. Beijing, Science Press.

The Iron Age in Serakhs Oasis (Turkmenistan). The Preliminary Results of the Application of Geographic Information System in the Study of the Settlement Pattern of the Earliest Confirmed Occupation of the Oasis

Nazarij Buławka
nazar.bulawka@gmail.com
Institute of Archaeology, University of Warsaw, Poland

Barbara Kaim
barbara.kaim@uw.edu.pl
Department of the Near Eastern Archaeology, Institute of Archaeology, University of Warsaw, Poland

Abstract: For almost twenty years the Serakhs Oasis in southern Turkmenistan has been studied by the Polish-Turkmen Archaeological Mission headed by Barbara Kaim. The intensive field survey, conducted since 2007, resulted not only in a discovery of almost 150 sites of different periods, but it also sheds light on the Yaz period and the earliest confirmed occupation of the oasis.

The ArcGIS database created, which includes satellite imagery, digital elevation data, topographic maps, vector data related to hydrology, ancient and recent occupation, is used as a tool to discuss some important questions relating to the settlement pattern of the oasis. The main issue of this contribution is an evaluation of the current state of research regarding the oldest settlement pattern (Iron Age), water management and the landscape taphonomy of the Serakhs Oasis. The possibility of the detection of the oldest sites will be also discussed.

Keywords: Central Asia, Landscape taphonomy, Iron Age, Irrigation, Settlement pattern

Introduction

Change within ancient settlement patterns, as detected by field survey techniques, is one of the main preoccupations of archaeologists today (Willey 1953; Schiffer *et al.* 1978: 1; Banning 1996: 26; Wheatley and Gillings 2002: 4–7). The collected data, however, is open to misinterpretation, especially when scholars treat it as a final picture. In fact, most of the archaeological landscapes have been and are constantly transformed, which often has negative influences on archaeological sites (Gaffney and Stančič 1991: 68-9; Wells 2001: 108; Wilkinson 2003: 41, 107). The aim of this paper is to evaluate how much of the ancient landscape of the Serakhs Oasis is available for archaeological study and what the present-day results may reveal in terms of the oldest settlement pattern.

1 The local conditions and the availability of archaeological sites.

Similar to the Near East, vast archaeological landscapes within southern regions of Central Asia consist of multi-stratified mound sites and palimpsests of dry levees or ravines that speak of the water-courses or irrigation networks that once existed here in the remote past. To some degree most of these areas were changed by recent human activities. Especially in Turkmenistan, the construction of the Karakum Canal led to a rapid urban sprawl and an intensive cotton cultivation program (Efremov *et al*. 1970). The Serakhs Oasis is one of such landscapes, but due its location the large investments were never conducted in the area. In fact, the shift of settlement to the territory irrigated by the Karakum Canal in the 1960s and the political transformation after the collapse of Soviet Union extended the existence of many archaeological sites located here. However, study in this area has never been easy in terms of the oldest settlement pattern, which seems to be drastically unrepresented.

The state of recognition of settlement patterns in a given place depends on the fortunate combination of field survey techniques, applied chronology and the nature of the area itself. Beyond doubt, the problem of 'visibility' and 'obtrusiveness' of sites, as mentioned by M.B. Schiffer (Schiffer *et al.* 1978: 6-8) and F.P. McManamon (1984: 223), is one of the crucial issues for Near Eastern archaeology (Banning 1996: 30). In the context of Central Asia this matter is also very topical. The efficiency of different survey techniques, however, has been discussed many times and their selection depends on the character of the sites and the archaeological landscape (Schiffer *et al*. 1978; McManamon, 1984: 223; Banning 1996). Thus, this paper will address the other aspects of surface survey which have been introduced to archaeology from environmental studies as 'landscape taphonomy' (Zvelebil *et al.* 1992: 204-7; Green 1997: 17; Barton 2002: 166; Wilkinson 2003: 41-3; Niknami 2007; Burger *et al*. 2008).

Following the ideas of M. B. Schiffer, we can agree that archaeological sites have 'undergone successive transformations' (1975: 838) and that this affects the whole of their surroundings as well. The non-cultural transformations (n-tranforms) distinguished by Schiffer (1975: 839-40) are the subject of study by geomorphologists, whereas cultural ones (Schiffer 1975: 840-1), with regard to whole settlement patterns cannot be formalized into a set of laws because they are poorly understood and dependent on the specific area and form of land-use performed there. The cultural transformation of any site after its abandonment can be very different, for example it may imply the use of its layers to manure the agricultural fields

(Wilkinson 1994: 491-2; Wilkinson 2003: 56, 119) or vineyards (Brookes *et al.* 1982, p. 295), to level the ground before the construction of a new house, or to produce construction material, etc. (Boyer *et al*. 2006: 676). T. J Wilkinson has argued that cultural transformations might cause the 'selective loss of landscape features' and they must be included in the analysis (Wilkinson 2003: 8); here we can add an example from our place of study. In the Serakhs Oasis, and possibly in other areas of Central Asia, the pastoral communities build their pit-houses on archaeological sites, sometimes even digging into the hard surface of the floor (Wagner 2011), possibly in order to gain better visibility from the top of the mound. This, however, could be also a coincidence, since pastoral communities locate their camps near wells, where archaeological sites are sometimes present.

Even though these issues are crucial to settlement pattern analysis they were often ignored in many early settlement pattern studies. Especially in the context of Central Asian archaeology there are examples showing that the lack of understanding of 'landscape taphonomy' can result in wrong assumptions about the development of settlement in specific areas (Masson 1959: 90-2; Hlopin 1964: 137-41). It should be noted that the absence of sites, which means the lack of archaeological record, cannot be easily explained with the methods traditionally used by archaeologists. Thus, explanations should be derived from other disciplines. In fact, especially in light of processual archaeology, those issues were put into equations in order to produce significant scientific laws (Schiffer *et al*. 1978). This practice was often criticized by later scholars. Fortunately, the study of this complex issue is now much easier due to the widespread development of spatial analysis available within Geographic Information Systems (GIS) in archaeology (Wheatley and Gillings 2002). Moreover, the scientific literature that published over several decades has produced an immense body of evidence.

The processes involved within 'landscape taphonomy' of dry environments of the Near East and Central Asia fall within two main categories – natural processes and human activity – which can result in the destruction or masking of possible sites. And beyond doubt most of these processes can occur together as well.

The largest impact on the preservation of sites is present-day agriculture, which, with contemporary machinery, can obliterate most low elevated sites. There are many examples of the impact of agriculture on the preservation of archaeological sites in Near Eastern archaeology (Adams 1981: 35, 47; Banning 1996: 27; Hritz 2010: 189; 2013: 1978.). Modern agriculture, however, often occurs in the form of orthogonal fields, which often require the construction of modern irrigation networks, and as result many of the archaeological sites can be destroyed. In fact, especially in Turkmenistan, this issue has been emphasized on many occasions (Bondioli and Tosi 1998: IX; Cremaschi 1998: 16; Cattani *et al.* 2008: 42). On the other hand, the agricultural transformation of the landscape can occur together with urban sprawl, which impedes access to archaeological features by masking them (Wilkinson 1994: 487) or resulting in their destruction (Pilipko 2005: 57). This applies to the construction of roads and other infrastructure elements as well.

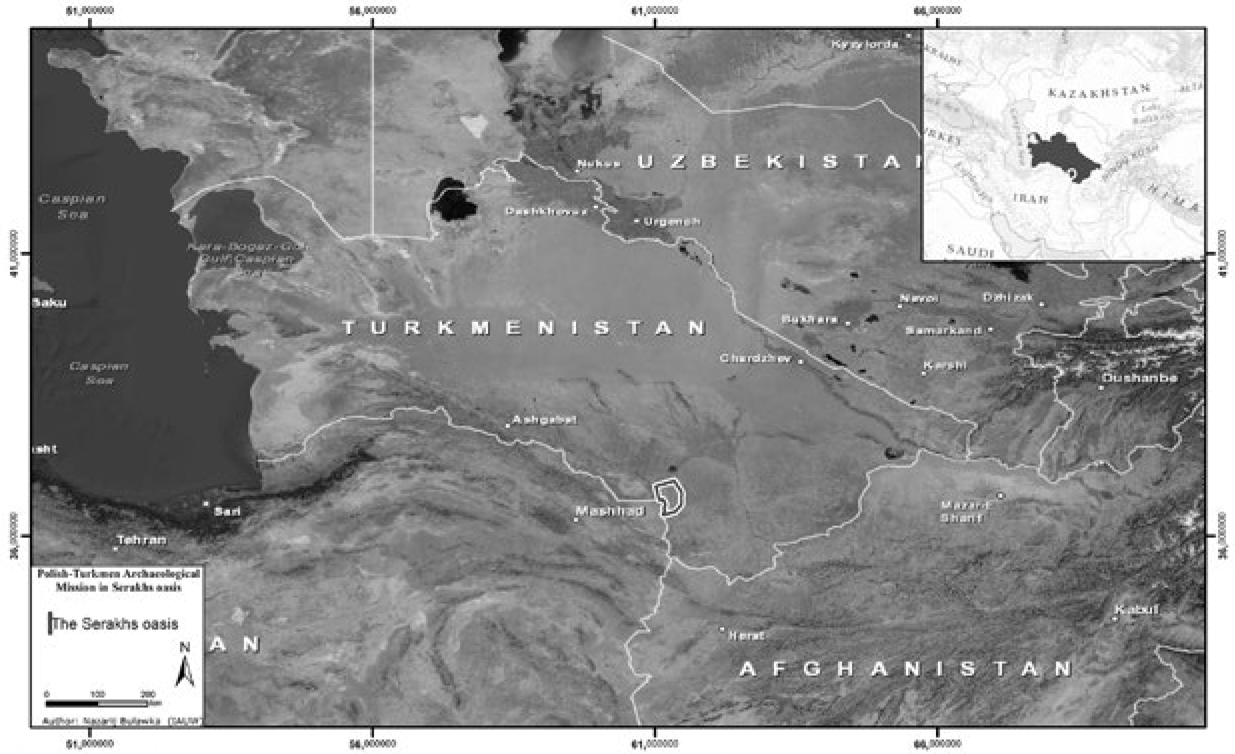
The impact of agriculture and layers of occupation, however, should not be restricted to contemporary human activities: landscape transformation is also caused of course by previous and dense population and agriculture (Wilkinson 2003: 18, 219). The presence of layers of later occupation is an especially difficult issue for investigating the oldest settlement patterns (Adams 1981: 39-40, 63; Wilkinson 1990b: 55-6; 1994: 487). Since many mound sites often reflect the persistent presence of human occupation, the area of the oldest settlements is difficult to delineate without concerted studies, for examples with use of drilling and systematic sampling (Wilkinson *et al*. 2007: 225).

The natural processes that could influence the preservation of individual sites or their visibility are numerous and are strongly dependent on the character of an area. Some of them, however, influence the shape and height of individual sites, but in terms of preservation of the entire landscape they have less importance for the study of dry environments. A good example is hill slope erosion (Brookes *et al*. 1982: 295), which, together with wind erosion, can influence the shape of the site, even if the actual destruction of a medium size site is rather doubtful (Adams 1981: 31, 50). Even in the extremely dry environment of a desert, where wind erosion is usually greater, the stability of processes might form the best environment for the preservation of the archaeological sites. On the other hand, especially in the desert, the winds cause the sand dunes to move, which can cover the archaeological sites (Hritz 2006: 396). The other type of site coverage, such as by vegetation, and which is characteristic of European landscapes, can also occur in dry environments, especially near water courses (Banning 1996: 31-2).

Importantly, specific parts of the Near East, Egypt, Iran and Central Asia differentiate in their ratios between sedimentation and erosion, which is mainly caused by distances to available water courses (rivers/streams) and their character, soil and the gradient of terrain. Due to river activity the associated sites are endangered by water erosion (Wilkinson 1998: 73, 82; Challis *et al*. 2004: 145; Boyer *et al*. 2006: 676; Hritz 2013: 1976, 1978.); this also implies to episodes of flooding (Hassan 1997: 63; Wilkinson: 2003: 195). It should, however, be emphasized that in the upper parts of water courses rapid water erosion occurs, while in lower parts, specifically near the desert's edge, sedimentation prevails. Since most of the rivers in arid continental conditions frequently do not reach any open water or reservoir and end in the desert, they often form alluvial landscapes in their deltas or crevasse splays. The visibility of sites located in such areas is drastically influenced by the process of alluviation; this phenomenon has been much discussed in the scientific literature related to the archaeology of Mesopotamia and Syria.

2.1 The area of study

The Serakhs Oasis, the sub-delta of the Tedjen River, is located in southern Turkmenistan near the border with Iran and Afghanistan (Fig. 1). The gradient of the oasis falls from 300 to 225m.a.s.l. in its northern part, marked by the range of present-day irrigation. The southern and eastern edges of the oasis touch the Badkhyz uplands and Karakum desert (Orazov 1973: 3; Kaim 2008: 129; Buławka 2015: 12). The Serakhs Oasis is the subject of study by the Polish-Turkmen mission for almost twenty years. Intensive field surveys conducted since 2007 have revealed over 150 sites of different periods in the



Service Layer Credits: Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Fig. 1. The location of the Serakhs Oasis.

oasis. The current state of research suggests that 20 of these represent the oldest known period – the Iron Age (Yaz I-III periods – 1400-300 BC) (Buławka 2015-2016b).

Since agriculture is one of the main aspects of the traditional Central Asian economy, the time of the emergence of artificial irrigation, which is crucial to existence of sedentary life in the region, is very important. The second aspect of both ancient and present-day economies, is, of course, pastoralism, which must have thrived here, especially when water resources were scarce.

Contrary to other regions in Turkmenistan, the Serakhs Oasis is not irrigated by the Karakum canal. All the water available for irrigation here comes from the Tedjen River or wells. The present-day network is based on one main canal (the Salyr-yap), which is derived from the river near the mountains of Kizil Koi at about 310m.a.s.l. It is then divided into several branches, which are named after Turkmen tribes – Kichi-aga-yap, Ata-yap, Han-yap, and so on (Orazov 1973: 30; Kaim 2008: 130-1). It is obvious that this is the contemporary irrigation network and it is different from the ancient one.

According to the current state of research in the oasis, the locations of all the Iron Age sites (Yaz culture) are all very close to the present-day irrigation network. The average distance between sites and canals is 123m, which indicates that most of the sites follow the location of today's irrigation systems. It should be noted, however, that some sites here are located further away and others are ringed by canals. Taking the measured distances it is possible to assume that the irrigation network might date to the Iron Age. This assumption, however, could be wrong, since the canals are dated only by 'association'. More recent studies conducted in Central Asia suggest that the existence of monumental irrigation networks in the Iron Age is more and more questionable (Košelenko *et al*. 1994: 78-91; Stride *et al.* 2009: 77-8; Malatesta *et al.* 2012: 91, 103). Thus, the emergence of irrigation in the studied area is problematic when studied in depth.

The subject of the oldest settlement pattern is also very challenging as there is no direct evidence of settlement predating the Iron Age, in contrast to surroundings areas. The only example of an older site, *Serahskoe Poselenie* (dated to Aeneolithic - Early Bronze Age) (Adykov and Masson 1960: 62; Orazov 1973: 53-4; Kohl 1984: 67) is located at the edge of a river terrace and could not be taken as an argument that the entire oasis was settled during the mentioned period. It is assumed, however, that access to the oldest sites in the Serakhs Oasis could somehow be impeded by the processes included in the 'landscape taphonomy' of the oasis.

The distribution of presently known Yaz sites in the oasis also points to the fragmentary recognition of the oldest settlement pattern. The largest cluster of sites is located in the northern part of the oasis, about 40km from the town of Serakhs. The average distance between the sites of Yaz culture here is about 879m, but some settlements are located much closer to each other. The Yaz sites are known in the central part of the oasis as well. They are, however, more dispersed, with an average distance of 2982m between their nearest neighbours (Buławka 2015-2016a, Fig. 3). This can also be observed in cases of sites of specific phases of the Iron Age and the occurrence of sites dated to other periods. However most of the Iron Age sites can

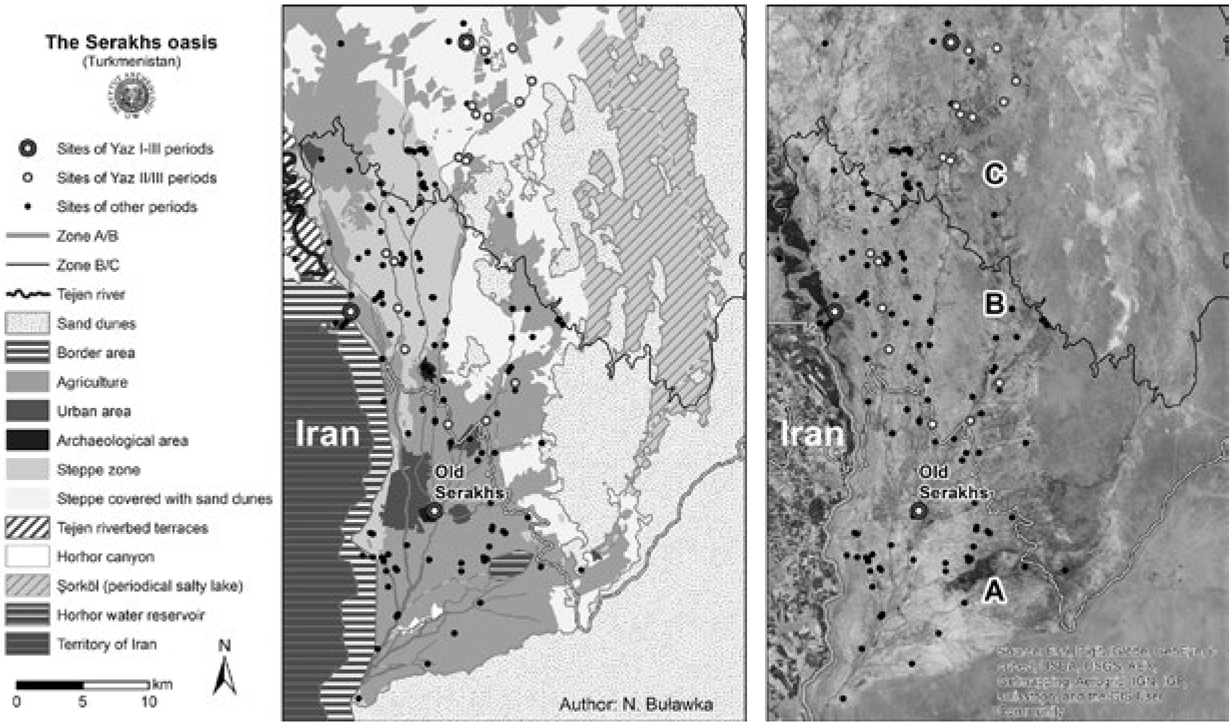


Fig. 2. The analysis of 'landscape taphonomy' of the Serakhs Oasis.

be dated to Yaz II-III periods. The painted pottery of the Yaz I period accidently found in 2014 at Goşa-depe (about 50km from Serakhs) was not identified elsewhere in the oasis during our surface survey (Buławka, 2015-2016a; 2015-2016b) (Fig. 5). It should be mentioned, however, that it was found during the excavation of A.A. Marushchenko at Old Serakhs, but the layers are covered there by 9m of later occupation (Marušenko 1956: 174-5) (Fig. 2, 4). What is more, apart from the Iron Age, there are no clear traces of later occupation in the northern cluster of the sites, with exception of rare glazed Muslim pottery sherds (dated to 12th century AD) and two sites clearly dated to Muslim periods (Gala Burun and Atamyrat gala) (Fig. 5). This could indicate that most of the sites here were abandoned after the Iron Age (Buławka 2015-2016a; 2015-2016b). On the contrary, in the southern part of the oasis all the remaining sites were settled during later periods. It is unclear whether the large-scale irrigation also functioned during Mediaeval times, this has not yet been confirmed by historical data.

In the 9th century Al-Ya'qubi noted that there were no canals or streams in Serakhs and city dwellers had to draw water from wells (BGA VIII: 279). It is to Ibn Rusta, a 10th-century Persian explorer and geographer, that we owe our first information about irrigation in the oasis. He wrote that a canal that irrigated Serakhs flows from the river to a distance of two farasakhs (ca 12km) above the town (BGA VII: 173). The same information is provided by al-Maqdīsī as well (BGA III: 329, 333). In 10th century, despite the presence of irrigation canals, the region of Serakhs was rich in pastures, but its cultivated fields were limited by the lack of a constant water supply (Le Strange 1905: 396). Evidence about irrigation in the region disappears in 13th century AD, to return only in the early 19th century in the period when the Serakhs Oasis was an area of political tension between the British and Russian Empires (Alihanov 1883: 90-1; Geier 1901: 82; Logofet 1909: 195-214).

The situation described by early Islamic authors is therefore quite different from what is suggested by Iron Age settlement patterns identified some 40km north of Old Serakhs. It is not clear, however, whether large-scale canals were used already during the early Iron Age, or if the fields were irrigated by ditches carrying water from smaller natural streams forming the ancient sub-delta of the Tedjen River, which dried out in the following periods because of climatic changes and then their former beds and features were transformed into irrigation canals. Hence it was clear that without deeper study of the landscape taphonomy and topography it is not possible to undermine the previous hypothesis.

2.2 Research strategy

In order to address different issues that appeared in the studies, a GIS database was created. The database consisted of different vector and raster data, which were analysed with ArcGIS. Some data, such as SRTM, were also processed in SAGA GIS. The vector data represented the archaeological sites, irrigation network, agricultural fields, urban areas, roads, etc. About 25 thousand kilometres of irrigation canals and other watercourses were mapped in the oasis. The archaeological sites were documented both as points (the geographic coordinates taken with GPS receiver) and polygons, which represent their contours. All the data comes from vectorization of available raster data or our survey. A very important part of the raster data are the digital elevation models (DEM) that are available through the US Geological Survey (SRTM v2) or METI and NASA (Aster GDEM v2). Besides these mentioned, specially produced digital elevation models on the basis of large scale topographic maps were also prepared. The collection of topographic maps represented the oasis from the late 18th to the early 1990s. The most useful are the large-scale military maps (1:10000m). A variety of satellite imagery is available for

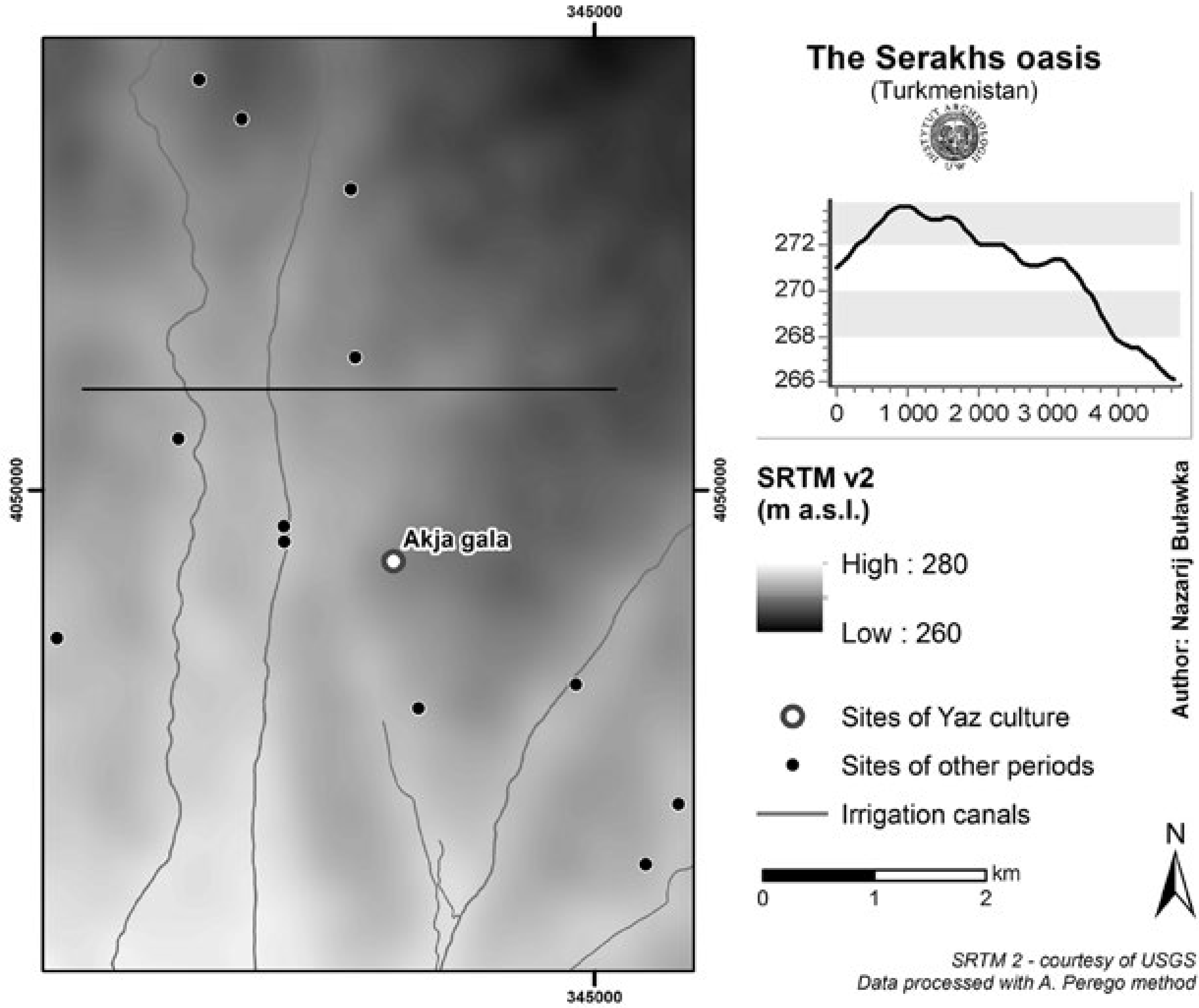


Fig. 3. Analyses of the height of the levees and location of present-day irrigation.

the Serakhs Oasis, which included the freely available Landsat 1-8, Orbview-3 and Corona images. All the mentioned raster data are courtesy of the US Geological Survey. The coverage of panchromatic Orbview-3 imagery, publicly released by GeoEye, and with a resolution of 1m, gives the area near to the border with Iran. Taking in to account their resolution and the time of acquisition, they provide a good tool to locate most of the sites in the area near the border. Besides these mentioned, the Serakhs Oasis at the moment has very good coverage by Bing Maps and Google Earth as well. The high resolution Bing Maps of the Serakhs Oasis are provided by Digital Globe (27 November 2010, Worldview-2, resolution 0.5m, accuracy 10.2m).

With respect to the scale of the topographic maps, they give some insights into the location of archaeological sites and changes within the overall irrigation network. The latter could be supplemented by historical data. The combination of all the above-mentioned data makes it possible not only to plan and document the archaeological surface survey, locate new sites and analyse the collected data in ArcGIS environment, but also in some degree to evaluate and study the landscape taphonomy of the Serakhs Oasis.

2.3 The Serakhs Oasis as a test area

The landscape taphonomy of the Serakhs Oasis was studied in much detail. First of all, this implied the use of different available raster data. One of the most important goals of this study was to find 'taphonomic windows' that could reveal sites of the oldest periods in the region; this first of all required the analysis of main cultural and non-cultural processes involved here.

One of the most evident human activities in the area is agriculture. In order to evaluate the extent of the agricultural fields, four sets of satellite imagery were compared. This implied the use of Bing Maps imagery (WorldView 2 - 27 November 2010), available in ArcGIS, the georeferenced scenes taken from Google Earth Pro (1 February 2013), Corona images (17 August 1965 - DS1023 mission) and Landsat 8 (18 April 2014 - LC81580352014108). The main aim of the study was to document the changes between 1960s and contemporary land use. While the Corona and Bing Maps images clearly indicated the shift within size, shape of fields and the scale of agricultural use of terrain between mentioned periods, the use of other sources produced a rather disturbing result. The use of

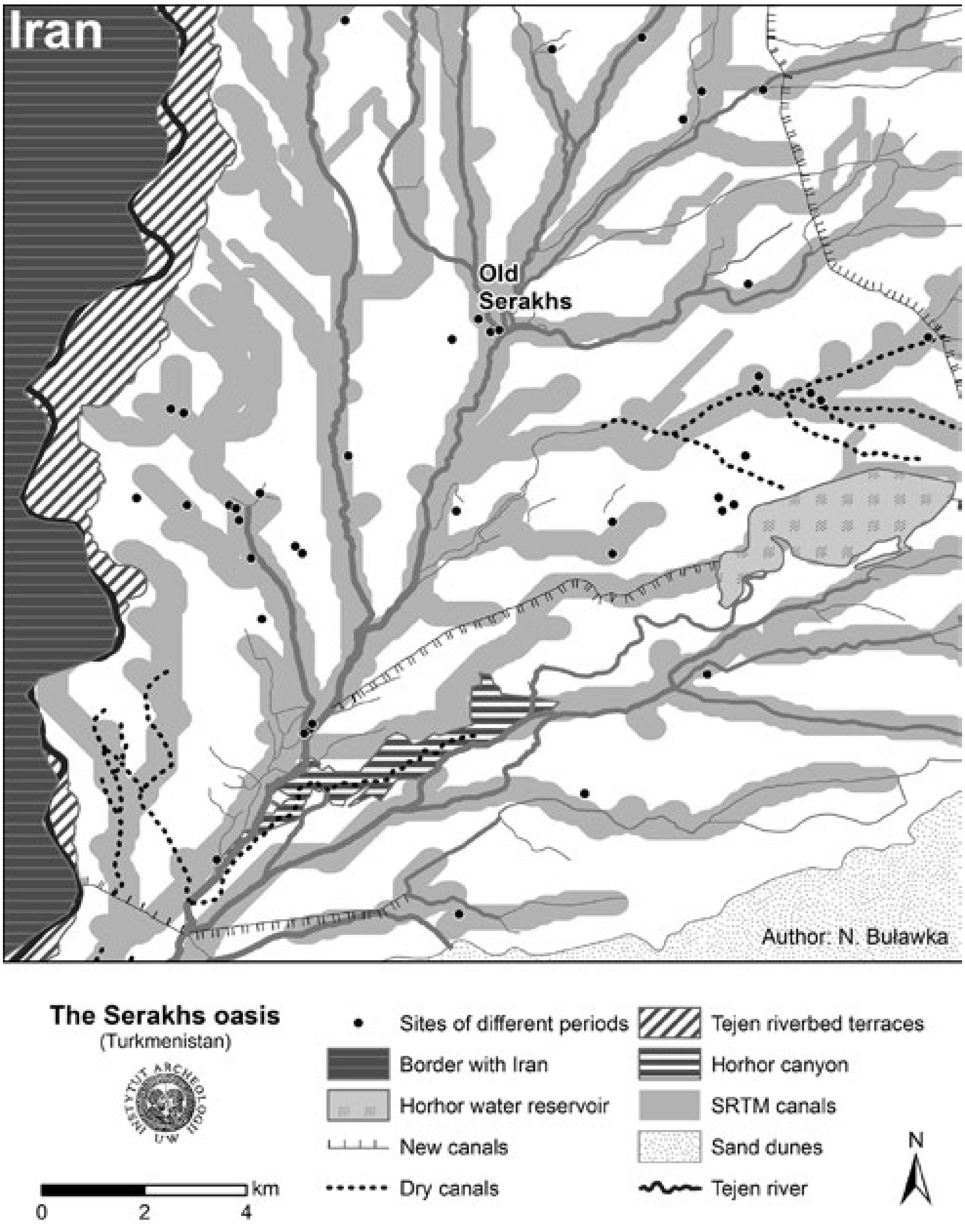


Fig. 4. The comparison of present-day irrigation and location of main levees derived from RTM data.

a combination of SWIR 2, NIR and Green bands of Landsat 8 (753) and historical Google Earth images (1 February 2013) revealed that the area changed by agriculture is even larger than was shown by previous raster data (Fig. 2).

A similar set of imagery was used in order to estimate the boundaries of urban areas. The comparison of historic Corona images and the recently acquired ones, revealed the enlargement of some urban areas, such as the town of Serakhs, which occupied space between two adjacent villages located in its vicinity. The abandonment of a few small villages was also observed (Fig. 2).

The other recent human activities could also be analysed, i.e. the construction of modern irrigation canals and the Hor Hor reservoir, which apparently was built before 1965 and destroyed the possible sites in its range. A further peculiar cultural transformation of the landscape is the zone that is constantly ploughed to improve protection of the large fence near the border with Iran. Behind this fence lies a further large protected border zone, which our mission was unable to study. This, however, in some degree preserved the landscape in the mentioned region (Fig. 2).

The non-cultural aspects of landscape transformation are more complicated to study on the basis of raster data only. Several aspects, however, can be discussed here. The largest impact in this category is the Tedjen River activity itself. The area affected by the river was mapped with the use of satellite imagery and large-scale topographic maps, and confirmed on

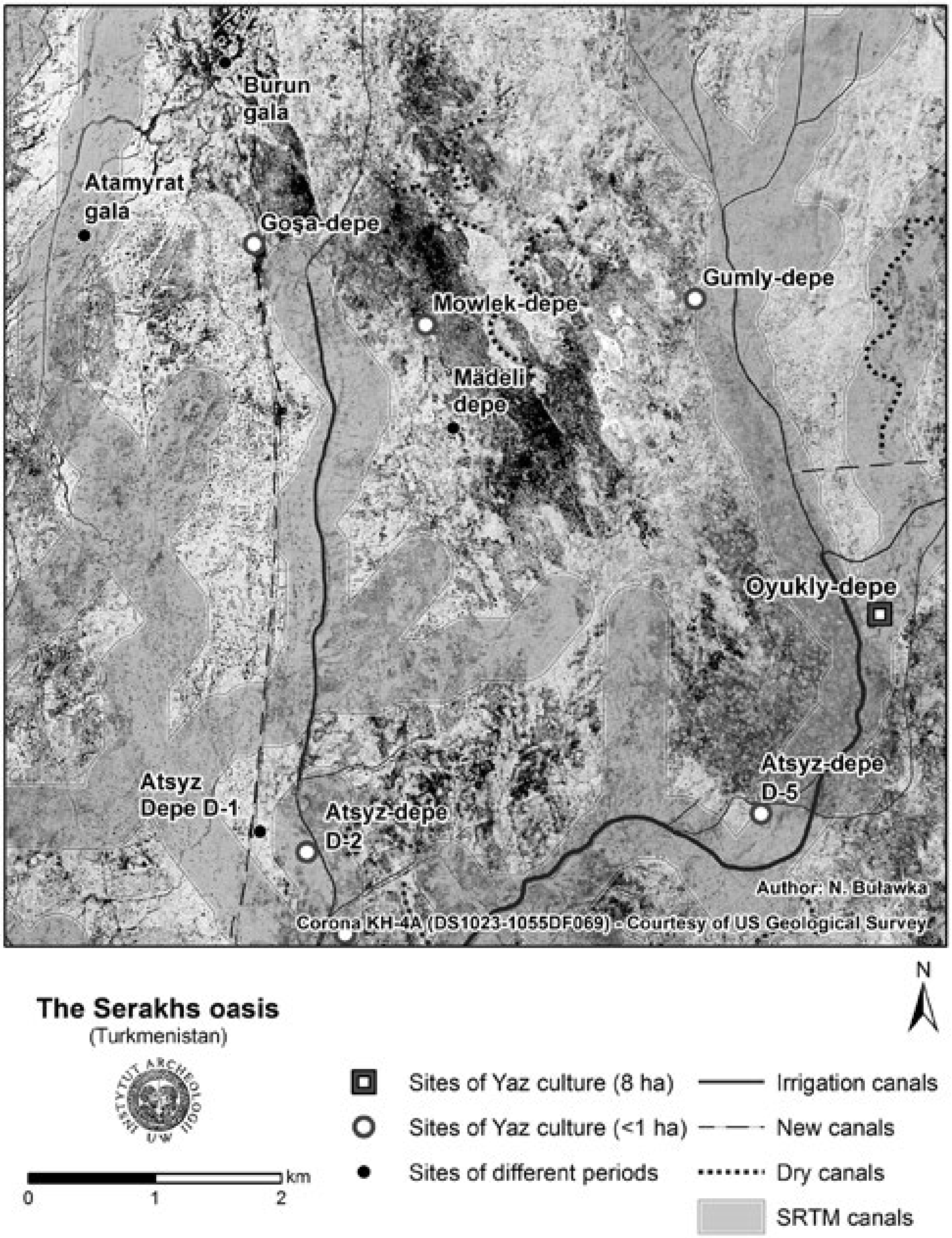


Fig. 5. The comparison of present-day irrigation and location of main levees derived from SRTM data near the northern cluster of sites.

the basis of SRTM data. It is difficult to estimate the precise data loss related to river activity, but even in the last 50 years the river meanders changed have their locations several times.

The most important non-cultural transformation process in the Serakhs Oasis is alluviation. This phenomenon could be easily observed on the basis of available Digital Elevation Models. The use of shaded relief maps, profile graphs and the simple approach of visualizing the maximum and minimum values for specific areas, with the use of a choropleth representation of elevation data, clearly show the differences in topography. These include the palimpsest of levees corresponding to the irrigation network (Buławka 2015: 18-9) and large areas covered by sand dunes located in the eastern part of the oasis. Also, at the eastern edge a salty perennial lake called Shor Kel is located, which is also well recognizable on the shaded relief (Fig. 2). The detailed analysis of the alluviation phenomenon required the automatic extraction of linear feature related to the ridges (levees) visible at SRTM and their comparison with the present-day irrigation network. This implied the removal of characteristic stripes (Oimonen 2000; Perego 2009) and then 'despeckling' the SRTM data (Sun *et al.* 2007; Stevenson *et al.* 2010). The elevation data was further processed in order to extract the features mentioned. This approach revealed that the modern irrigation system generally follows the location of the levees, but some of the canals are clearly beyond their range, which indicates that they are recent. Surprisingly, the comparison of the results with Corona images exposed the presence of relict meander-shaped water courses that are located separately or could be partly covered by present day irrigation. Moreover, one of the examples also corresponds to the location of data derived from SRTM results (Fig. 4, 5).

Analysis of the occurrence of the above-mentioned phenomena indicates that the Serakhs Oasis could be divided into three zones that represent different landscape taphonomies. Those zones are named here as zones A, B and C. The actual borders are arbitrary, but they are based on the location of specific contour lines derived from SRTM.

The most southerly zone (A) is a landscape completely changed by agriculture and urban areas. Here only the high multiperiod sites protrude, while the rest of the medium-elevated ones have been possibly deleted by modern human activity. There are, however, few 'taphonomic windows' such as the Old Serakhs archaeological park. As mentioned above, it is only at Old Serakhs that Yaz pottery was found in the southern part of the oasis, and the layers of this period are covered by 9m of later occupation (Fig. 2, 4).

To the north, zone B is also changed by agriculture to some degree, but the presence of a vast landscape used by pastoralists should be noted. Here eight sites containing Yaz pottery were found, which were settled during later periods as well. Both mentioned zones of landscape taphonomy are deeply influenced by the alluviation process. In fact the differences between the areas where the main canals are located and their surroundings are the largest here (Fig. 3). A significant difference between zones A and B is visible in the presence of sand coverage in the eastern part of the oasis, which could mask any possible sites or watercourses (Fig. 2).

The most northern taphonomy zone (C) was also changed by present day agriculture. But the agricultural activities seems to be less important here, since the presence of ploughing could be recognised only on the basis of satellite images made in winter, when the sun is very low (Google Earth - 1 February 2013). This zone is also affected by alluviation, but considering the low contrast between the areas where the watercourses are located, the actual impact could be minimal. It should be noted that, contrary to previous areas, the number of sites dated to Yaz culture is also larger. The sites of later periods are very unrepresented here. Since the sites are clustered in a particular area more surface surveys in the region should be conducted. It is assumed that the circumstances mentioned enable 'taphonomic windows' to be found, where the low elevated sites could be present. It should be emphasized, however, that the most significant impediment to the surface survey is the presence of low- to medium-size sand dunes that are difficult to distinguish from the archaeological sites on the satellite imagery (Fig. 2).

3 Conclusions

The range of the above-mentioned taphonomic processes is clearly related to the distribution of the sites of the Iron Age. It seems that they not only create a large impediment to the study of the sites of the oldest periods, but also disturb the character of previous water management systems. It should be noted that the presence of the taphonomic processes mentioned not only disturb the state of recognition of the settlement patterns of the Iron Age, but also explain the lack of sites of older periods in the oasis.

The correspondence between the sites of the oldest periods in the northern part of the oasis and the dry meander-shaped features mentioned could indicate the existence of a different water management system during the Iron Age. In order to confirm or reject this hypothesis, a thorough geomorphological study should be conducted. It should be noted that usually in Central Asia all Iron Age canals are dated only by 'association'. The results from the Serakhs Oasis could significantly undermine the existing hypothesis of the construction of a large-scale irrigation network during the Iron Age. Recently this issue was also questioned by Sebastian Stride, who proved that the valley near Samarkand could have been irrigated during the Iron Age by a network of natural streams (Stride *et al*. 2009: 77-8).

Taking into account the historical records it is assumed that the present-day irrigation network could be explained merely by the activity of the pre-modern occupation of the oasis, which began in the 19th century AD. The layout of the canals, however, follows the variation within the topography formed by the previous water management systems.

4 Discussion

The taphonomic zone A in the Serakhs oasis could be easily linked with the 4th zone distinguished by T. J. Wilkinson (2003: 41-3). It should be noted, however, that the character of the Serakhs alluvial plain, with the addition of past and recent taphonomic processes, made it possible to distinguish two intermediate zones here. Zone B, to some degree, also could be treated as the zone of attrition for the oldest settlement pattern (the 4th zone in T. J. Wilkinson 2003: 41-3), but it became inhospitable for sedentary economy when the irrigation of this region stopped. Since then the area has been used by pastoral communities for several hundred years. This caused the preservation of a large amount of sites dated to the Partho-Sasanian and Islamic periods. On the other hand, the concentration of settlement in the above-mentioned periods masked or destroyed all the possible Iron Age sites that could be located here. It assumed, however, that the visibility of the sites was decreased mainly by alluvial layers. Nevertheless, the quantity of known Yaz culture sites located here is surprisingly large, but all of them are very distant from each other. Taking this into account, it is assumed that the area between the known sites could have been settled in the Iron Age as well. Zone C clearly represents a large taphonomic window for the oldest settlements. The favourable conditions for further studies were confirmed by the results of the recent season of surface surveys (2014), which revealed a large cluster of sites at the southern edge of zone C. It is assumed that following this approach the entire intermediate area between zones B and C should be studied. It should be noted, however, that the presence of sand dunes and the lack of roads makes the archaeological study very difficult here.

Credits

Maps throughout this paper were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ material is the intellectual property of Esri and are used herein under licence.

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Bibliography

Abay, E. 2003. The Neolithic Figurines from Ulucak Höyük: Reconsideration of the Figurine Issue by Contextual Evidence. Neo-Lithics. 2/03. p. 16–22. Available at: http://www.exoriente.org/docs/00046.pdf [Accessed: 4 February 2015].

Adams, R.M. 1981. *Heartland of Cities. Surveys of ancient settlement and land use on the central floodplain of the Euphrates*. Chicago and London, The University of Chicago Press.

Adykov, K. A. and Masson, V. M. 1960. Drevnosti Tedžen-Murgabskogo meždureč´â (k izučeniû arheologičeskih pamâtnikov v zone 2-oj očeredi Karakumskogo kanala). Izvestiâ Akademii Nauk TSSR. Seriâ obŝestvennyh nauk 2: 58–66.

Alihanov' 1883. Mervskij oazis' i dorogi veduŝiâ k' nemu. S.-Peterburg': Tipografiâ i hromolitografiâ A. Travšelâ, Stremânnaâ 12.

Andrianov, B. V. 1958. Arheologo-topografičeskie issledovaniâ drevnej irrigacionnoj seti kanala Čermen-Âb. Arheologičeskie i ètnografičeskie Raboty Horezmskoj Èkspedicii 1949-1953 gg. II: 311-29. Moskva

Al-Yaʿqūbī, *Kitāb al-Buldān*, M. J. de Goeje (ed.) 1860. *Bibliotheca Geographorum Arabicorum VII*. Leiden, Brill.

Al-Masʿūdī, *Kitab al-Tanbīh wa al-ishrāf*. M.J. de Goeje (ed.) 1893-4. *Bibliotheca Geographorum Arabicorum VIII*. Leiden, Brill.

Al-Maqdīsī, *Kitāb Aḥsan al-taqāsīm fī maʿrifat al-ʿaqālīm*. M. J. de Goeje (ed.) 1906. *Bibliotheca Geographorum Arabicorum III*. Leiden, Brill.

Andrianov, B. V. 1969. Drevnie orositel´nye sistemy Priaral´â, Moskva: Izdatel′stvo «Nauka».

Andrianov, B. V. and Muhamedžanov, A. R. 1986. Rol′ irrigacii v social′noj istorii drevnej Srednej Azii. In V. M. Masson (ed.), Drevnee civilizacii vostoka (Materialy II Sovetsko-amerikanskogo simpoziuma), Taškent: Izdatel′stvo Fan: 34-44.

Banning, E. B. 1996. Highlands and Lowlands: Problems and Survey Frameworks for Rural Archaeology in the near East. *Bulletin of the American Schools of Oriental Research* 301. Available at: http://www.jstor.org/stable/10.2307/1357294?origin=crossref [Accessed: 4 August 2014].

Barton, C. M., Bernabeu, J., Aura, J. E., Garcia, O., La Roca, N. 2002. Dynamic Landscapes, Artifact Taphonomy, and Landuse Modeling in the Western Mediterranean. *Geoarchaeology - An International Journal* 17 (2): 155–90. DOI:10.1002/gea.10008.

Bondioli, L. and Tosi, M. 1998. Introduction. In A. Gubaev, G. Koshelenko, M. Tosi (eds.), *The Archaeological Map of the Murghab delta. Preliminary reports 1990–95, Centro Scavi e Ricerche Archeologiche, Reports and Memoirs, Series Minor 3, Istituto Italiano per l'Africa e l'Oriente*: IX-XIX. Rome, La Nuova Poligrafica.

Boyer, P., Roberts, N., Baird, D. 2006. Holocene environment and settlement on the Çarşamba alluvial fan, south-central Turkey: Integrating geoarchaeology and archaeological field survey, *Geoarchaeology* 21 (7): 675–98. DOI:10.1002/gea.20133.

Brookes, I. A., Levine, L. D., Dennell, R. W. 1982. Alluvial Sequence in Central West Iran and Implications for Archaeological Survey. *Journal of Field Archaeology* 9 (3): 285–99. DOI:10.1179/009346982791504544.

Buławka, N. 2015. Przykłady zastosowania programu ArcGIS w badaniu osadnictwa kultury Jaz w oazie Serachs (Turkmenistan). In J. Lechnio (ed), *GIS w UW. Pierwsze forum użytkowników licencji edukacyjnej SITE oprogramowania ArcGIS na Uniwersytecie Warszawskim. Materiały pokonferencyjne. WGiSR UW*: 11-25. Warszawa, Uniwersytet Warszawski, Wydział Geografii i Studiów Regionalnych

Buławka, N. 2015-2016a. Settlement pattern of the Yaz culture in the deltas of Tejen River in Turkmenistan. In *Proceedings of the Conference: A millennium of history: The Iron Age in Central Asia (2nd and 1st millennia BC)*, Archäologie in Iran und Turan (submitted).

Buławka, N. 2015-2016b. Yaz II-III settlement pattern in Serakhs Oasis, southern Turkmenistan. *Iran. Journal of the British Institute of Persian Studies* (submitted).

Burger, O., Todd, L., Burnett, P. 2008. The Behavior of Surface Artifacts: Building a Landscape Taphonomy on the High Plains. In L. L. Scheiber and B. J. Clark (eds.), *Archaeological Landscapes on the High Plains*: 203-36. Boulder, Colorado, University Press of Colorado.

Cattani, M., Cerasetti, B., Salvatori, S., Tosi, M. 2008. The Murghab Delta in Central Asia 1990-2001: the GIS from research resource to a reasoning tool for the study of settlement change in long-term fluctuations. In S. Salvatori, M. Tosi, B. Cerasetti (eds.), *Volume II. The Bronze Age and Early Iron Age in the Margiana lowlands: facts and methodological proposal for a redefinition of the research strategies*, *The Archaeological Map of the Murghab Delta. Studies and Reports*. British Archaeological Reports International Series 1806: 39-45. Oxford, Archaeopress.

Cerasetti, B. 2008. A GIS for the archaeology of the Murghab Delta. In S. Salvatori, M. Tosi, B. Cerasetti (eds.), *Volume II. The Bronze Age and Early Iron Age in the Margiana lowlands: facts and methodological proposal for a redefinition of the research strategies*, *The Archaeological Map of the Murghab Delta. Studies and Reports*. British Archaeological Reports International Series 1806: 29-37. Oxford, Archaeopress.

Challis, K., Priestnall, G., Gardner, A., Henderson, J., O'Hara, S. 2004. Corona Remotely-Sensed Imagery in Dryland Archaeology: The Islamic City of al-Raqqa, Syria. *Journal of Field Archaeology* 29 (1-2): 139–53. DOI:10.1179/jfa.2004.29.1-2.139.

Cremaschi, M. 1998. Palaeohydrography and middle holocene desetification in the northern fridge of the Murghab delta. In A. Gubaev, G. A. Koshelenko, M. Tosi (eds.), *The*

Archaeological Map of the Murghab Delta. Preliminary Reports 1990-95: 15-26. Rome, La Nuova Poligrafica.

French, D. H. 1970. Notes on Site Distribution in the Cumra Area. *Anatolian Studies* 20: 139-48. DOI:10.2307/3642592.

Gaffney, V. and Stančič, Z. 1991. *GIS Approaches to Regional Analysis: A Case Study of the Island of Hvar*. Ljubljana, Znanstveni Inštitut Filozofske Fakultete.

Gejer, I. I. 1901. *Putevoditel′ po Turkiestanu*, Taškent″. Tipo-Litografiâ V.M. Il′ina.

Green, S. W. 1997. Reuniting the truth : integrating anthropology, geography, and history through landscape archaeology. In L. F. Stine (ed.), *Carolina's historical landscapes : archaeological perspectives*: 17–22. Knoxville, University of Tennessee Press.

Hassan, F. A. 1997. The Dynamics of a Riverine Civilization: A Geoarchaeological Perspective on the Nile Valley, Egypt. *World Archaeology* 29 (1): 51–74. DOI:10.2307/124996.

Hlopin, I. N. 1964. *Geoksûrskaâ gruppa poselenij èpohi èneolita*. Leningrad, Izdatel′stvo «Nauka».

Hritz, C. 2006. The changing Mesopotamian landscape as seen from Spot and Corona images. In M. W. Mehrer and K. L. Wescott (eds.), *GIS and archaeological site location modelling*: 380–402. Boca Raton, London and New York, Taylor & Francis.

Hritz, C. 2010. Tracing Settlement Patterns and Channel Systems in Southern Mesopotamia Using Remote Sensing. *Journal of Field Archaeology* 35 (2): 184–203.

Hritz, C. 2013. A malarial-ridden swamp: using Google Earth Pro and Corona to access the southern Balikh valley, Syria. *Journal of Archaeological Science* 40 (4): 1975–87.

Jeffreys, D. 2008. Settlements in Egypt: Alluvial Settlements in the Nile Valley (and Delta), in H. Selin (ed.), *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures SE – 8427*: 1994–8. Springer Netherlands.

Johnston, K. 2002. Protrusion, Bioturbation, and Settlement Detection during Surface Survey: The Lowland Maya Case. *Journal of Archaeological Method and Theory* 9 (1): 1–67.

Kaim, B. 2008. The Parthian settlements in the Serakhs Oasis. *Parthica* 10: 129–34.

Kohl, P. L. 1981. Introduction. In. P. L. Kohl (ed.), *The Bronze Age Civilization of Central Asia. Recent Soviet Discoveries*: I-XXXIX. New York, M.E. Sharpe

Kohl, P. L. 1984. *Central Asia. Palaeolithic beginnings to the Iron Age*. Paris, Editions Recherche sur les civilisations.

Košelenko, G. A., Gubaev, A. G., Gaibov, A. V., Bader, A. 1994. Mervskij oazis: dinamika sistem rasseleniâ i irrigacii. *Vestnik Drevnej Istorii* 4: 78-91.

Le Strange, G. 1905 *The Lands of the Eastern Caliphate: Mesopotamia, Persia, and Central Asia from the Moslem Conquest to the Time of Timur*. Cambridge, University Press.

Lisicyna, G. N. 1978. *Stanovlenie i razvitie orošaemogo zemledeliâ v ûžnoj Turkmenii*, Moskva, Izdatel′stvo «Nauka».

Lisitsina, G. N. 1981. The History of Irrigation Agriculture in Southern Turkmenia, In P. L. Kohl (ed.), *The Bronze Age Civilization of Central Asia. Recent Soviet Discoveries*: 350-9. New York, M. E. Sharpe.

Logofet', D. N. 1909. *Na granicah Srednej Azii. Putevye očerki v'3-h'knigah'. Kniga 1. Persidskaâ granica*, S.-Peterburg', V. Berezovskiij.

Malatesta, L. C., Castelltort, S., Mantellini, S., Picotti, V., Hajdas, I., Simpson, G., Berdimuradov, A.E., Tosi, M., Willett, S. D. 2012. Dating the Irrigation System of the Samarkand Oasis: A Geoarchaeological Study. *Radiocarbon* 54 (1): 91–105.

Markofsky, S. 2010. *Illuminating the Black Sands: survey and settlement in the Bronze Age Murghab Delta, Turkmenistan*. Unpublished PhD thesis, University College London. Available from: http://discovery.ucl.ac.uk/770433/

Marušenko, A. A. 1956. Staryj Serahs (Otčët o raskopkah 1953 g.). *Trudy Instituta Istorii, Arheologii i Ètnografii Akademii Nauk Turkmenskoj SSR* 2: 161–205.

Mcmanamon, F. P. 1984. Discovering Sites Unseen. In M. B. Schiffer (ed.), *Advances in Archaeological Method and Theory 7*: 223–92. Orlando, Academic Press.

Niknami, K. A. 2007. A stochastic model to simulate and predict archaeological landscape taphonomy: monitoring cultural landscape values based on an Iranian survey project. *Archeologia e Calcolatori* 18: 101-20.

Oimoen, M. 2000. An effective filter for removal of production artifacts in US Geological Survey 7.5-minute digital elevation models. In *Proceedings of the Fourteenth International Conference on Applied Geologic Remote Sensing*: 6-8. Las Vegas. Available at: http://edna.usgs.gov/Edna/pubs/artifacts.pdf [Accessed: 3 June 2015]

Orazov, O. 1973. *Arheologičeskie i arhitekturnye pamâtniki Serahskogo oazisa*, Ašhabad, Izdatel′stvo «Turkmenistan».

Perego, A. 2009. SRTM DEM destriping with SAGA GIS: consequences on drainage network extraction, Available from: http://www.webalice.it/alper78/ [Accessed: 3 June 2015]

Pilipko, V. N. 2005. Raskopki na Hyrly-depe. *Problemy Istorii, Filologii, Kul′tury. Journal of Historical, Philological and Cultural Studies* 15: 57–80.

Salvatori, S. 2008. The Margiana settlement pattern from the Middle Bronze Age to the Parthian-Sasanian: a contribution to the study of complexity. In S. Salvatori, M. Tosi, B. Cerasetti (eds.), *Volume II. The Bronze Age and Early Iron Age in the Margiana lowlands: facts and methodological proposal for a redefinition of the research strategies. The Archaeological Map of the Murghab Delta. Studies and Reports*. British Archaeological Reports International Series 1806: 57-74. Oxford, Archaeopress.

Schiffer, M. B., Sullivan, A. P., Klinger, T. C. 1978. The Design of Archaeological Surveys, *World Archaeology* 10 (1): 1–28. Available from: http://www.jstor.org/stable/124409 [Accessed: 4 May 2015]

Schmidt, A. and Fazeli, H. 2007. Tepe Ghabristan: a Chalcolithic tell buried in alluvium. *Archaeological Prospection* 14 (1): 38–46. Available at: DOI:10.1002/arp.291.

Stevenson, J. A., Sun, X., Mitchell, N. C. 2010. Despeckling SRTM and other topographic data with a denoising algorithm. *Geomorphology* 114: 238–52. Available at: doi:10.1016/j.geomorph.2009.07.006.

Stride, S., Rondelli, B., Mantellini, S. 2009. Canals versus horses: political power in the oasis of Samarkand. *World Archaeology* 41 (1): 73–87. Available at: http://www.tandfonline.com/doi/abs/10.1080/00438240802655302 [Accessed: 9 February 2015].

Sullivan, A. P. III (ed.) 1998. *Surface Archaeology*. Albuquerque, University of New Mexico Press.

Sun, X., Rosin, P. L., Martin, R. R., Langbein, F. C. 2007. Fast and effective feature-preserving mesh denoising. *IEEE*

Transactions on Visualisation and Computer Graphics 13: 925–38.

Tolstov, S. P. 1948. *Drevnij Horezm. Opyt istoriko-arheologičeskogo issledovaniâ*, Moskva, Izdanie MGU.

Wagner, M. 2011. The first season of excavations at Topaz Gala Depe in the Sarakhs oasis, southern Turkmenistan. *Światowit* Vol. VII (XLIX)/A 2009–2010: 209-11.

Wells, L. E. 2001. A geomorphological approach to reconstructing archaeological settlement patterns based on surficial artifact distribution: replacing humans on the landscape. In P. Goldberg, V. Holliday, C. R. Ferring (eds.), *Earth Sciences and Archaeology SE – 5*: 107–41. Springer US. Available at: http://link.springer.com/chapter/10.1007/978-1-4615-1183-0_5 [Accessed: 16 May 2015]

Wheatley, D., Gillings, M. 2002. *Spatial technology and archaeology: a guide to the archaeological applications of GIS*. London and New York, Taylor & Francis.

Wilkinson, T. J. 1990a. Early Channels and Landscape Development around Abu Salabikh, a Preliminary Report. *Iraq* 52: 75–83.

Wilkinson, T. J. 1990b. The Development of Settlement in the North Jazira between the 7th and 1st Millennia BC. *Iraq* 52: 49–62.

Wilkinson, T. J. 1994. The Structure and Dynamics of Dry-Farming States in Upper Mesopotamia [and Comments and Reply]. *Current Anthropology* 35 (5): 483–520. Available at: http://www.jstor.org/stable/2744079.

Wilkinson, T. J. 1998. Water and Human Settlement in the Balikh Valley, Syria: Investigations from 1992-1995, *Journal of Field Archaeology* 25 (1): 63–87. Available from: http://www.jstor.org/stable/530458 [Accessed: 17 May 2015]

Wilkinson, T. J. 1999. Holocene valley fills of southern Turkey and northwestern Syria: Recent geoarchaeological contributions. *Quaternary Science Reviews* 18 (4-5): 555–71. Available at: DOI:10.1016/S0277-3791(98)00097-3.

Wilkinson, T. J. 2003. *Archaeological landscapes of the Near East*. Tucson, University of Arizona Press.

Wilkinson, T. J., Boucharlat, R., Ertsen, M. W., Gillmore, G., Kennet, D., Magee, P., Rezakhani, K., De Schacht, T. 2012. From human niche construction to imperial power: long-term trends in ancient Iranian water systems. *Water History* 4 (2): 155–76. Available at: DOI:10.1007/s12685-012-0056-9.

Wilkinson, T. J., Peltenburg, E., Mccarthy, A., Wilkinson, E. B., Brown, M. 2007. Archaeology in the land of Carchemish: landscape surveys in the area of Jerablus Tahtani, 2006. *Levant* 39: 213–47.

Wilkinson, T. J., Philip, G., Bradbury, J., Dunford, R., Donoghue, D., Galiatsatos, N., Lawrence, D., Ricci, A., Smith, S. L. 2014. Contextualizing Early Urbanization: Settlement Cores, Early States and Agro-pastoral Strategies in the Fertile Crescent During the Fourth and Third Millennia BC. *Journal of World Prehistory* 27: 43-109. Available at: DOI:10.1007/s10963-014-9072-2.

Willey, G. R. 1953. Prehistoric Settlement Patterns in the Virú Valley, Perú. *Bureau of American Ethnology Bulletin* 155. Washington D. C., Government Printing Office.

Zvelebil, M., Green S. W., Macklin, M. G. 1992. Archaeological landscapes, lithic scatters, and human behavior. In J. Rossignol and L. Wandsnider (eds.), *Space, Time, and Archaeological Landscapes*: 193-226. Boston, MA, Springer US. Available at: DOI:10.1007/978-1-4899-2450-6.

Multi-Scale Approach for the Reconstruction of a Past Urban Environment. From Remote Sensing to Space Syntax: the Case of *Dionysias* (Fayum, Egypt)

Gabriella Carpentiero
gcarpentiero@gmail.com
Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Carlo Tessaro
carlotessaro@gmail.com
Laboratorio di Informatica Applicata alla Ricerca Preistorica (LIARP),
Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Abstract: This paper discusses the results obtained inside the 'Dionysias Archaeological Project' with the application of a multi-scale methodology and urban network analysis on remotely sensed data. Given the lack of any data from the excavations, it was necessary to exploit the results of all possible techniques in order to obtain new sources of knowledge.

The study of the entire urban complex through non-invasive techniques has shown a detailed map of the ancient settlement of Dionysias, while the application of spatial analysis has given new interpretative models. The challenge of this approach has been focused on the exploitation of remotely sensed data with the application of Space Syntax analysis of the entire urban complex. The use of space syntax added new perspective to the study of the entire settlement, adding a new interpretation of the function of space and of the interactions between social and spatial elements.

Keywords: Remote sensing, Magnetic survey, Spatial Network Analysis, Space Syntax

Introduction

Traditional research in the analysis of ancient cities has given particular emphasis to the study of the construction process and built environments as well as their development over time. At the same time a key question is the study of infra-structural capacity and the ability to adapt to dynamic urban process in different cultures. Current approaches give evidence to the organisation and perception of space, in particular in small areas or fractions of ancient cities, trying to identify also the social interactions between the built space and its surrounding environment.

In the last few years this kind of approach has been widely applied in particular in extensively excavated contexts. Most recently, a few researches have used the application of this approach to data coming from different kinds of geospatial techniques and non-destructive methods. The combination and integration of satellite imagery, LIDAR, aerial photography, archaeological geophysics, and surface survey can give invaluable information about features that are still underneath the soil with a high level of accuracy. The possibility offered by technological advances can increase not only the amount of information that is possible to obtain but also as a consequence, the further analysis that is possible to apply. Recent researches have tried to stress further remote sensing results, with the application of different kinds of spatial analysis, trying to enhance interpretation of still buried archaeological features. This technological and conceptual development has been possible thanks to a growing awareness of its possible benefits.

Within the frame of the 'Dionysias Archaeological Project' we applied an approach, which considers the entire urban complex as a whole and gives an active role to spatial characteristics of the city itself. Various aspects of the city planning were taken into consideration together with cultural (and partially social) components underlying urban design.

1 The 'Dionysias Archaeological Project': from remote sensing to close range analysis and beyond (G.C.)

1.1 Site location and previous researches

The settlement of *Dionysias* is located on the western end of the Fayum region in Egypt, 3.5 km from the Birket Qarun, ancient *Moeris*, a saltwater lake that occupies the northern side of the region, about 80 km southwest of Cairo (Fig. 1). The site is known thanks to the well-preserved Ptolemaic temple, believed to be connected to the legend of the Korah/Qarun castle. The village was active from the 3rd century BC to the 6th century AD[1] and was a new foundation of the Ptolemies in the context of the massive land reclamation work started in 250-240 BC and constructed by the engineer Cleon (Bouché-Leclercq 1908: 122). The lake extension was substantially reduced to about its current size with a huge enlargement of the arable land. New cities were founded in the area formerly occupied by the lake for incoming Greek colonies which were

[1] The first quote of the village is a papyrus found in Kom Medinet Ghoran dated to 229-228 BC (De Cenival 1980: 193); the last quote dates to the VI century AD (P. Laur. 393, II.3).

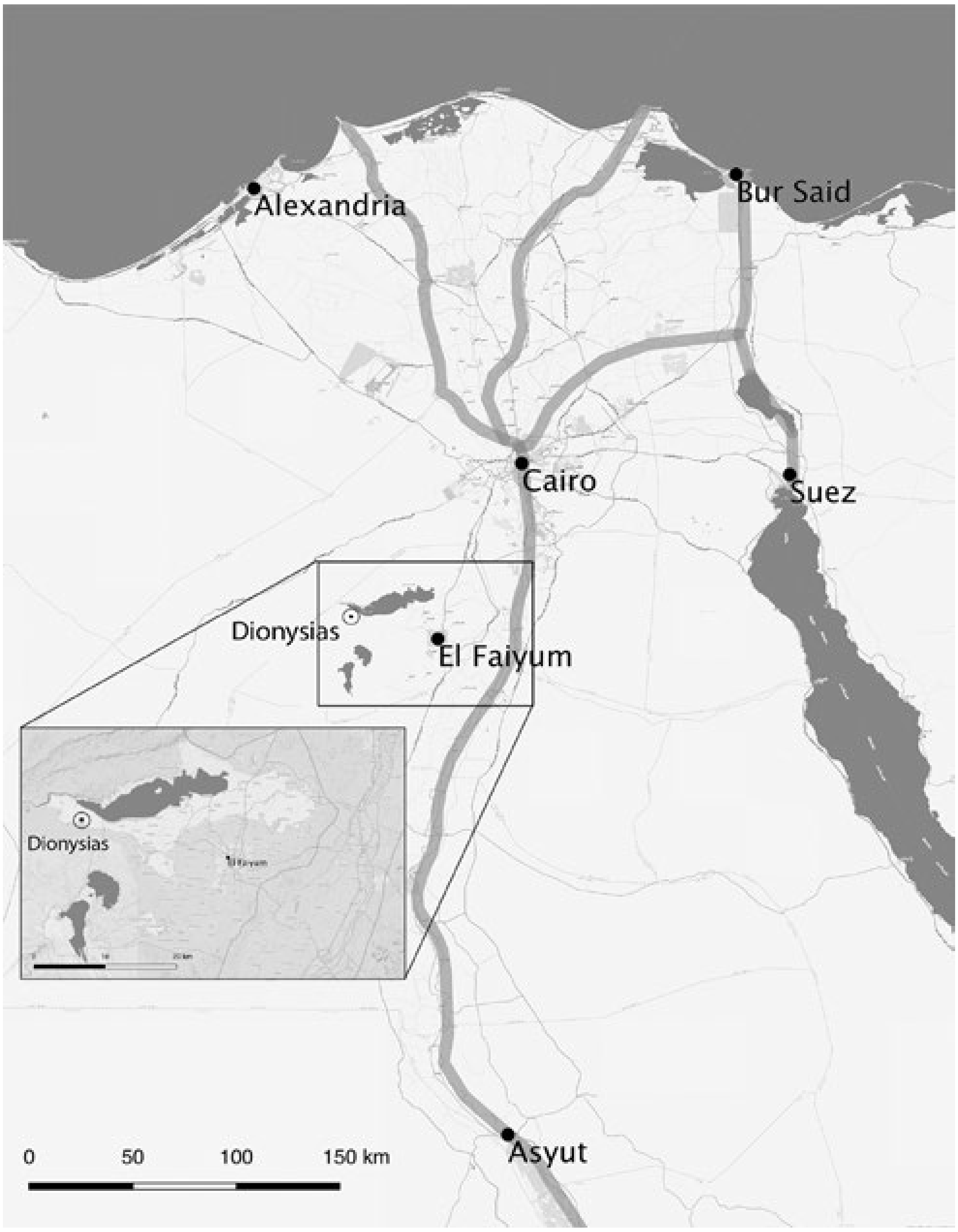

FIG. 1. LOCATION OF THE SITE.

probably constituted in the 3rd century BC about 20% of the total population, according to studies on papyrological sources (Rathbone 1990: 113).

Ptolemaic settlements, new foundation and pre-existing cities, were spread all over the region around the *Moeris* lake (corresponding to the actual Birket Qarun), in particular along the shore or main canals (Fig. 2).

Nowadays the settlement is characterised by a flat surface with a medium altitude of 4 m below sea level and just few archaeological features are visible on the ground (Fig. 3). Only some parts of the ancient village have been excavated during the French-Swiss mission between 1948 and 1950 (Schwartz and Wild 1950). Before the beginning of the project in 2009, structures that were known in the ancient village are: the Ptolemaic temple dedicated to Sobek, the crocodile god, and studied by many scholars (Lucas, Sicard, Pococke, Jomard, Lepsius, Arnold etc.);[2] the military camp of the 3rd century AD, known from papyrological sources as the *castra dionysiadi*;[3] the procession station (the *komasterion*) which was at the beginning of the processional road (the *dromos*); the Roman mausoleum; the so-called *maison blanche* (Schwartz and Wild 1950: 7). Some of the streets are barely recognisable, such as the *dromos* and the street that runs parallel to the south.

1.2 Data collection

Since 2009 the settlement was surveyed with different methods of non destructive techniques and it appeared to be

2 For a history of the studies about *Dionysias* see: Cestari 2010.
3 Ostr. Fay. 50 in Schwartz and Wild 1950: 2.

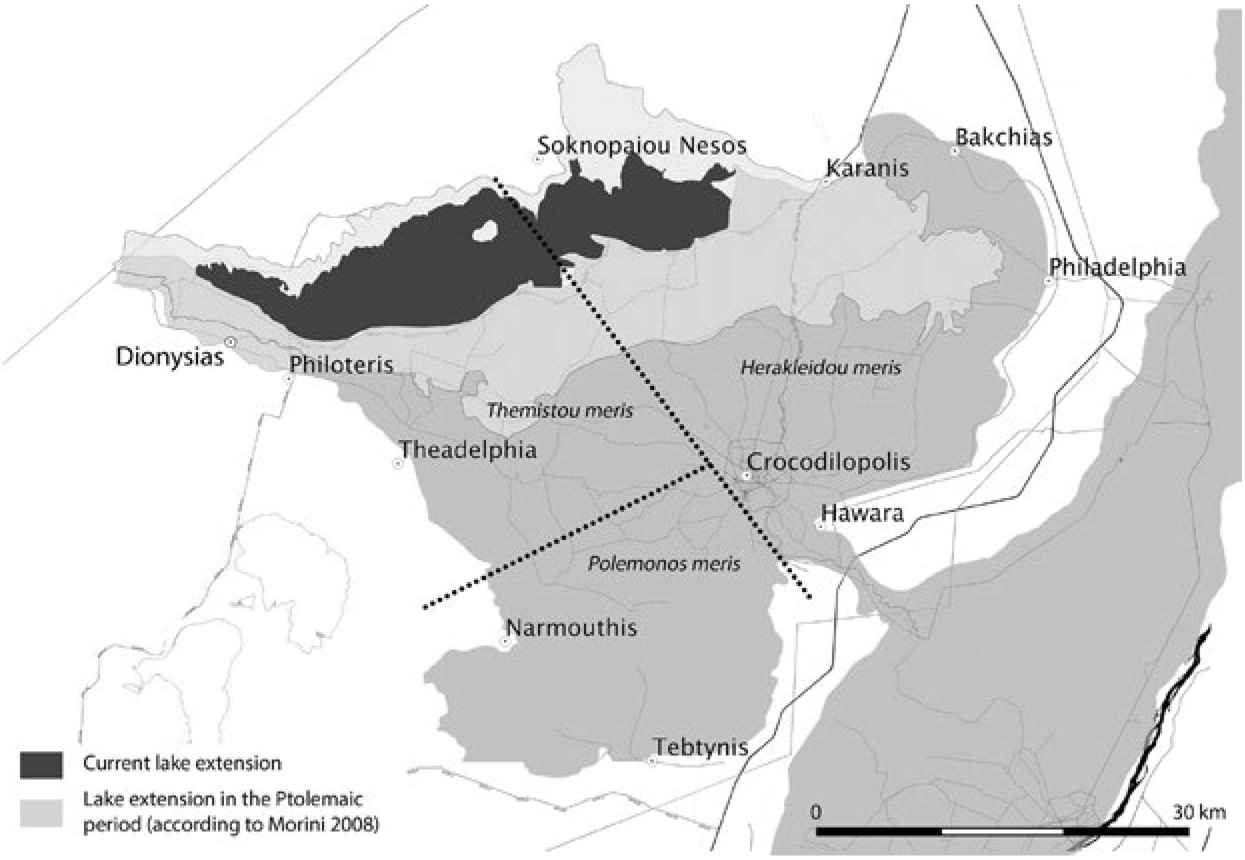

Fig. 2. The Fayum region during Graeco-Roman times.

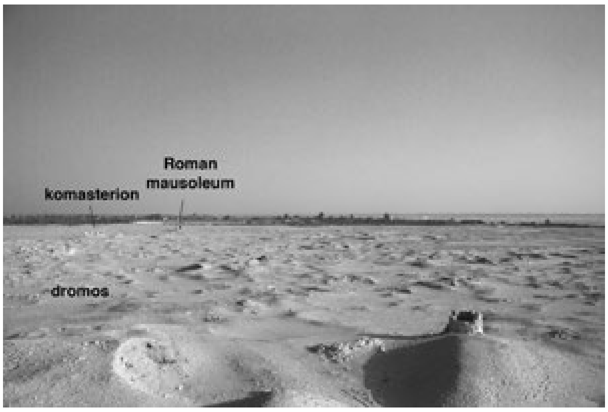

Fig. 3. The ground surface at *Dionysias* from the temple (looking east).

a good opportunity to apply and test different remote sensing methodology. *Dionysias* was investigated with a multi-scale approach at different levels of resolution, from macro-scale to close-range analysis. Before acquiring new data, the first step of the research was dedicated to the digitisation of pre-existing maps, aerial photographs and all other available forms of information.

The first campaign was dedicated mostly to the realisation of the Digital Elevation Model (DEM) with the use of a Differential GPS (DGPS Trimble 5700) of about 66 hectares.[4] This detailed DEM was overlapped to the ASTER GDEM-V2 of the entire region. The analysis of elevation data has already showed some remarkable feature, such as the extension of the settlement, the presence of two pathways running from the southern corner to the extra-urban district and some working ancient canals.

The analysis of a GeoEye-1 satellite image (MS and PAN) provided supplementary information. The image has been processed through the selection of peculiar spectral values identified by a spectral analysis of Maximum Likelihood. This kind of unsupervisioned reclassification was principally related to the differences between the near-infrared and the blue bands (Fig. 4A). They represent the spectral fan characterized by the lowest correlation value (R2= 0.461), and therefore by the chance of outlining most categories of anomalies. Three principal classes has been mapped (n. 8, 9, 10), chosen as the ones characterized on the ground by regular geometries and by peculiar distribution of artefacts, presence of walls and ground anomalies (Fig. 4C). Moreover these three classes have been chosen as they are strongly differentiated by the rest of the image by the reflectance values: usually less than 40% between the 500 and 750 nm wavelength, with a peak around the near-infrared gap, and a completely different tendency respect to the rest of this portion of the satellite image (Fig. 4B). Finally classes 8, 9 and 10 have been selected and cut off (Fig. 4D), hence giving a clear general description of the city plan. On

[4] The DEM was realised by Emanuele Mariotti: see Papi *et al*. 2010: 239-41, Fig. C.

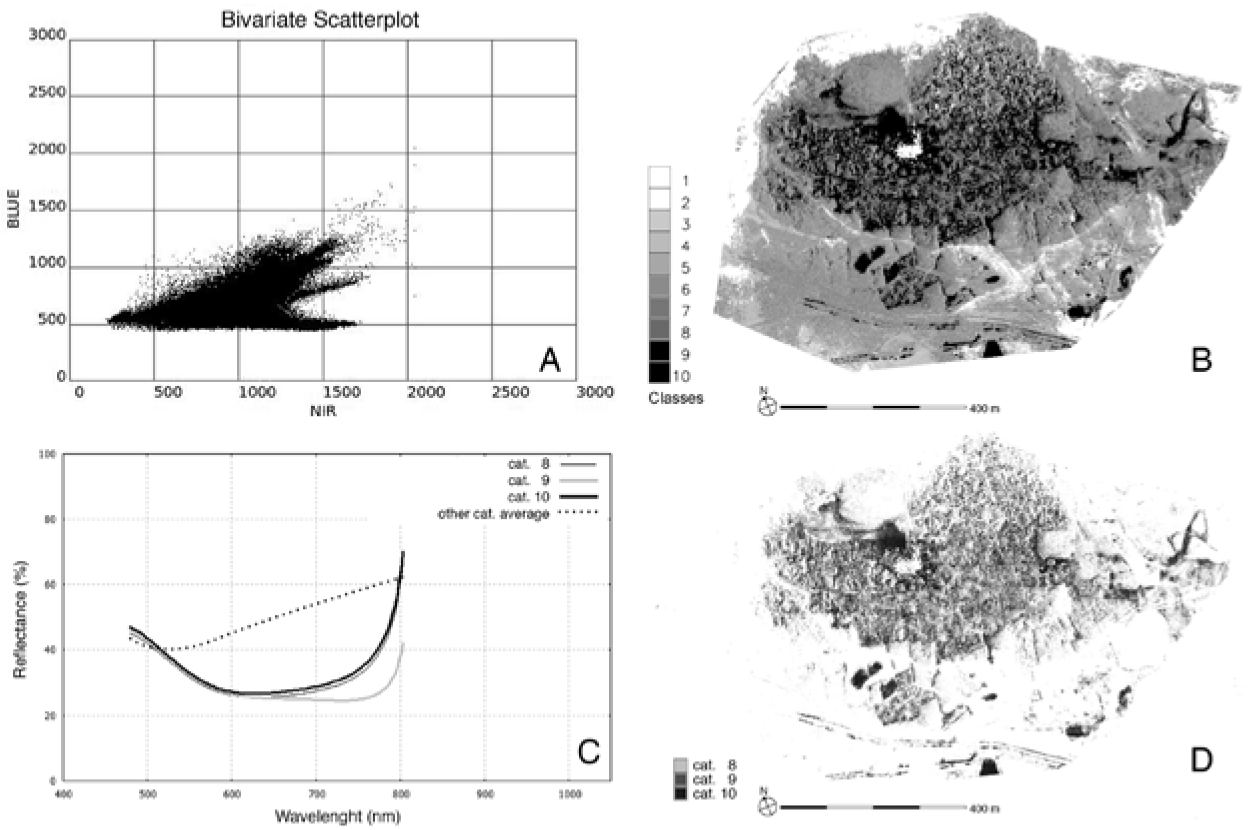

Fig. 4. Reclassification of spectral values (Maximum Likelihood): scatterplot of the NI and blue bands (A), Maximum Likelihood at *Dionysias* (B), chart of the reflectance of classes 8, 9 and 10 (C), maps obtained by the selection of spectral values for classes 8, 9 and 10 (D).

the basis of this enhanced data and by the classification of the archaeological areas and their extension, we selected the area where to perform the magnetic survey.

During the years 2009, 2010 and 2012 the total coverage of the so-called urban area was performed through magnetometry (Carpentiero 2016). The instruments employed for this analysis were a Fluxgate Gradiometer FM36 (in 2009 and 2010) and a FM256 (in 2012) (Geoscan Research ltd.). During eight weeks of fieldwork, 16 hectares were prospected, divided into a grid of 20 x 20 m squares, and georeferenced with a Total Station. The vectorisation of all the magnetic anomalies in GIS environment has shown an image of the entire urban layout with a high level of accuracy. Results of all the remote sensing together (satellite image analysis, magnetic prospections and total station survey of all features visible on the surface) yielded a more complete understanding of the settlement as a whole, including its city walls, the street network, the disposition of blocks and, in some cases, also the internal organisation of each district (Fig. 5). The lack of excavation data made these results particularly significant as they allow a detailed reconstruction of the settlement. This is even more important if we consider that no city of Graeco-Roman Egypt has been excavated for more than a small fraction of its total area.

The combination of different surveying approaches (remote sensing, DEM, geophysical prospection, mapping, surface collections etc.) is the base of our urban-spatial analysis.

2 Application of Urban Network Analysis and Space Syntax (G.C.)

2.1 Preliminary remarks: Application of Space Syntax to remotely sensed data

An accurate study and analysis of the urban layout requires an extensive and detailed knowledge of the urban plan, which is not common without excavation and only with the use of remote sensing techniques or geophysical prospections. Nevertheless the detail of the *Dionysias* magnetic map has given the opportunity to realise a theoretical urban layout and to attempt the study of urban interactions, access and visibility. The combination between satellite image interpretation and magnetic prospection at *Dionysias* shows such a detailed and complete image of the entire layout, which is not visible on the ground, that it allowed the opportunity to study the urban plan as a whole. In our analysis we have also considered that the interpretation of remote sensing data (satellite imagery and geophysical maps) gives only an overview on the last state of occupation of the site and does not give the possibility to argue anything about the evolution nor the development of the city and its urban plan. Therefore in our analysis the street network outlined belongs to the last phase of occupation, but it gives the possibility to make hypothesis about the original plan and urban layout.

The application of Space Syntax seemed to be the most logical step to gain further information on such detailed plans (Stöger

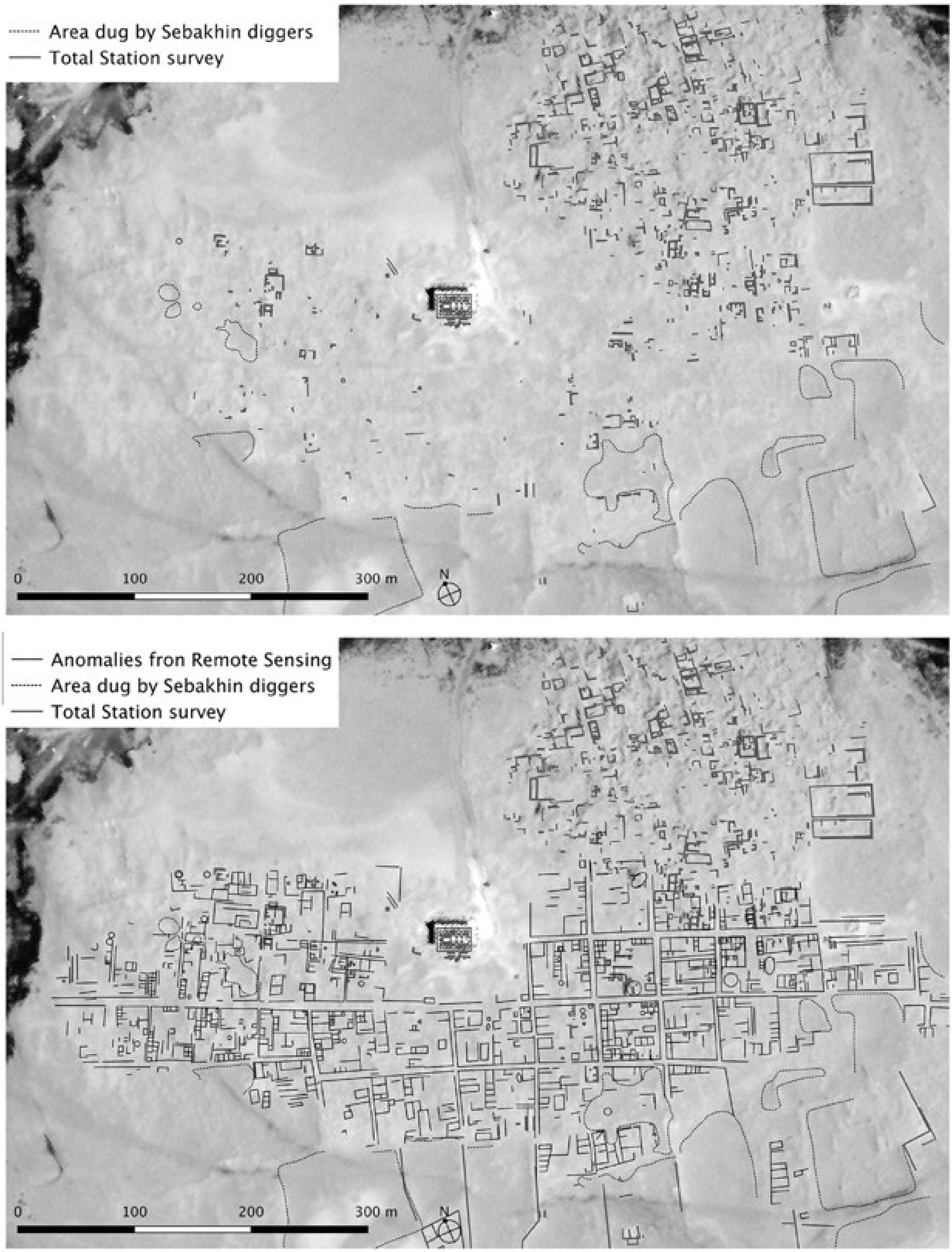

Fig. 5. The urban layout before (above) and after (below) Remote Sensing.

2011a: 49), even if these techniques are usually applied to urban archaeology or on excavation data and in contexts with high levels of detail, such as Pompeii and Ostia.[5] Space Syntax has gained a growing popularity among archaeologists for the last 30 years[6] as it offers a range of tools which are relatively user-friendly. It has been applied in different researches, most of the time incorporating only selected aspects of the more general technique. This so-called 'toolbox' approach has the benefit for archaeological application to encourage the integration of network analysis within a wider and complementary perspective (Thaler 2005: 324). The use of Space Syntax at *Dionysias* is only part of the research, which takes into consideration different aspects of remote sensing and spatial techniques.

The description and visual investigation of urban space often seem enough to understand spatial characteristics, which often give the impression of being evident and obvious (Stöger 2008: 324). However a merely visual analysis does not allow us to perceive some of the spatial relations which need to be discovered and/or demonstrated with the use of quantitative methods. All the concerns about the application of Space Syntax to archaeology are understandable given the often poor quality of the data, and opinions range from disapproval (Bernbeck 1997: 201; Cutting 2003: 15-6) to enthusiastic interpretation (Fairclough 1992: 353-60). A more moderate position could make the assumption that only some aspects of the spatial characteristics can be assessed with these techniques and they are limited to the data available and its level of detail.

The application of Space Syntax tools to remote sensing data is therefore even less common and hazardous, but in recent years it has given the possibility to fully exploit the data and to identify key elements of ancient street network and the use and perception of the space. The first case is probably the application of GIS transportation network analysis made by Branting at the iron age site of Kerkenes Dag, prospected for an extension of 300 ha with geophysical survey (namely magnetometry and resistivity: Branting 2004). Other examples are the application made by Benech in Syria at Doura Europos and Tell Sheirat (Benech 2007 and 2010; Benech and Gondet 2009) and by Morrow at Tiwanaku, Bolivia (Morrow 2009). More recently we can find the attempts made on Roman street network at Ampurias (Kaiser 2011), Ostia (Stöger 2011b) and Ammaia (Paliou and Corsi 2013).

At *Dionysias* the further application of agent based modelling could give the added benefit to study the movements in past built environments and to encourage contemplation about human practices and social use of the space, not seen only as an unpopulated environment (Paliou 2008: 334). Moreover the computational approach to the study of movement in archaeology can reveal the social context that lies beneath landscape and/or townscape: cultural markers assume extra significance as they influence movement and the perception of space, as it has been underlined by Lock *et al*. (2014: 24).

2.2 Axial analysis at *Dionysias* (C.T.)

The possibility of data visualisation, interrelation and management within a GIS platform significantly increased the spatial information at our disposal and consequently the possibility to cross-check the data. The result is a clear general image of the urban plan, with a good level of detail of the street network and the inner organisation of blocks and buildings gained thanks only to the application of remote sensing techniques (Fig. 5).

A first attempt of GIS based spatial analysis within the urban layout has shown the presence of a precise hierarchy of the streets. In particular in the eastern part of the settlement, which was probably the first nucleus of the site itself, the longitudinal streets (running from northwest to southeast) are clearly wider (between 5 and 6.50 m for the processional road and the parallel street to the south) than the perpendicular ones (between 2 and 5 m). The alleys inside the blocks are even smaller (between 0.50 and 2 m) (Fig. 6).

Further interpretation of urban network organisation is based on the analytic proposal of *Space Syntax* (Hillier and Hanson 1984), using *DepthmapX*[7] The Space Syntax theory provides a useful set of techniques related to the study of urban morphology, with the aim to investigate the hypothetical human movement and its integration inside a street network. The analysis is connected to both urban shape (conceived as empty space) and to the social organisation of the space with the idea that human societies design spaces in the same way they manage their social relations (Ankerl 1981, *passim*). The principal assumption is that the global urban arrangement can show the social structure through the investigation of ideological, social and economic patterns. In summary, *space syntax* recognises the space as a connected set of spatial units (lines and nodes[8]) and it presumes a constant mutual modification between space and society. The analytic theoretical bases are anchored in the graph theory and offer some main analytic values. It is therefore based on centrality measures (choice, connectivity, integration, depth, etc.) (Hillier and Hanson 1984; De Adurra Campos and Fong 2003), their spatial location and finally their relation between with the spatial configuration of human activities, taking into account the archaeological survey and peculiar kinds of buildings, characterised by functional, economic and cultural activities, like temple areas, granaries, public baths, etc. The centrality measures can be explained as follows:

- *choice*: number of shortest segment or line comprises in a node.
- *connectivity*: the degree of interconnection among their nodes.
- *integration* (Hillier and Hanson 1984, *passim*): the relationship of every nodes to all others inside a network and the measure of the distance from any space of origin to any other in the system This value calculates also

[5] Pompeii has been examined with the use of Space Syntax in many works (see Stöger 2011a: 46); about Ostia see Delaine (1999; 2004) and Stöger (2008; 2011a; 2011b).

[6] For a summary of the application of Space Syntax to archaeology see: Thaler 2005: 324-6; Stöger 2011a: 46-49.

[7] DepthMapX (www.spacesyntax.net/software/ucl-depthmap) is an open-source software developed by the UCL London, the Bartlett Centre for Advanced Spatial Analysis (see Turner 2004).

[8] Nodes are points where two segments of roads encounter; in particular the nodes counts are the measures of the number of lines (or segments) encountered on the route from the selected line (or segment) to all others (Turner 2004: 29).

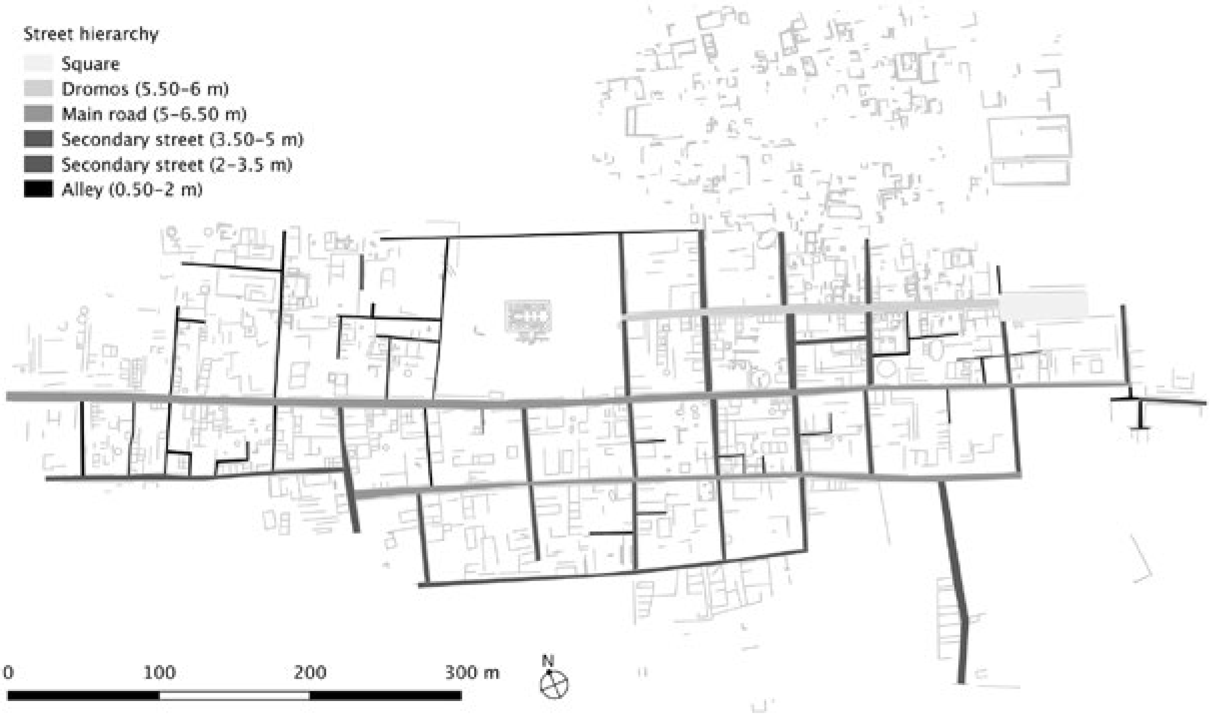

Fig. 6. Analysis of street hierarchy.

the relative asymmetry (RA) or relative depth and is the opposite of segregation (Hillier and Hanson 1984: 108-9).

- *depth*: the measure of the topological steps (the turnings) from an axial line of origin to other line or lines of destination (Hillier and Hanson 1984: 104).

In regards to the study of the street network, our approach consisted in the analysis of axial maps,[9] with the aim of exploring how spatial configuration of the streets can favour or discourage human movement and interactions. Within the Space Syntax analysis, streets are not considered as independent features, but as a whole open space (Benech 2010: 405). The axial map can be considered as the basic analysis of the urban network in terms of axiality and connection and represents the longest lines that can be drawn from an arbitrary point inside the spatial configuration.

2.3 Data integration: Space Syntax and surface survey

In the case of *Dionysias* the application of Space Syntax tools has led to infer a clearer image of the ancient city that show an urban space far from being homogeneous and equally organised, despite the orthogonal and Hellenistic arrangement of the street network. Segments analysed in the map are 102, and provide a good approximation of the city movement in his entire extension. The four space syntax diagrams taken into consideration (choice, connectivity, integration and step depth) produce quite similar results and show similar distribution of the values within the space (Fig. 7). The lines represent the most intensive frequency of shortest routes between origin and destination of each path and all the values are intended as representation of human decision process before moving anywhere in the space.

Graphs (Fig. 8) and statistics (tab.1) outline a unimodal distribution of values, with a high standard deviation typical of a hierarchical use of space. The choice diagram is characterised by the domination of one class of values (0-500) that represents 80% of the total set of segments. The other classes are distributed in a few number of axial lines located between the central node and the eastern part of the city. This result is strongly biased on the length of street-segments, which show a correlation between the data (Fig. 9), and has the tendency of high values of choice generally relied on the increase in the length.

It is possible to identify as most integrated area (the central node area) a patch located in the south-eastern part of the city, to the east of the temple, between the longest central street and three longitudinal street to the north (Fig. 7D). This area with an extension of 35 hectares represents 10% of the investigated surface, and was probably the central core of the village from an economic and social point of view. Usually high integrated areas are related to this kind of spatial patterns.

These outputs again determine a clear hierarchy of streets. Despite the fact that the main street, which corresponds to the processional road (the *dromos*) leading from the kiosk to the temple, plays a major role on a symbolic level, in terms of connectivity it does not register as the highest value. The most connected street instead is the longitudinal road (oriented east-west), which is immediately to the south of the *dromos* (Fig. 7D).

9 Axial maps are representations of the continuous structure of open space, and can be considered like a method for simplifying continuous spatial network of urban space in a set of component parts made of lines and nodes (Desyllas and Duxbury 2001).

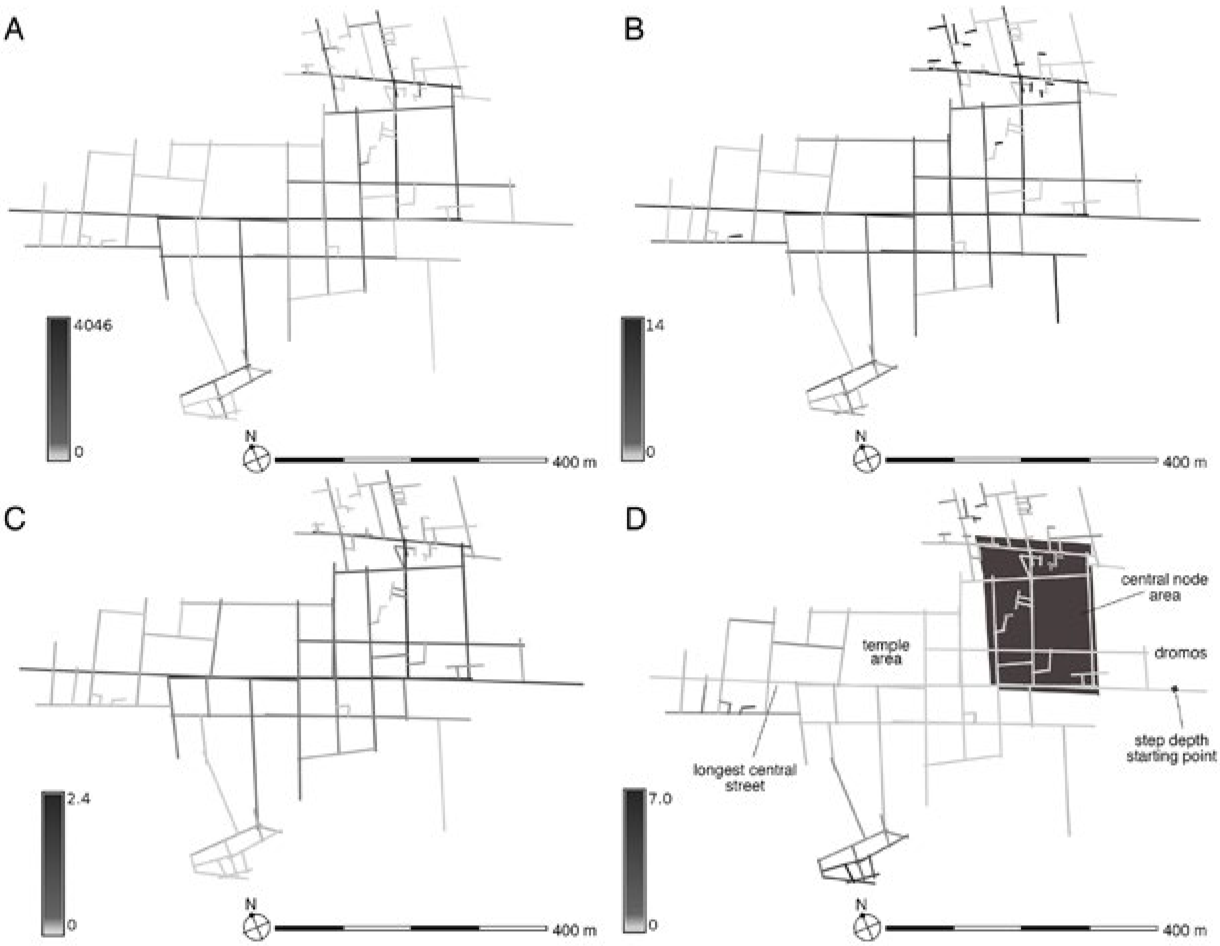

Fig. 7. Axial maps of *Dionysias*: choice (A), connectivity (B), integration (C) and step depth (D). Highest value (dark) corresponds to the most 'integrated' segments.

In order to cross-check these results we compared space syntax analysis outputs to the spatial distribution of archaeological finds and artefacts inside the survey area.[10] In total there are 117 records here divided into three main classes (manger, grindstones and millstones), related to particular activities like oil and grain production (Fig. 10). The processing of density maps is based on a quartic kernel algorithm, with a proper kernel radius for each distribution, as regards to cluster and number of artefacts.

In particular on the vector maps we have 12 records for mangers, 52 for grindstones, 82 for oil millstones, 117 in total with the following radius values 65, 42, 82 and 43 metres, respectively (Fig. 10). If we considerer the space distribution of one category at a time, or all of them together, we obtain similar results. Even if there is a different quantity of records per each category, raster density maps give similar results and show how the mean centre is located inside the limits of what we have previously identified as the central node of the city. This last aspect is confirmed also by the calculation of the *step depth* (Fig. 7D), which clearly describes a very depth network starting from that node.

[10] This application is part of a wider study about oil and grain production made by Leonardo Bigi; see also Papi *et al.* 2010, 248-249.

3 Summary and Conclusions (G.C., C.T.)

This first attempt of the application of network analysis to study the urban complex of *Dionysias* has given new insights on the interpretation of some functional, as well as cultural, elements.

In the first part of the research the combination of results of satellite image analysis and magnetic survey has demonstrated that the urban layout of *Dionysias* was organised according to a regular orthogonal grid, and that the temple, the processional road (*dromos*) and the procession station (*komasterion*) were located at the very centre of the city. In ancient Egypt during Pharaonic period, and later during Graeco-Roman time, this was a characteristic typical of new foundations and worship places representing the fulcrum of urban planning and design.

Considering the orthogonal layout it is not possible to argue with certainty if this is an external cultural features, coming from the Greek culture – as in other Hellenistic villages and cities in Egypt, such as Philadelphia in Fayum and probably Antinopolis and Hermopolis – or part of a local tradition of orthogonal planning – such as Kahun, Qasr el-Sagha and Deir el-Medina.

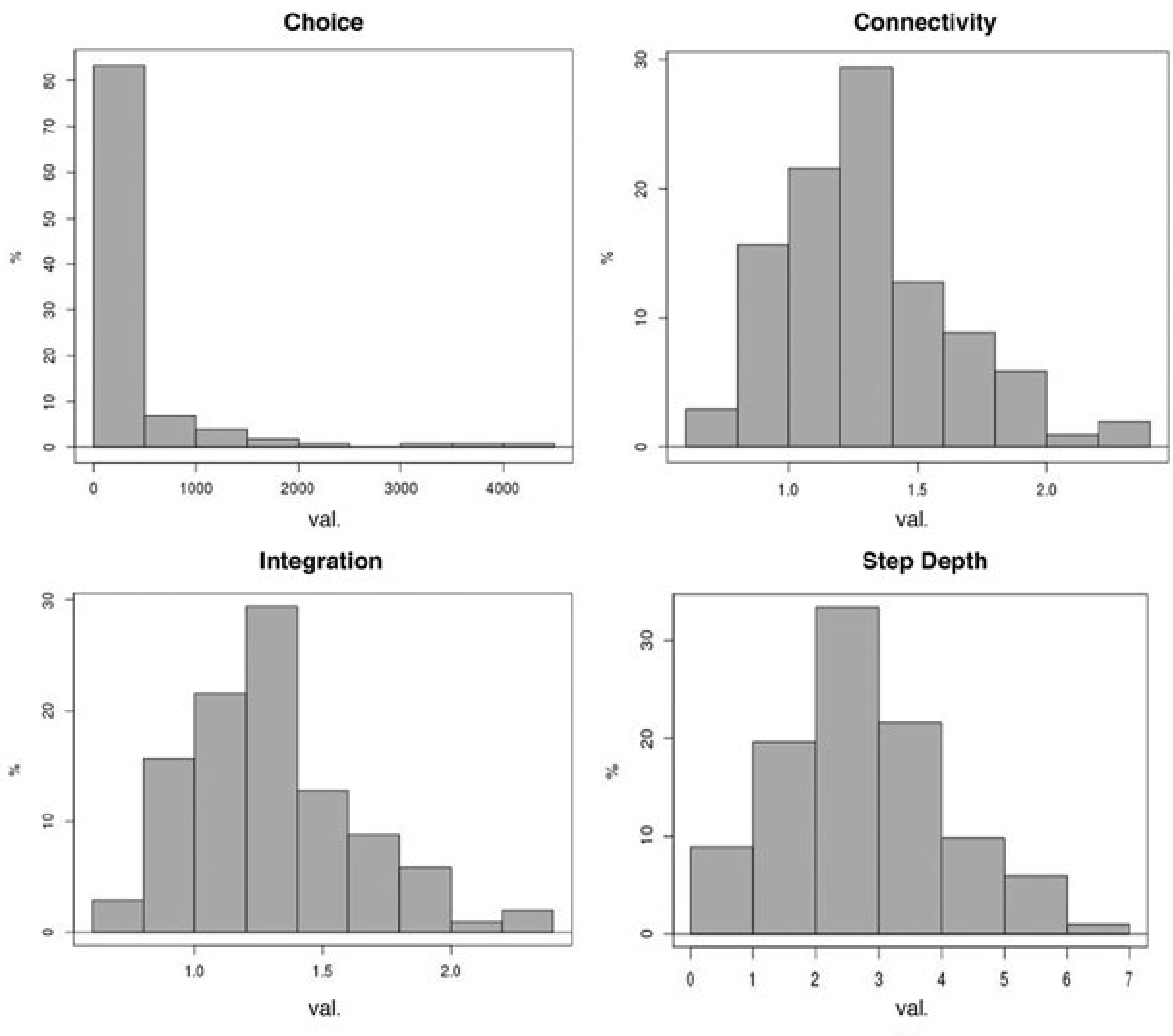

Fig. 8. Chart of frequency of the axial maps of space syntax measure.

The application of spatial analysis, and in particular of Space Syntax tools, gives some insights on the discussions about cultural elements involved in the planning and construction of the village. In effect despite the orthogonal layout of the settlement, the urban space is not homogeneous and regularly organised. According to axial maps the temple is not the most integrated spot as well the *dromos*, which is not the most connected street of the settlement (Fig. 7). The central node area of the entire settlement is slightly more eastern than the topographic centre, in a position that could probably be identified as the most important area from an economic and/or social point of view. This data can be probably related to some peculiar structures within the urban layout with the decentralisation of economic and social activity.

Moreover Space Syntax results have shown a preferential movement from east to west, along the longest street (Fig. 7D), with a probable main access at the eastern end of the same street. The most likely main entrance to the village could have been located in this area, probably connected to a side-canal running north-south to the east of *Dionysias* and connected to the canal oriented east-west, which is visible from satellite images to the south of the settlement.

Despite temple, *dromos* and *komasterion* were the most distinctive and important symbolic features at *Dionysias*, as attested elsewhere in Graeco-Roman Egypt, particularly in Fayum (e.g. at *Tebtynis*, *Soknopaiou Nesos*, and in part also at *Narmouthis*), they were not the centre of the life in the village as they were not accessible from all the population. Even if the temple represented the main architectural complex of the settlement and was located at the very centre, Space Syntax axial maps have shown that worship places were not the most integrated spots of the urban network. In the Pharaonic period, and later in the Hellenistic foundations in Egypt, places of worship represented the fulcrum of the urban design and the relationship between temple and city played a fundamental role within the local society, but merely from a symbolic and religious point of view.

The importance of the eastern part of the village, with the temple and what we have defined as the central node, could also suggest that this was also the first nucleus of the village and the zone where the settlement originated. The hierarchy of the street-network can confirm this statement: streets and alleys are regularly arranged in the eastern part of the settlement and lose their uniformity going to the west. Probably the first

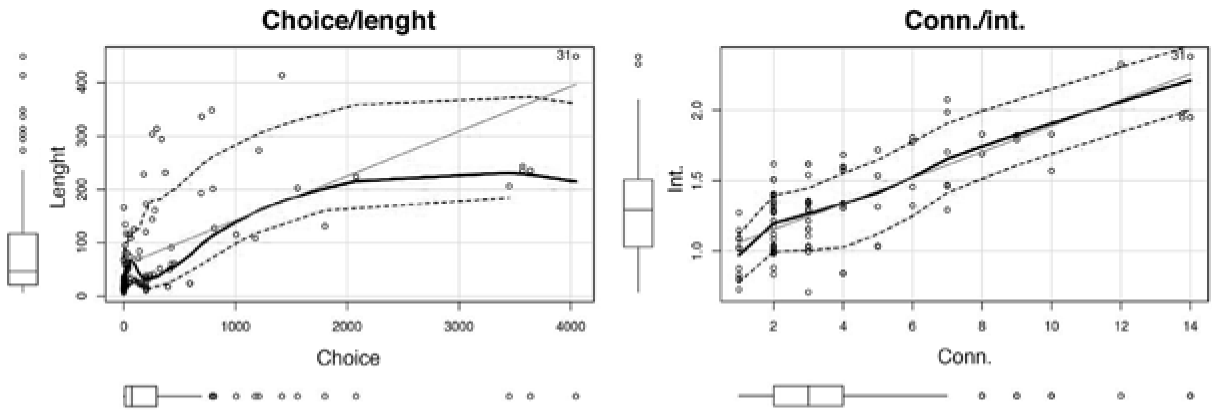

Fig. 9. Correlation graph of choice/length (left) and connectivity/integration (right).

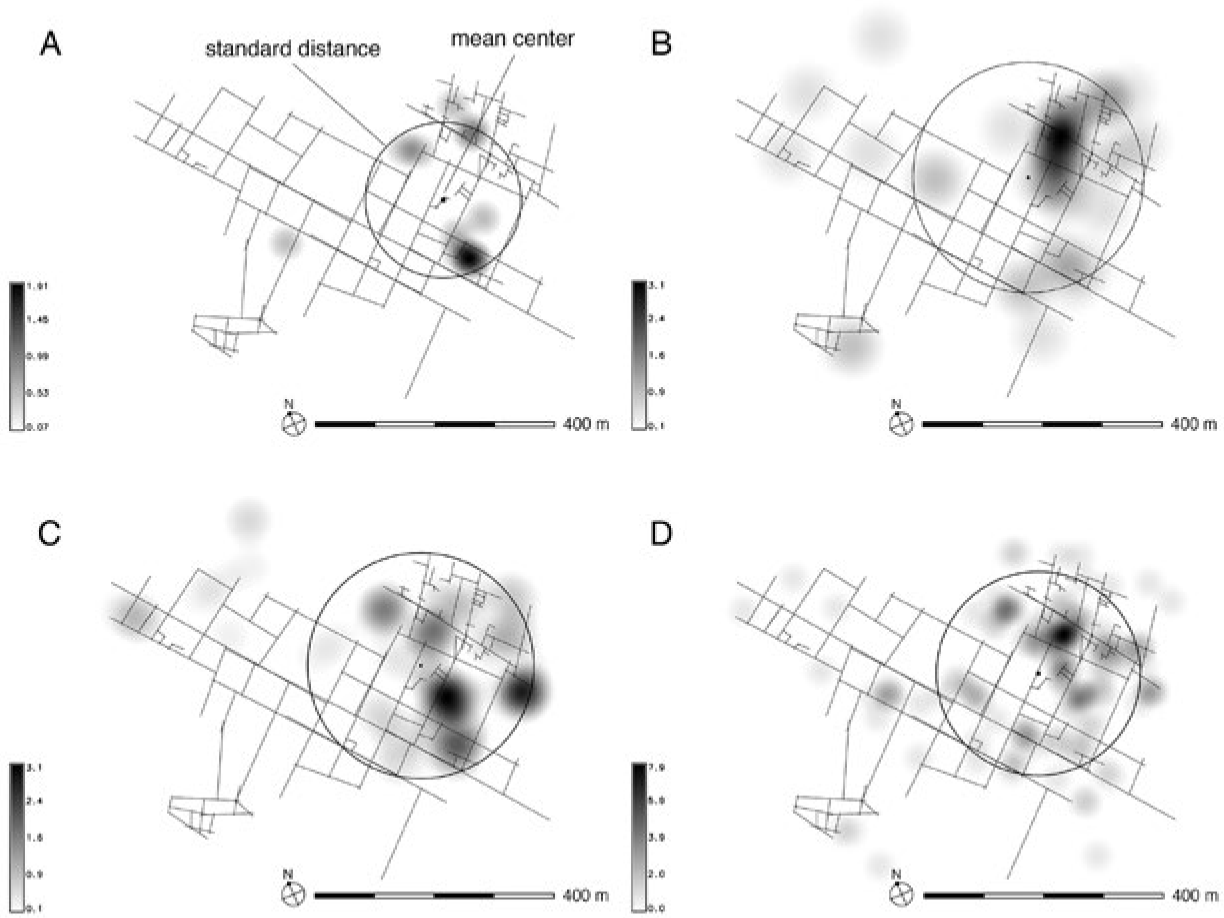

Fig. 10. Kernel density of the space distribution of archaeological records for: manger (A), grindstones (B), millstones (C) and total artefacts (D) and the relative mean centre and standard distance (points and circles).

settlement, or the Ptolemaic town plan, originated at the centre of the temple (exactly to the entrance of the *cella*) where the extension of the *dromos* and the central north-south road meet. This can be considered to be the symbolic centre of the settlement and the point from which the town plan originated.

The analysis undertaken so far has clearly shown that, even if the urban settlement was organised following a regular and orthogonal grid system (essentially, but not certainly, Hellenistic), and some important constructions were later built according to Roman architectural principles (such as the mausoleum), many other characteristics (know-how, probably manpower, as well as cultural values) could be associated with the local Egyptian influence and endogenous culture.

Cultural elements involved in the planning and then in the construction of the village of *Dionysias* are probably more closely connected to the local Egyptian tradition, than what has been the general belief in scholarly studies. Even if we accept that coordinated arrangements of the buildings and spaces comes from Alexandria and Greece, other categories of urban planning, however, were inspired by Egyptian tradition, as well as the organisation of the space. The presence of a low degree of coordination and standardisation of the space in comparison to other Hellenistic city examples is probable proof of the predominance and influence of the local Egyptian cultural components or of the fusion between local and external (Greek) cultural elements.

The case of *Dionysias*, has proven to be an interest sample for the use of the application of Space Syntax to remote sensing data and suggests that urban network analysis can be successfully applied to similar case studies in order to enrich our interpretation of ancient urban sites, even without data from excavations.

Although the analysis applied for the site of *Dionysias* has produced interesting results, more suggestions about the life and the organisation of the ancient settlement could be inferred with further network analysis and agent based modelling techniques. Moreover the application of the methods discussed above could be complemented with the analysis of other settlements with similar characteristics and/or involve the application of Space Syntax analysis in other Hellenistic settlements in Greece and in other middle-eastern contexts, which present a similar set of questions and problems.

Acknowledgments

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Bibliography

Ankerl, G. 1981. *Experimental sociology of architecture: a guide to theory, research and literature*. Berlin, Moutaon.

Benech, C. 2007. New approach to the study of city planning and domestic dwellings in the Ancient Near East. *Archaeological Prospection* 14: 87-103.

Benech, C. 2010. The use of space syntax for the study of city planning and household from geophysical maps: the case study of Dura-Europos (Syria). In S. Ladstätter (ed.), *Proceedings, Urban Living in the Eastern Mediterranean 4th BC - 1st century AD, Vienna, 24-27 October 2007*: 403-16.

Benech, C., Gondet, S. 2009. Application of the space syntax to the study of city planning from Syrian Late Bronze Age circular cities. *ArchéoSciences* 33: 217-9.

Bernbeck, R. 1997. *Theorien in der Archäologie*. Tübingen, Francke.

Bouché-Leclercq, A. 1908. L'ingénieur Cléon. *Revue des Études Grecques* 21: 121-52.

Branting, S. A. 2004. *Iron Age pedestrinas at Kerekens Dag: an archaeological GIST approach to movement and transportation*. Unpublished PhD thesis, The State University of New York at Buffalo.

Butzer, K. W. 1982. *Archaeology as human ecology: Method and theory for a contextual approach.* Cambridge, Cambridge University Press.

Carpentiero, G. (forthcoming 2016). Continuity and change in Hellenistic town planning in Fayum (Egypt): between tradition and innovation. In N. Mugnai, J. Nikolaus, N. Ray (eds.), *De Africa Romaque: Merging Cultures across North Africa*. London, Society for Libyan Studies.

Cestari, I. 2010. *Villaggi dell'antico Egitto 3. Dionysias*. Imola, La Mandragora.

Cutting, M. 2003. The use of spatial analysis to study prehistoric settlement architecture. *Oxford Journal of Archaeology* 22: 1-21.

Davoli, P. 2008. Nuovi risultati delle campagne di scavo 2004-2006 a Soknopaiou Nesos (Egitto). In S. Lippert, M. Schentuleit (eds.), *Graeco-Roman Fayum – Texts and Archaeology*: 75-92. Wiesbaden, Harrassowitz Verlag.

De Adurra Campos, M. B., Fong, P. S. P. 2003. Bending the axial line: Smoothly continuous road centre-line segments as a basis for road network analysis. In J. Hanson (ed.), *Proceedings of the 4th International Symposium on Space Syntax, UCL, London, UK*: 35.1-10.

De Cenival, F. 1980. Compte de céréales de plusieurs village du Fayoum: P. Dém. Lille 110 (Inv. Sorbonne 205 à 2013). In *Livre du Centenaire de l'IFAO (1880-1980)*, Le Caire: 193-203.

DeLaine, J. 1999. High Status Insula Apartments in Early Imperial Ostia - a reading. In S. Mols and C. van der Laan (eds.), *Mededelingen van het Nederlands Intituut te Rome: Antiquity*: 175-89. Nederlands Instituut te Rome.

DeLaine, J. 2004. Designing for a Market: Medianum Apartments at Ostia. *Journal of Roman Archaeology* 17: 146-76.

Desyllas, J., Duxbury, E. 2001. Axial Maps and Visibility Graph Analysis. A comparison of their methodology and use in models of urban pedestrian movement. In J. Peponis, J. Wineman, S. Bafna (eds.), *Proceedings, Space Syntax 3rd International Symposium, Georgia Institute of Technology, Atlanta, 7-11 may 2001*: 27.1-13.

Fairclough, G. 1992. Meaningful constructions - spatial and functional analysis of medieval buildings. *Antiquity* 66: 348-66.

Hillier, B., Hanson, J. 1984. *The Social Logic of Space*. Cambridge, Cambridge University Press.

Kaiser, A. 2011. *Roman urban street networks*. London, Routledge.

Lock, G., Kormann, M., Pouncett, J. 2014. Visibility and movement: towards a GIS-based integrated approach. In S. Polla, P. Verhagen (eds.), *Computational approaches to the* *study of movement in archaeology. Theory, practice and interpretation of factors and effects of long term landscape formation and transformation*: 23-42. Berlin, Boston, De Gruyter.

Morini, A. 2008. Templi e canali del Fayyum: alcune osservazioni In S. Pernigotti, M. Zecchi, (eds.), *Sacerdozio e società civile nell'Egitto antico. Atti del terzo colloquio, Bologna, 30-31 maggio 2007*: 115-21. Imola, La Mandragora.

Morrow, G. 2009. Analysing the invisible syntactic interpretation of archaeological remains through geophysical prospection. In D. Koch, L. Marcus, J. Steen (eds.), *Proceedings of the 7th International Space Syntax Symposium*: 106:1-10. Stockholm, KTH.

Paliou, E. 2008. An autonomous agent approach to the investigation of intra-site movement and visibility: The visual consumption of Theran Murals from the public spaces of LBA Akrotiri (Thera, Greece). In A. Posluschny, K. Lambers, I. Herzog, I. (eds.), *Layers of Perception, Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, 2-6 april 2007*: 328-35. Berlin, Dr. Rudolf Habelt Verlag.

Paliou, E., Corsi, C. 2013. 'The Whole is More than the Sum of its Parts'- Geospatial Data Integration, Visualisation and Analysis at the Roman Site of Ammaia (Marvão, Portugal). In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 march 2012*: 592-607. Amsterdam, Amsterdam University Press.

Papi, E., Bigi, L., Camporeale, S., Carpentiero, G., D'Aco, D., Kenawi, M., Mariotti, E., Passalacqua, L. 2010. La missione dell'Università di Siena a Qasr Qaroun – *Dionysias* (2009-10). *Ricerche italiane e scavi in Egitto, Il Cairo: Centro Archeologico Italiano* 4: 239-55.

Rathbone, D. 1990. Villages, land and population in Graeco-Roman Egypt. *Proceedings of the Cambridge Philological Society* 36: 103-42.

Schwartz, J., Wild, H. 1950. *Qasr-Qarun/Dionysias 1948, Fouilles franco-suisses, Rapports I*. Le Caire.

Shapiro, J. S. 2005. *A Space Syntax Analysis of Arroyo Hondo Pueblo, New Mexico. Community Formation in the Northern Rio Grande*. Santa Fe (New Mexico), School of American Research Press.

Stöger, H. 2008. Roman Ostia: Space Syntax and the Domestication of Space. In A. Posluschny, K. Lambers, I. Herzog, I. (eds.), *Layers of Perception, Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, 2-6 april 2007*: 322-7. Berlin, Dr. Rudolf Habelt Verlag.

Stöger, H. 2011a. *Rethinking Ostia: a spatial enquiry into the Urban Society of Rome's Imperial Port-Town*. Archaeological Studies Leiden University 24. Leiden, Leiden University Press.

Stöger, H. 2011b. The Spatial Organisation of the Movement Economy: The Analysis of Ostia's Scholae. In R. Laurence, D. J. Newsome (eds.), *Rome, Ostia, Pompeii: Movement and Space*: 215-42. Oxford, Oxford University Press.

Thaler, U. 2005. Narrative and Syntax: new perspectives on the Late Bronze Age palace of Pylos, Greece. In A. Van Nes (ed.), *Space Syntax: 5th International Symposium*: 323-39. Amsterdam, Techne Press

Thaler, U. 2005. Narrative and Syntax: new perspectives on the Late Bronze Age palace of Pylos, Greece. In A. Van Nes (ed.), *Space Syntax: 5th International Symposium*: 323-39. Amsterdam, Techne Press.

Turner, A. 2004. *Depthmap 4. A Researcher's Handbook*, London, Bartlett School of Graduate Studies, University College London.

Enhancing GIS Urban Data with the 3rd Dimension: A Procedural Modelling Approach

Chiara Piccoli
c.b.m.piccoli@arch.leidenuniv.nl
Leiden University, Netherlands

Abstract: Urban surveys investigate past cityscapes by integrating heterogeneous data sources such as architectural documentation, pottery collection and geophysical prospections. Handling such complex data sets and combining them in order to obtain a coherent picture of the ancient spatial structure is challenging. This paper presents the preliminary results of the creation of a 3D GIS of the ancient town of Koroneia (Boeotia, Greece), which is currently being investigated using non-destructive methods within the Ancient Cities of Boeotia project. The workflow consists of two phases: 1) mapping of the finds onto the DEM of the hill to visualize their distribution and characteristics as recorded during fieldwork; 2) reconstructing the ancient terrain and the possible layout of the town in the 4th century BC. To tackle this task, we have adopted a novel methodology, which is based on the combination of GIS and procedural modelling. Specifically, a set of procedural rules was written, which represent a formal and parametric description of Classical Greek architecture. An additional rule was created to automatically visualize the properties of the architectural finds in ArcGIS. This approach allows us to quickly update the 3D visualization when new data become available and to test alternative reconstruction hypotheses. Moreover, this implementation enables the creation of an intellectually transparent 3D reconstruction and forms the basis for a quantitative analysis of the built environment.

Keywords: Procedural modelling, 3D GIS, Data visualization, Urban survey, Classical Greek architecture.

Introduction

Of the great majority of the about 800 *poleis* that populated Greece in Archaic and Classical times, only a few standing ruins are visible to the present day traveller. Athens was an exceptional city in antiquity and is exceptional nowadays for its imposing archaeological remains. Only faint traces are, however, left even of important *poleis* such as Sparta and Thebes, once competing with Athens for the supremacy in Hellas. The total excavation of these ancient cities would be infeasible due to time and cost constraints. The excavations at Corinth, which began at the end of the 19th century, have in fact uncovered only a small part of the estimated extent of the Greco-Roman town.

The application of non-destructive methods, such as surface surveys and geophysical prospections, on the other hand, allows the study of large areas and the collection of a vast quantity of data in a reasonable amount of time. Such investigations add key elements to the comprehension of the regional historical development, creating also new narratives for local communities as testimony of their own neighbouring heritage (Bintliff 2013). The sites that are investigated with such methods continue however to be invisible for the untrained eye, which poses challenges for their protection, preservation and valorisation.

Digital reconstructions have proved to be useful tools for presenting archaeological sites, making the results of the archaeological investigations more comprehensible for the public. However, the 3D model is often created when the interpretation is completed, purely as a presentation aid, thus excluding it from the process of data interpretation and hypothesis generation. In this paper we present the approach that we adopted for the ancient town of Koroneia in Boeotia (Greece), which is currently under investigation with non-destructive methods within the broader Boeotia survey project. We wanted to create a 3D GIS of the site that allows us to better display and investigate our survey data, and that helps us to visualize and test our hypotheses while the survey is still in progress. We adopted a novel methodology based on procedural modelling, which allows us to quickly update the 3D visualization when new data become available, while testing alternative reconstruction hypotheses. When the iterative process of hypothesis visualization will be completed, we aim to use this platform for communicating the survey results.

1 Koroneia: geographical context and historical background

Koroneia (Fig. 1) lies on a hill on the spurs of Mount Helicon and overlooked a marshy plain which was occupied by Lake Kopaïs until its drainage took place in the 19th century AD to make space for agricultural land. The hill shows traces of occupation from Prehistory up to the 14th century AD when the site was abandoned and the nearby town of Agios Georgios was founded. The town, which is mentioned in Homer's Catalogue of Ships (*Il*. 2.503), was situated at a strategical location on the communication axis between northern and southern Greece, and controlled the road between eastern and western Boeotia. It is not a coincidence, in fact, that the most important Pan-Boeotian festival was celebrated at Koroneia in honour of Athena Itonia, whose sanctuary had been built in the plain to the north of the city in Archaic times according to ancient sources.

A further proof of the strategic importance of the town is the fact that two important battles of the Greek city-state wars (in 447 and in 394 BC) were fought in the plain to the north of the *polis*, and additionally the Phokian general Onomarchos succeeded in taking control of Koroneia during the Third Sacred War against Thebes. The Phokian stronghold that was established on Koroneia's acropolis did not last long as Philip of Macedonia reconquered the city and handed it over to Thebes in 346 BC. It is in relation to this episode that a destruction and subsequent rebuilding of the *polis* might have occurred. The Thebans in fact punished the town with an *andrapodismos*

Fig. 1. Koroneia hill from the south.

(Dem. 5.22; 6.13; 19.112, 325), a form of heavy punishment that entails the enslavement of the inhabitants and often the partial destruction of the urban centre (Hansen 2000, 150). The town, however, must have been resettled quite quickly since a Koroneian citizen is indicated as state treasurer in an inscription from Delphi in 337/6 (*CID* II 74.50; Hansen 2004: 445).

After this episode, we find Koroneia mentioned again in Roman sources as one of the Boeotian cities that strongly opposed the Romans. Livy in fact refers to Roman soldiers brutally murdered in the Kopaic swamps at the beginning of the second century BC (Livy 33.29). Some twenty years later, in 172/171 BC, Koroneia supported Perseus of Macedonia against the Romans, who subsequently punished the inhabitants by sacking the town and selling them into slavery. The relationship between Koroneia and the Romans seems to improve during the Imperial period, when a number of inscribed letters from the emperors to the city testifies to their euergetism in financing the construction of an aqueduct and works to channel the rivers flowing into Lake Kopaïs that were flooding agricultural land, as well as intervening in a boundary dispute with neighbouring Thisbe (Fossey 1981; Fossey 1979). The 2nd century AD traveller Pausanias visiting Koroneia recorded the presence of an altar dedicated to Hermes Epimelius (the keeper of flocks) and an altar of the winds on the market place, and 'a little lower down' a sanctuary dedicated to Hera (Paus. 9.34.3). Other cults are attested from inscriptions, such as Arthemis Orthosia and Demeter Thesmophoros (Schachter 1981).

An Imperial period inscription that has been recently re-discovered in Thebes' museum contains important information about the topography and life of the town in Roman times, attesting the existence of houses on the acropolis, and recording the names of 10 male slaves and 12 female slaves (Kalliontzis and Papazarkadas 2014: 551). Historical sources do not give us much information about the city in Late Antiquity, but we know from Procopius that the city was destroyed by an earthquake in 551 AD (*Bel. Goth*. VIII, 25.17). The written accounts of travellers who passed by Koroneia in the 18th and 19th century are also an important source of information for ruins that have now disappeared. The English antiquarian William Martin Leake, for example, describes the presence of three ruined churches – that are now lost – where ancient blocks were re-used: two on the south-east part of the hill and a third one just below the Frankish tower that is situated on a small eminence below and to the north-east of the acropolis (Leake 1835: 134).

2 Archaeological data

Excavations were carried out in the 1920's by Nikolaos Pappadakis and in the 1970's by Theodoros Spyropoulos, leading to the uncovering of some (late) Roman buildings on the acropolis and of the remains of a temple to the north of the hill that was tentatively identified as the sanctuary of Athena Itonia. The archaeological investigation by the Boeotia survey project commenced in 2006. A DEM was created by manually recording points with a DGPS across the site over several survey seasons in order to obtain an accurate representation of the shape of the hill (Van Zwienen and Noordervliet 2007). The hill has been heavily modified by ancient and more recent terraces, some of which have in the last few years been bulldozed to make space for olive trees. Through past and current maintenance and improvement of these terraces, the architectural elements that were still visible on the surface have been pushed towards the terraces' edges. The terraces have been subsequently investigated to establish whether they were part of the original morphology of the hill or the result of modern bulldozing and documented with a DGPS (Wilkinson 2008).

The hill was divided into grids of approximately 20x20 m (adapting them to the terrain) that were recorded by a DGPS and mapped onto a GIS in order to be able to relate the surface finds to their location (Bintliff, 2009, 19). An architectural survey was undertaken that resulted in the recording of about 2700 pieces, using a GPS for the loose blocks and a DGPS for the *in situ* walls (Uytterhoeven 2012; 2014a; 2014b).[1] The 145

[1] The architecture survey team was composed of Bart Noordervliet, Janneke van Zwienen, Yannick Boswinkel, Ipek Dagli and the author

```
1.  attr buildingHeight = rand (6, 8)
2.  attr storeyHeight = 3
3.  attr windowWidth = 2
4.  Lot --> extrude (buildingHeight) building
5.  building --> comp(f) {top : roof | front : facade | side: sideWalls}
6.  facade --> split(y) {storeyHeight : groundFloor | ~1 : upperFloor}
7.  upperFloor --> split(x) {~1 : wall | windowWidth : window}*
8.  window --> i ("window_frame.obj")
9.  groundFloor --> …
```

Fig 2. Example of the starting lines of a CGA rule for the creation of a building. Numerical values are stored as attributes at the beginning of the rule to control them more easily. In this case, buildings are assigned a random height between 6 and 8 meters (line 1); the height of each storey is set to 3 meters (line 2), and the windows' width to 2 meters (line 3). The 2D initial shape 'Lot' is turned into a 3D building shell by extrusion (line 4). Next, a component split is used to separate the obtained 3D geometry in individual faces (line 5). A split rule along the y axis is used to divide horizontally the selected face corresponding to the building façade to create two floors (line 6). The upper floor is then recursively split along the x axis to create a series of windows (line 7), which are substituted by an OBJ file containing a more detailed window frame (line 8).

recorded *in situ* walls show a roughly north-south and east-west orientation in the northern part of the town with a shift of about N25°E in the southern part. This arrangement seems to be confirmed by the ongoing geophysical survey, which has investigated so far the northern and south-eastern section of the town, as well as disclosing traces of the lower wall circuit (Verdonck 2013; Meyer and Pilz 2015). The pottery sherds that were collected in the field are currently being studied by a team of pottery specialists, yielding a database with an elaborate description of each entry.

The results of these combined efforts have allowed us so far to: 1) establish the path of the lower city wall circuit with certainty along the west and north of the hill, and tentatively towards the east and south; 2) position the ancient market place on a plateau below and east of the acropolis; 3) locate several *necropoleis* that marked the boundary between the town and the extra mural areas; and 4) map provisional functional zones such as housing and public areas. The completion of the study of the architectural and pottery finds and the continuation of the geophysical investigations will further refine this provisional information. There will however remain areas that are not accessible for surveying or that have been only partially investigated due to the presence of overgrown vegetation or a steep slope.

3 Methods and Results

The approach that we have applied to deal with the data of this complex urban site is based on exploiting GIS in combination with procedural modelling techniques. Procedural modelling allows a formal, parametric and hierarchically encoded description of the 3D geometry that is obtained by writing rule files that follow a specific syntax. Such a strategy is particularly useful for the efficient modelling of recursive geometry and large scenes that can be populated from a concise set of rules. Parametric values are used to define the characteristics of the 3D entities. These parameters can be easily modified when needed and the 3D model will update accordingly, thus making this modelling method interesting for archaeological reconstructions to display different hypotheses.

We have used CityEngine as the procedural modelling software because of its modelling capabilities and its interoperability with ArcGIS. This software can import georeferenced images and shapefiles, maintaining their coordinate system and all their original attributes, and can export the created 3D scene as a geodatabase containing textured multipatches. The procedural generation of buildings in CityEngine follows the CGA (Computer Generated Architecture) shape grammar created by Pascal Müller and Peter Wonka (see Müller *et al*. 2006 for a description of its implementation and previous work). The CGA grammar is based on a sequence of rules defining steps and parameters for shape creation, which can be further detailed with the insertion of 3D models in OBJ and Collada DAE formats. An example of CGA rule file is shown in Fig. 2.

3.1 General workflow

The workflow we adopted consists of two phases: 1) mapping of the finds onto the DEM of the hill to visualize their distribution and characteristics as recorded during fieldwork; 2) reconstruction of the ancient terrain and the possible layout of the *polis* in the 4th century BC (Fig. 3). GIS based survey data were complemented by comparisons with other Greco-Roman towns in the Boeotia region and elsewhere in Greece. *Ad hoc* created procedural rules were applied to the survey data to obtain a 3D GIS of the survey results, and to the reconstructed terrain and street network to create a 3D reconstruction hypothesis of the ancient *polis*. Each of these components can be modified in isolation from the others, thus enabling an efficient workflow given that data are still being collected in our study. Moreover, the same rule can be applied to an updated dataset, thus making it possible to iteratively change the 3D scene when new data are available or new hypotheses have to be visualized.

During phase 1, the architectural data and the terraces categorized by age were mapped onto the DEM of the hill in

under the direction of Inge Uytterhoeven.

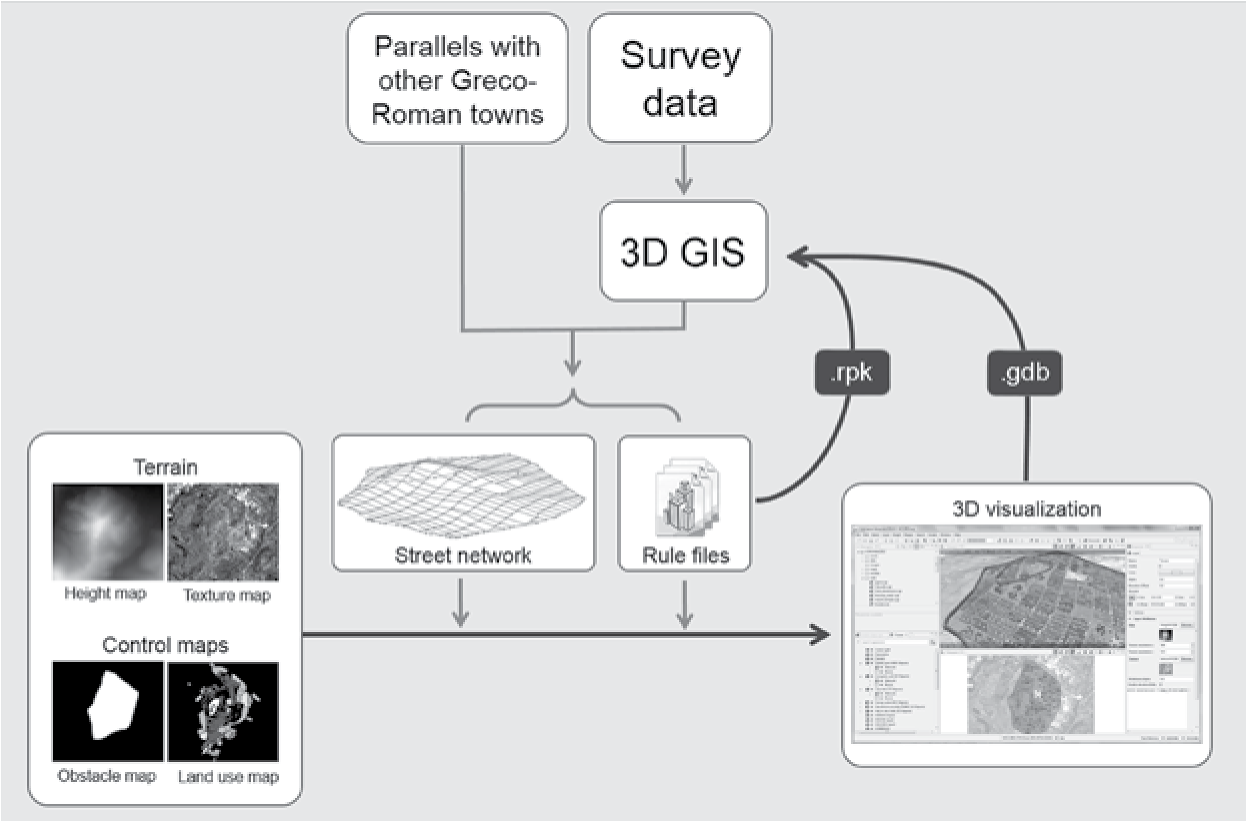

Fig. 3. The workflow for the creation of Koroneia's 3D visualization.

ArcScene.[2] Instead of using ArcGIS 3D symbology, which would display the architectural pieces in a standardized way, a rule was compiled in CityEngine, which interrogates the attribute table of the shapefile containing the architectural elements, and scales the latter according to their real dimensions (i.e. length, width and height) as recorded in the field. Moreover, the rule file automatically associates different textures to the types of stone that the blocks are made of.[3] The rule package was imported in ArcScene in rpk format and was applied to the selected 2D features using the CityEngine toolbox that has been introduced in ArgGIS 10.2 among the 3D Analyst tools.[4] In this way, concentrations of smaller or bigger blocks, and clusters of specific types of stone can be immediately appreciated (Fig. 4). In addition, possible correlations between the dimensions of blocks and the stone that was used can be easily spotted by zooming into the 3D scene. Assuming that larger blocks were used for more imposing architecture, such as buildings with a public character, this visualization provides an intuitive insight into the functional zoning of the ancient town. For instance, a concentration to investigate further is that of schist and large conglomerate blocks, which emerges from the predominant limestone (textured in black) to the south-east, close to the city wall circuit. Moreover, a high number of blocks made of tuff, a relatively soft stone that lends itself to carving and moulding, is visible on the plateau where the agora was located and on the nearby hollow which was occupied by the theatre.[5]

Phase 2 comprises the modelling of a reconstruction hypothesis both for the ancient terrain and for the ancient town. The ancient terrain was created starting from the points that were recorded in the field with a DGPS. Points were deleted or added in ArcScene where the terraces or quarries that were identified as modern during the geomorphological survey needed to be smoothed off or filled. For example, points were added to fill in the large quarry that was opened on the north-western side of the hill in modern times in order to facilitate the interpolation of the new DEM. All the points that were deleted or added have been stored in separate shapefiles in order to keep the record of the operations that were performed to change the DEM. A Kriging interpolation method was used to create the reconstructed terrain and was exported as a height map to be used as the terrain in CityEngine. A black and white image ('obstacle map') was used to limit the generation of the 3D scene to the area within the city wall. Moreover, the possibility was implemented to control the creation of different types of buildings according to a grey scale image displaying the provisional zoning of the ancient town. A reconstruction

2 Additional open source software packages were used such as QuantumGIS for the creation of shapefiles, GIMP for the creation and editing of textures, and Blender to manually model the theatre.

3 For the moment the stone types have been clustered in 7 broad groups with associated texture (limestone = black, conglomerate = orange, sandstone = beige, schist = brown, tuff = light grey, marble = white and 'city wall type' = yellow), which simplifies the more detailed description that was made in the field by I. Uytterhoeven, who recorded also the colour of each block.

4 The *in situ* walls were recorded as polylines and the building blocks as points. Since CityEngine rules have to be applied to polygons, a buffer was created around polylines and points to create polygons and overcome this problem.

5 A series of density analyses of the architecture dataset has been carried out by Y. Boswinkel (Boswinkel 2015).

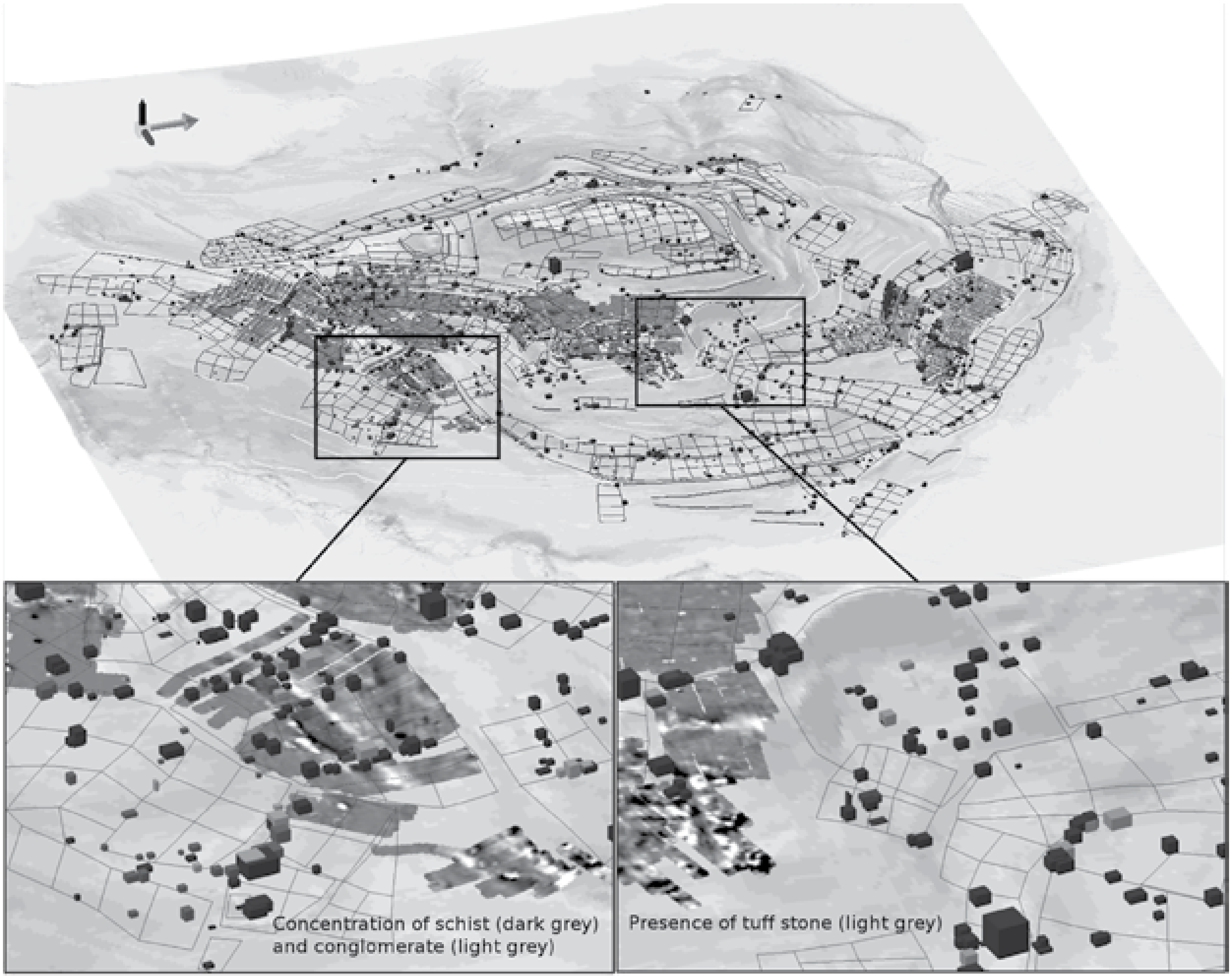

Fig. 4. An example of some data layers of Koroneia's 3D GIS: the DEM with overlaid grid of the areas that were accessible during the survey, the terraces mapped during the geomorphological survey, the provisional results of the ongoing geophysical prospections, and the architectural finds. The latter are scaled according to their dimensions (here multiplied by a factor of 10 for visualization purposes) as recorded in the field, and categorized per stone type with a procedural rule that was written in CityEngine and imported in ArcGIS. In this way, clusters of stones and the relationship between the dimension of the blocks and the stone type become apparent.

hypothesis of the street network was then created based on the available survey results.

3.2 Procedural modelling of Greek Classical architecture

Procedural rules were written for domestic architecture and vegetation, streets and city walls with towers. The rule 'parthenon.cga', which was written by Pascal Müller, was adapted to display alternative reconstruction hypotheses for the temple architecture. Comparisons from excavated sites and examples of vernacular architecture were used to create the 3D geometry. Despite local variability, some common features can be recognized in Greek Classical houses, such as the tendency of an inward looking configuration of space, with rooms gravitating around a central multifunctional courtyard connected to a porch and high located windows to protect the privacy of the household (Bintliff 2014; Ault 2005: 58-63). The upper floor is a matter of debate since the state of conservation of the investigated archaeological sites does not allow conclusive arguments. Stairs, stair bases, postholes and other indirect evidence of an upper floor were found in excavated houses at several sites, such as at Olynthos and Halieis (Cahill 2002: *passim*; Ault 2005: 73), but in other contexts evidence for upper floors was not found (e.g. in Hellenistic Halos, Haagsma 2010: 38-9). In any case, it remains unclear if the upper floor would cover the entire building or only part of it.[6] Parameters and probability values were set in the rule file to allow for the display of different possibilities, e.g. changing the dimensions of the buildings, the extension and appearance of an upper floor (covering the whole surface of the house, only the back, or either side of the courtyard), the presence and quantity of windows and the appearance of roofs (Fig. 6a).

[6] For a discussion on the presence of a second storey in the Olynthian houses, see Nevett 1999: 75. The evidence from the excavations at the Hellenistic site of Petres of Florina suggests the presence of a semi-open area at the front of the upper floor which was reached by an external stone staircase (Adam-Veleni 2000: 58-9). This configuration is similar to the examples of vernacular architecture that are characterised by a wooden gallery-like construction ('hayiati') on the houses' façade (cfr. Sigalos 2004: 327).

```
1.  attr criticalSlope = 30
2.  slopeValueDegrees = atan (scope.sy / sqrt((scope.sx * scope.sx) +
                        (scope.sz * scope.sz)))
3.  Lot --> alignScopeToAxes (y) LotAligned
4.  LotAligned --> case slopeValueDegrees > criticalSlope : vegetationLot
                   else : buildingLot
5.  vegetationLot --> …
```

Fig. 5. Example of CGA rule to calculate the slope degree. An attribute stores the critical slope value (line 1), which is currently set to 30°. The arctangent function is used to calculate the slope degree and adapt the geometry accordingly (line 2). The calculation is based on the size of the bounding box (scope), which defines the position in space of each shape. The y axis of the initial shape 'Lot' is aligned vertically in order to ensure a correct calculation (line 3). The following case-else statement sets the condition for geometry generation: buildings will be generated only if the calculated slope value does not exceed the set critical slope, otherwise vegetation will be created (line 4).

The city walls were created using the same tool that creates a street network; in this way the circuit can be easily adapted to the terrain and modified if new data would alter our hypothesis regarding its path along the eastern and southern slope. The rules for the city walls generate a polygonal masonry for the acropolis walls, as attested by the stretches that were found during the survey at Koroneia, and a regular, rectangular stone foundation with its higher elevation in mudbrick for the lower circuit wall, as this is the most common construction technique for Classical walls. The rule is constructed in such a way that towers are created at crossing points of the city wall circuit. So far, the architectural survey has only yielded evidence for two towers on the western slope but it is likely that geophysical prospections will provide further indication for the position of other towers (already one possible example was indicated in the south-east sector), so this strategy is convenient to easily introduce new towers at the target location.

A mathematical function was inserted in the rule files for streets and architecture, which calculates the terrain slope and adapts the geometry accordingly. Streets are in fact turned into steps when the slope becomes too steep to ascend. Moreover, in areas where the slope reaches the critical slope of 30°, which is indicated as the maximum preferred slope for construction by comparison with other sites (see e.g. Ephesus in Groh 2012: 68), the rule file creates vegetation instead of buildings (Fig. 5).

Three different levels of detail have been set in the rule files and can be changed rapidly when needed: high detail where roofs are made of individual roof tiles which can be used for close rendering purposes (LOD = 2); intermediate detail which creates detailed geometries, but keeps roofs as textures (LOD = 1), and low detail which creates schematic coloured volumes (LOD = 0), which is useful to keep the polygon count at the minimum for exporting the whole scene to another software when only the volumetric information is needed (Fig. 6a, b).

Additionally, the possibility to sample points and create panels on the buildings' surfaces has been implemented in the rule files (Fig. 6c). This workflow has been recently introduced for the spatial and visual impact analysis of modern cities (Van Maren 2014), and it is based on the possibility to export each of the so called leaf-shape that are generated by a rule as individual GIS features so that they can be used to perform visibility analysis on the built environment in ArcGIS. Points are used to run a Line of Sight analysis and panels can be used to map the frequency count in order to visualize the visibility of the portion of the building defined by each panel. This implementation opens up the possibilities to use the 3D visualization as an analytical tool, which is able to investigate the spatial relationships between buildings in a quantitative way (see proof of concept in Fig. 7). In the case of Koroneia, we implemented this workflow in order to determine for example which height the temple that we assume stood on the acropolis should have had, in order to be seen from the lower town, given the visual obstruction of the acropolis wall.

Similarly to scripting and programming languages, procedural modelling allows the insertion of comments in between the lines of the rule file. We used this possibility to include within the rules references to the sources that we have consulted for the reconstruction; in this ways the rule files become self-standing sources of information and can be shared as such. The provisional 3D visualization of Koroneia is shared using the CityEngine WebGL based web viewer, which maintains the possibility to display and search for the attributes of the GIS data that were used to create the scene. For the moment the visualization is available internally to the team as a platform for discussion, but will be made public after completion of the survey.

4 Discussion

In this paper we discussed the methodology that we have adopted for the creation of a GIS based 3D visualization of our survey data and of reconstruction hypotheses of Classical Koroneia. The methodology is based on a combination of GIS and procedural modelling, which met the requirements of the ongoing survey and that can be applied to other archaeological contexts with similar characteristics. Procedural modelling has already been used for other archaeological sites, such as Pompeii (Müller *et al*. 2005), the Maya city of Xkipche in Mexico (Müller *et al*. 2006), Rome (Haegler *et al*. 2009; Dylla *et al*. 2010; Saldaña and Johanson 2013), Bologna (Pescarin *et al*. 2010), Montegrotto (Ferdani and Fanini 2011), Portus (Harrison *et al*. 2013) and Regium Lepidi (Forte and Danelon 2015). To our knowledge, this is the first implementation of a set of procedural rules for Classical Greek architecture, which includes also the possibility of sampling points and panels on the buildings' surface to perform visibility analysis in ArcGIS.

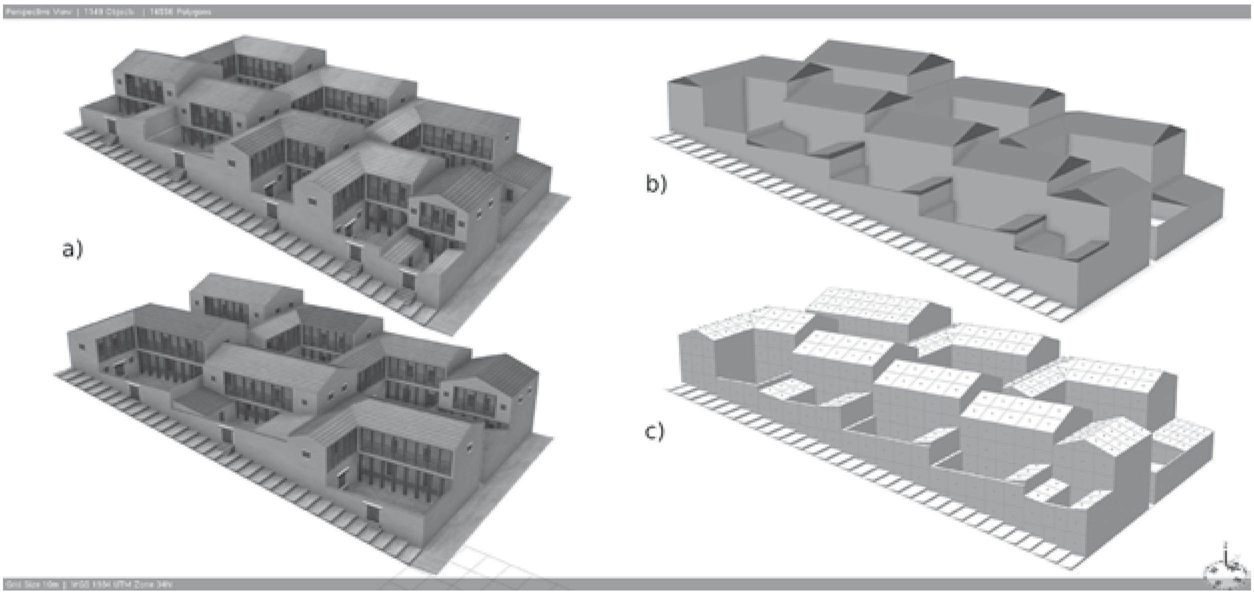

Fig. 6. A city block generated by the procedural rule for domestic architecture; in a) two of the possible different configurations of space that are encoded in the rule file are represented (LOD = 1); b) displays the low of level detail scene, which generates geometries as coloured volumes (LOD = 0); c) shows the panels and points that can be exported and used to perform visibility analysis in ArcGIS, as shown in Fig. 7.

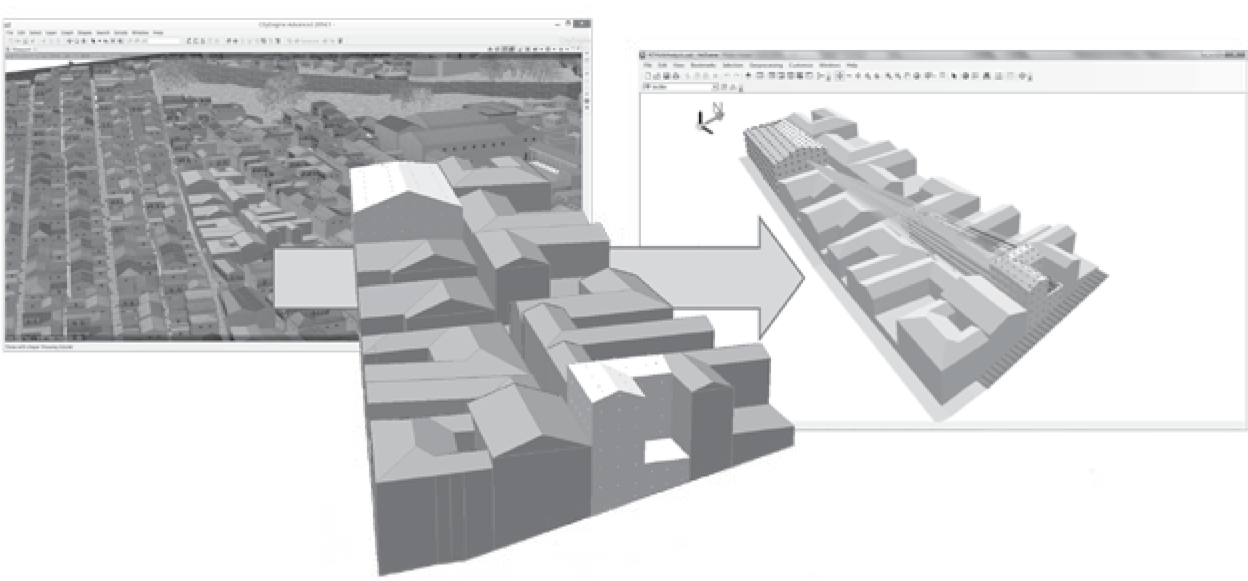

Fig. 7. Proof of concept of the visibility analysis enabled by the procedure of sampling points on the 3D geometry that is included in the created rule files. A procedurally modelled insula was exported from CityEngine as .gdb and imported into ArcScene to run the Line of Sight analysis between buildings.

An additional rule was written to be used as procedural symbology layer in ArcGIS, which exposes the properties of the architectural dataset (i.e. dimensions and stone type) in an automatic and more customizable way in comparison with standard 3D symbology. This provides an immediate overview of concentrations of larger or smaller blocks, and clusters of stone types, which can point to the presence of different types of buildings. Working in a 3D GIS environment has moreover the advantage that it is possible to observe – better than in a 2D GIS – the relationship between the hilly morphology of the terrain and the distribution of finds, such as the locations of the architectural blocks in relation to the terraces' edges. This workflow can be extended to other classes of finds (e.g. pottery sherds), and can be applied to other contexts where

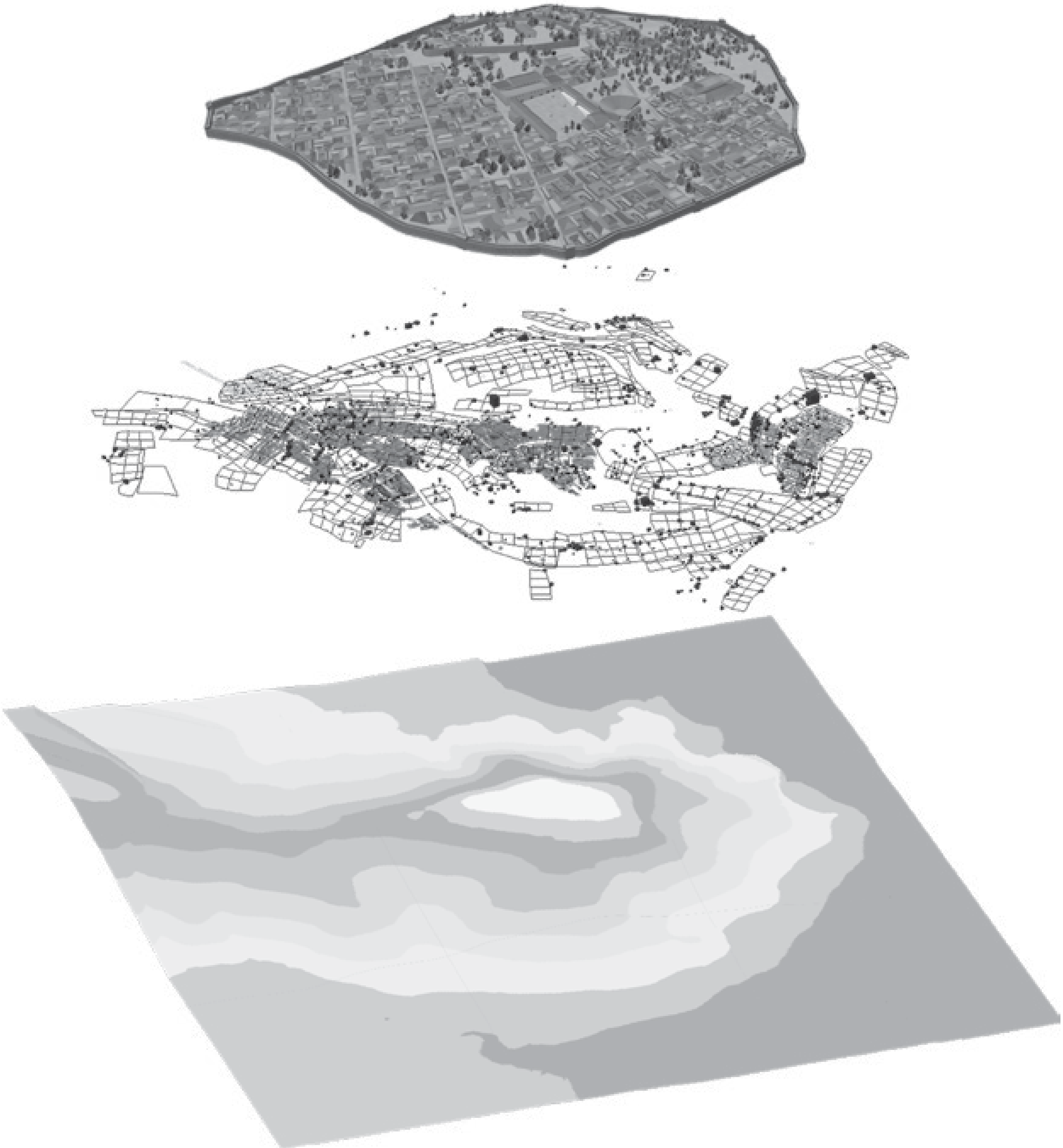

Fig. 8. The main layers that compose Koroneia's 3D GIS environment. Bottom: terrain layer; middle: survey data (for the moment limited to architecture and geophysical prospections) and survey grids; top: one of Koroneia's procedurally modelled reconstruction hypotheses based on the current state of the data. All the elements are generated from ad hoc procedural rules, apart from the theatre which has been created in Blender and imported into the scene as OBJ file format.

stratigraphic information is available to create a 3D GIS of excavated trenches.

The procedural modelling approach presented here is particularly suitable for creating a 3D visualization when the data collection and study are still in progress. In fact, this represents usually an obstacle when using manual modelling techniques and therefore discourages the use of a 3D visualization as a hypothesis generation tool. The implementation of the procedure to sample points and create panels on the buildings' surfaces opens up a range of possibilities to perform spatial analysis on the past built environment. For instance, a building can be analysed in its context, to evaluate its presence in relation to its surroundings and its visibility can be determined from a given location.

Using this 3D modelling strategy we were able to display different reconstruction hypotheses that matched our dataset.

Importantly, we could cover in a controlled and fast way the areas that were impossible to investigate during the survey due to the presence of overgrown vegetation. Rule files can be customized and reused on different configurations of street networks, thus making this approach time-efficient in the long term. Rules hierarchically record the steps that have been made for the creation of the 3D geometry, thus making the modelling process explicit, and have been annotated with the sources that were used. In addition, the 3D reconstruction is created on top of the GIS data within the same coordinate system, thus maintaining a spatial and visual relationship between the hypothesis and the original data, which provides an intellectually transparent visualization (Fig. 8).

Pursuing this method further will allow us to simulate the planning choices that were made in antiquity. We aim to investigate how buildings were constructed over the sloping ground and how many would fit within the estimated city wall circuit. As future work, we aim at creating more architectural variations in order to encompass the different possible arrangements of domestic space. Moreover, the rule files will include a color-coded mapping of the level of uncertainty of the reconstructed built environment in order to clarify the degrees of reliability of the reconstruction (e.g. green = based on survey data; yellow = inferred from survey data; red = based on comparison with other sites/conjectural).

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Bibliography

Adam-Veleni, P. 2000. *Πέτρες Φλώρινας: περιήγηση σε μια ελληνιστική πόλη. Petres of Florina: A walk around to a Hellenistic city. Thessaloniki.*

Ault, B. A. 2005. *The excavations at ancient Halieis (vol. 2). The houses: The organization and use of domestic space*. Bloomington, Indiana University Press.

Bintliff, J., Slapšak, B., Noordervliet, B., Van Zwienen, J., Verweij, J. 2009. The Leiden-Ljubljana Ancient Cities of Boeotia Project summer 2007 – spring 2008. *Pharos. Journal of the Netherlands Institute in Athens* XV: 17-42.

Bintliff, J. 2013. Public versus professional perceptions of an invisible heritage: A Greek case study. In E. Niklasson and T. Meyer (eds.), *Appropriate Narratives. Archaeologists, Publics and Stories*: 237-47. Budapest, Archaeolingua.

Bintliff, J. 2014. Spatial analysis of past built environments: Houses and society in the Aegean from the Early Iron Age to the impact of Rome. In E. Paliou, U. Lieberwirth, S. Polla (eds.), *Spatial analysis and social spaces*: 263-76. Berlin, Walter de Gruyter.

Bintliff, J. 2015. Beyond theoretical archaeology: A manifesto for reconstructing interpretation in archaeology. In K. Kristiansen, L. Šmejda, J. Turek (eds.), *Paradigm found. Archaeological Theory present, past and future*: 24-35. Oxford, Oxbow Books.

Boswinkel, Y. 2015. *Architecture as an archaeological proxy. The site of Koroneia, Greece as a case-study for researching a multi-period site through architecture and the methodology of studying architecture from a survey context*. Unpublished RMA thesis, Faculty of Archaeology, Leiden University.

Dylla, K., Frischer, B., Müller, P., Ulmer, A., Haegler, S. 2010. Rome Reborn 2.0: A case study of virtual city reconstruction using procedural modeling techniques. In B. Frischer, J. Webb Crawford, D. Koller (eds.), *Making History Interactive. Proceedings of the 37th Conference in Computer Applications and Quantitative Methods in Archaeology, 22-26 March 2009, Williamsburg, Virginia*: 62-6.

Ferdani, D. and Fanini, B. 2011. A New approach from 3D modelling and scanning of archaeological data to real time online exploration. In M. Zhou, I. Romanowska, Z. Wu, P. Xu, P. Verhagen (eds.), *Revive the Past. Proceedings of the 39th Conference in Computer Applications and Quantitative Methods in Archaeology, 12-16 April 2011, Beijing*: 107-15. Amsterdam, Pallas.

Forte, M. and Danelon, N. 2015. Regium@Lepidi 2200 Project, *Archeomatica* VI.1: 42-8.

Fossey, J. M. 1979. The cities of the Kopais in the Roman period. In *Aufsteig und Niedergang der Römischen Welt* II.7.1: 549-91. Berlin:, Walter de Gruyter.

Fossey, J. M. 1981. The City archive at Koroneia, Boiotia. *Euphrosyne* XI: 44-59.

Groh, S. 2012. Strategies and results of the urban survey in the Upper City of Ephesus. In F. Vermeulen, G.-J. Burgers, S. Keay, C. Corsi (eds.), *Urban Landscape Survey in Italy and the Mediterranean*: 62-71. Oxford, Oxbow Books.

Haegler, S., Müller, P., Van Gool, L. 2009. Procedural modeling for digital cultural heritage. *EURASIP Journal on Image and Video Processing 2009*.

Harrison, M., Keay, S., Earl, G. 2013. Grammar modelling and the visualization of an uncertain past: The case of Building V at Portus. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Proceedings of the 40th Conference in Computer Applications and Quantitative Methods in Archaeology, 26-29 March 2012, Southampton, UK*: 895-909. Amsterdam, Amsterdam University Press.

Kalliontzis, Y. and Papazarkadas, N. 2014. New Boeotian inscriptions from Akraiphia and Koroneia. In W. Eck and P. Funke (eds.), *Öffentlichkeit – Monument – Text. XIV Congressus Internationalis Epigraphiae Graecae et Latinae, Akten*: 550-2. Berlin, Walter de Gruyter.

Meyer, C. and Pilz, D. 2015. Magnetic survey in Koroneia. The Ancient Cities of Boeotia Project (Boeotia, Greece). Internal report.

Müller, P., Vereenooghe, T., Ulmer, A., Van Gool, L. 2005. Automatic reconstruction of Roman housing architecture. In M. Baltsavias, A. Gruen, L. Van Gool, M. Pateraki (eds.), *Recording, Modeling and Visualization of Cultural Heritage. Proceedings of a Conference held in Ascona, Switzerland, 22-27 May 2005*: 287-97.

Müller, P., Wonka, P., Haegler, S., Ulmer, A., Van Gool, L. 2006. Procedural modeling of buildings. *Proceedings of ACM SIGGRAPH* 25 (3): 614-23.

Müller, P., Vereenooghe, T., Wonka, P., Paap, I., Van Gool, L. 2006. Procedural 3D reconstruction of Puuc buildings in Xkipche. In M. Ioannides, D. B. Arnold, F. Niccolucci,

K. Mania (eds.), *VAST 2006: Proceedings of the 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Nicosia, Cyprus*: 139–46. Eurographics Associations.

Nevett, L. C. 1999. *House and society in the ancient Greek world*. Cambridge, Cambridge University Press.

Pescarin, S., Pietroni, E., Ferdani, D. 2010. A Procedural approach to the modeling of urban historical contexts. In F. Contreras, M. Farjas, F. J. Melero (eds.), *Fusion of Cultures. Proceedings of the 38th Conference on Computer Applications and Quantitative Methods in Archaeology, April 2010, Granada*, *Spain:* 63-70. Oxford, Archaeopress.

Saldaña, M. and Johanson, C. 2013. Procedural modelling for rapid-prototyping of multiple building phases. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5/W1: 205-10.

Schachter, A. 1981. *Cults of Boiotia 1: Acheloos to Hera*. London, University of London, Institute of Classical Studies.

Sigalos, E. 2004. *Housing in medieval and post-medieval Greece*. British Archaeological Reports International Series 1291. Oxford, Archaeopress.

Uytterhoeven, I. 2012. Architectural remains at Koroneia. In J. Bintliff, B. Slapšak, B. Noordervliet, J. Van Zwienen, I. Uytterhoeven, K. Sarri, M. Van Der Enden, R. Shiel, C. Piccoli, *The Leiden-Ljubljana Ancient Cities of Boeotia Project 2009 seasons*. *Pharos. Journal of the Netherlands Institute in Athens* XVII: 13-22.

Uytterhoeven, I. 2014a. *Koroneia 2012 – Architectural survey*. Internal report.

Uytterhoeven, I. 2014b. *Koroneia 2013 – Final architectural survey*. Internal report.

Van Maren, G. 2014. CityEngine 2014.1 released! Blog ArcGIS resources. Available from http://blogs.esri.com/esri/arcgis/2014/09/15/41619/ [Accessed: 11 june 2015]

Van Zwienen, J. and Noordervliet, B. 2009. Micro-topographical research using DGPS on Koroneia hill. In J. Bintliff, B. Slapšak, B. Noordervliet, J. Van Zwienen, J. Verweij, *The Leiden-Ljubljana Ancient Cities of Boeotia Project summer 2007 – spring 2008*. *Pharos. Journal of the Netherlands Institute in Athens* XV: 33-7.

Verdonck, L. 2013. *GPR prospection at Askra and Koroneia (Boeotia)*. Internal report.

Wilkinson, K. 2009. Geoarchaeological fieldwork carried out for the Ancient Cities of Boeotia Project. In J. Bintliff, B. Slapšak, B. Noordervliet, J. Van Zwienen, R. Shiel 2010. *The Leiden-Ljubljana Ancient cities of Boeotia Project 2008 season*. *Pharos. Journal of the Netherlands Institute in Athens* XV: 50-3.

Structural Integrity Modelling of an Early Bronze Age Corridor House in Helike of Achaea, NW Peloponnese, Greece

Mariza Kormann[(1)]
m.kormann@shu.ac.uk

Stella Katsarou[(2)]
stella@stellakatsarou.gr

Dora Katsonopoulou[(3)]
eliki@otenet.gr

Gary Lock[(4)]
gary.lock@arch.ox.ac.uk

[1] Communication and Computing Research Centre, Sheffield Hallam University, Sheffield, UK
[2] Department of Palaeoanthropology-Spelaeology, Athens, Greece
[3] The Helike Society and The Helike Project, Athens, Greece
[4] The University of Oxford, UK

Abstract: Structural integrity modelling and simulation studies were performed on the Helike Corridor House (HCH), a monumental building excavated at the Early Helladic (EH) site of Ancient Helike on the NW Peloponnese, Greece. The aims of the research were to explore building materials and plan alterations of an earlier phase into an EH II-III period Corridor House. Static load analysis followed by buckling (failure) analysis was simulated using ANSYS. Results demonstrate that buckling would develop in the narrow corridor area, being the critical spot in the structure due to its configuration of long tall sidewalls. It is shown that when stairs are introduced, the structure becomes less susceptible to buckling. We conclude that the doubling of the outer walls was a high structural and functional technical innovation which required specialized knowledge on planning and construction highlighting the critical role architecture played in response to upcoming social transformations.

Keywords: Helike, Corridor House, Early Helladic Architecture, Structural Integrity, Finite Element Analysis

Introduction

The Helike Corridor House (HCH) excavated foundation walls (Katsonopoulou, 2011) reveal an outstanding and monumental house prototype of the late Early Helladic (EH) II-early III (mid- to second half of the 3rd millennium BC), fitting with the mostly debated architectural template of the Greek mainland in this period. This paper investigates analytical modelling and simulation studies on the HCH to test the way innovative features were incorporated to guarantee its structural integrity, and assess the significance of such architectural innovations to proto-urban setting.

More specifically, reviewing older research in the southern Greek mainland, the corridor feature has been associated with various material transformations and innovations in the EH period (Peperaki 2004; Maran and Kostoula 2014). Although it emerged individually as a widespread but distinct architectural trait in several sites (Hägg and Konsola 1986; Harrison 1995; Wiersma 2013), it was adopted with a patterned arrangement along the side walls of certain houses for the configuration of this innovative and complex kind of building, called the 'Corridor House', at some stage of the EH II (Shaw 1987; 1990; 2007). One aspect of the complex debate about establishing these external corridors has derived from the implication that they hosted stairways leading to an added second storey. More than that, the recovery of precious equipment and distinct accessories from these houses, along with their presence as unique examples inside the settlements, has promoted arguments for their possible centralized administrative role and the rapid advance of the EH society towards hierarchical pre-state modes (Maran 1998; Pullen 2008).

On account of these regional and cultural connotations, further definition of the detailed material data of the known corridor houses has been long-attempted by an array of scholarly analysis of their design, purpose, construction techniques and material equipment (Themelis 1984; Pullen 1986; Aravantinos 1986; Shaw 1987; 1990; Wiencke 1989; 2000; Kalogerakou 1999; Maran and Kostoula 2014), always with an eye to verify the broader social advances of the period. Within this integrative framework, the present material and structural analysis of the particular HCH is expected to provide research on Helike with challenging implications that will go beyond the house's individual features and will contribute to understanding the social and economic significance of the settlement itself and also the rise of this long-debated building type in the wider mainland context.

The HCH was revealed during excavation work carried out by the Helike Project (Katsonopoulou 2011), an interdisciplinary and cross-cultural landscape archaeology and geomorphology project conducted in the major Helike area in Achaea, NW Peloponnese (Katsonopoulou 1998; 2005; Soter and

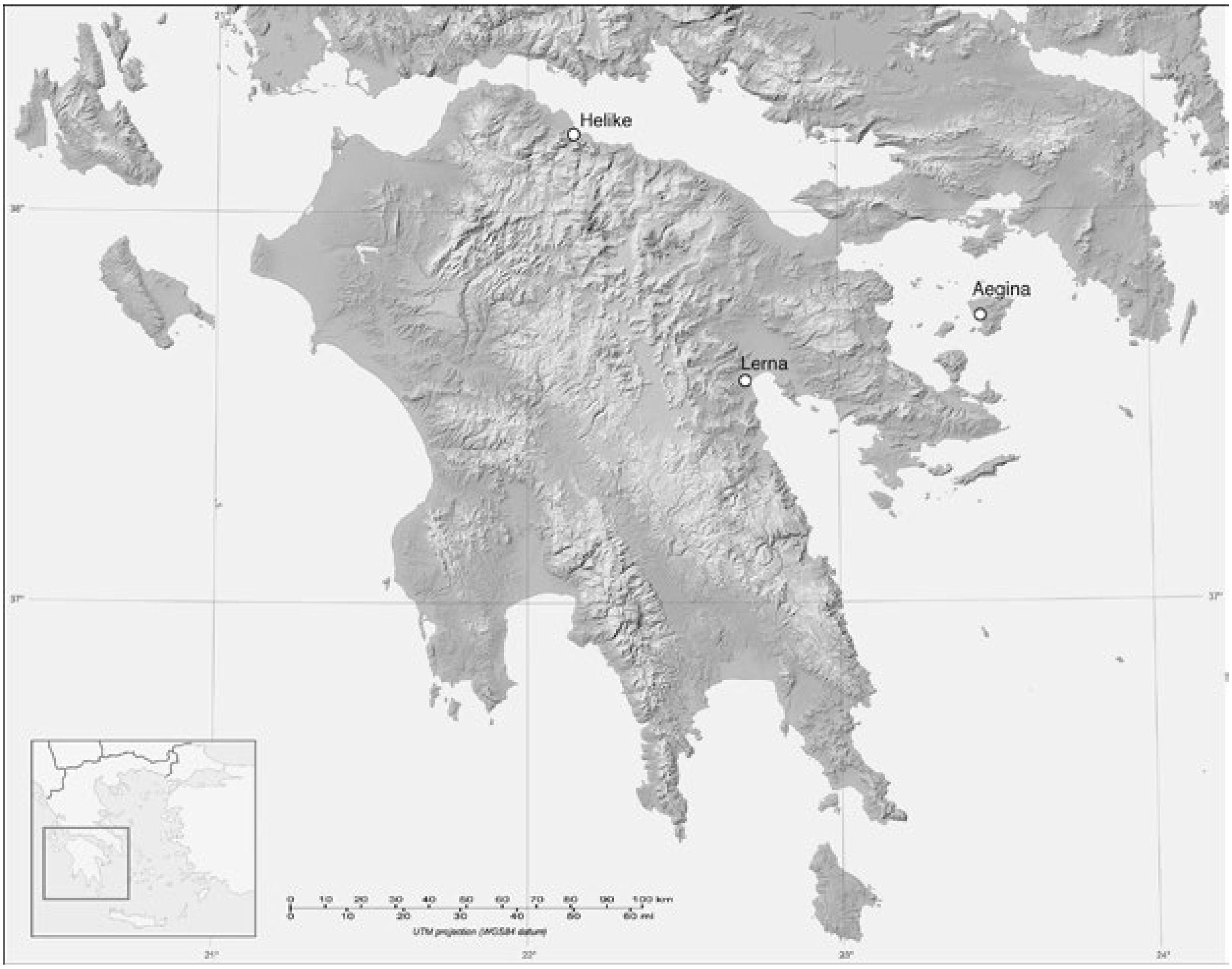


Fig. 1. The geographic location of the corridor houses at Helike, Lerna and Aegina.

Katsonopoulou 2011) from 1988 onwards. Although the particular structure was excavated along its western section only, as the rest of it extends into non-excavated neighbouring fields, its 'corridor' plan is testified by the arrangement of narrow corridors along the preserved external sides of an axially placed rectangular structure composed of a series of adjoining rooms.

In this paper we propose a tentative reconstruction of the HCH based on comparable reconstructed corridor house plans as assumed by Shaw (1987). In particular the closer association of the HCH should be established with the EH II 'House of the Tiles' at Lerna in the Argolid (Caskey 1959; Wiencke 2000), and the 'Weisses Haus' (although this one is more complex) at Kolonna in Aegina (Walter and Felten 1981), whose plans were critically assessed by Shaw (1987). The geographic locations of the mentioned sites are indicated in figure 1. In a brief account of the HCH, the reconstruction of the missing east long sidewall in terms of length and openings are mirrored on the excavated west walls as shown in the conjectural plan. The entrance, outside openings and blind rooms are hypothesized on the basis of the above equivalent houses. More noticeable parallels between the HCH and the latter include the interior rooms varying in width – the side chambers being wider than the intermediate area – and the non-axial arrangement of the interior doorways. Certainly one has to consider that other versions may be plausible for the reconstruction of the HCH in terms of minor features.

The account of rich interior items in the HCH and the evidence to the fact that it was modified from an earlier simpler long rectangular building are highly significant to the research questions posed in this paper. A large number of cooking and drinking vessels were revealed in the central rooms together with a remarkable assemblage of big storage jars placed in a row along the long wall and bordering pebbled floor areas (Katsarou 2011). Hearths and a rich collection of tableware from the centre of the chamber were also revealed. The changing plan indicates the addition of the corridor areas to the long and narrow sides in order to accommodate the storage facilities on the ground floor. Furthermore it implies the addition of a stairway to the upper floor, sheltered entrance, balcony appendages, and other side rooms to acquire increased space and monumentality.

We should also note that the EH settlement of Helike has revealed a number of free-standing long rectangular houses built across an area of about 30 hectares (Katsonopoulou 2011). The buildings are arranged in poleodomic insulae and are aligned with long straight crossing cobbled roads, even featuring the presence of at least one open plaza (Katsonopoulou 2011), all of which seem to have been built according to an earlier plan of the settlement. The clear-cut town planning of Helike is strongly indicative of a collective communal project and thus of an administrative regime to organize its accomplishment before putting it into practice. The precious possessions of several houses in gold and silver and intimate exotic clay imports as implied by the unique *depas* cup (Katsonopoulou 2011), strengthen the view that EH Helike constituted a rich trading community on the southwestern coast of the Corinthian Gulf. Within this context, the attribution of an administrative or socially differentiated role to the HCH, as assumed for corridor houses from other sites (Peperaki 2004; Maran and Kostoula 2014) are strongly justified. The above considerations provide an interpretative context for the HCH 3D reconstruction, materials characterization and structural analysis simulations described in the next sections.

1 Research Aims and Methodology

Reconstruction modelling, sometimes called 'solid modelling', 'three-dimensional modelling' or 'Virtual Reality modelling', has been used in archaeology since the late 1980s (Lock 2003: 152) and is now commonplace. The resultant 'constructs, simulations and hyperreal worlds' (Goodrick and Gillings 2000) have largely moved on from attempting to offer objective and accurate representations of the past as was claimed for many early models, to being a more exploratory method of thinking about what the past may have entailed. It is within this context of 'what if modelling' that we present this work based on an aspect of reconstruction that is relatively new to archaeology, that of testing the structural integrity of buildings.

Structural analyses through computer models are widely used in architecture and engineering to study the behaviour of real world structures (Lawrence 2012). These studies can replace real experimentation and measurements as the simulations are based on precise physical models allowing the specification of materials, geometries, and their ability to withstand a large variety of loads. Structural analysis requires thus, the specification of materials, their physical and mechanical properties, geometry, and the loads acting on the structures. This kind of analysis has been used before in connection to cultural heritage. For instance, finite element analysis has been employed to assess seismic vulnerability as a way to predict ruptures in the case of earthquakes (Shakya *et al.* 2012; Dowling 2004), as a guide to the restoration of monastic buildings (Miles 2014), to study the durability of materials (Varum *et al*. 2011; Ruano *et al*. 2012), and to test historical masonry structures for the restoration of the Bam Citadel destroyed by an earthquake in 2002 (Hejazi and Saradj 2014).

This research is based on ANSYS (Lawrence 2012; Sharpe 2008), which is a sophisticated modelling and simulation platform for testing and validating the physical behaviour of structures based on Finite Element Analysis and mechanical properties of materials. ANSYS provides a number of tools and utilities integrated and deployed from a single workbench. The HCH is the first Early Helladic corridor house to be analysed by this methodological tool.

The aims of the research are to formulate and validate hypotheses based on finite element modelling to test the structural integrity of the HCH. Results and conclusions would be directly relevant to similar buildings where evidence is scanty (e.g. mostly foundation walls). Related research questions include:

- What is the structural value of the added corridors to the monumentality of the building, i.e. in terms of load bearing, can a clear indication be provided of whether or not a second floor might have existed?
- On what structural properties was the choice of construction materials based?
- Why and how was the plan of the earlier house modified resulting in long narrow corridors and their relationships to facilities on the ground and upper floor?
- How does the HCH compare with the 'House of the Tiles' at Lerna and the 'Weisses Haus' at Kolonna, Aegina, in terms of isometric relationships and building materials?

The modelling and simulations reported in this paper involves static structural analysis followed by linear buckling analysis, which aims to determine at which level the load (i.e. the weight of the roof and other structural components) renders the structure unstable. Developing such a simulation and analysis in ANSYS involves the following steps:

- Select the analysis to perform (e.g. linear buckling).
- Specify materials engineering data, i.e. their mechanical properties, which include the material's density, compressive and tensile yield strengths, Young's modulus of elasticity and Poisson ratio. Other properties such as the bulk and shear modulus are derived from Young's modulus and Poisson ratio.
- Define the geometry of the structure as a solid 3D model.
- Specify the physical model and assign materials to various parts of the structure.
- Set up the initial forces and loads acting on the structure.
- Select a solution to perform (e.g. stress). The APDL (ANSYS Parametric Design Language) is used to solve the physical model and perform the simulations.
- Display the results in graphic and text report formats.

These steps are described in Sections 3 and 4.

2 Geometry and Materials Characterisation

2.1 Geometry Modelling

The ANSYS Design Modeler is a geometric modelling package with predefined geometric shapes and operations such as extrude, revolve and sweep together with advanced operators such as logic Boolean and blending. However, a number of operations are not intuitive and require various steps to complete and for this reason the 3D models of the house structure were drawn using SketchUp (2015), which provides a finer level of control and is more user-friendly. The models are then exported from SketchUp to a standard 3D file format and

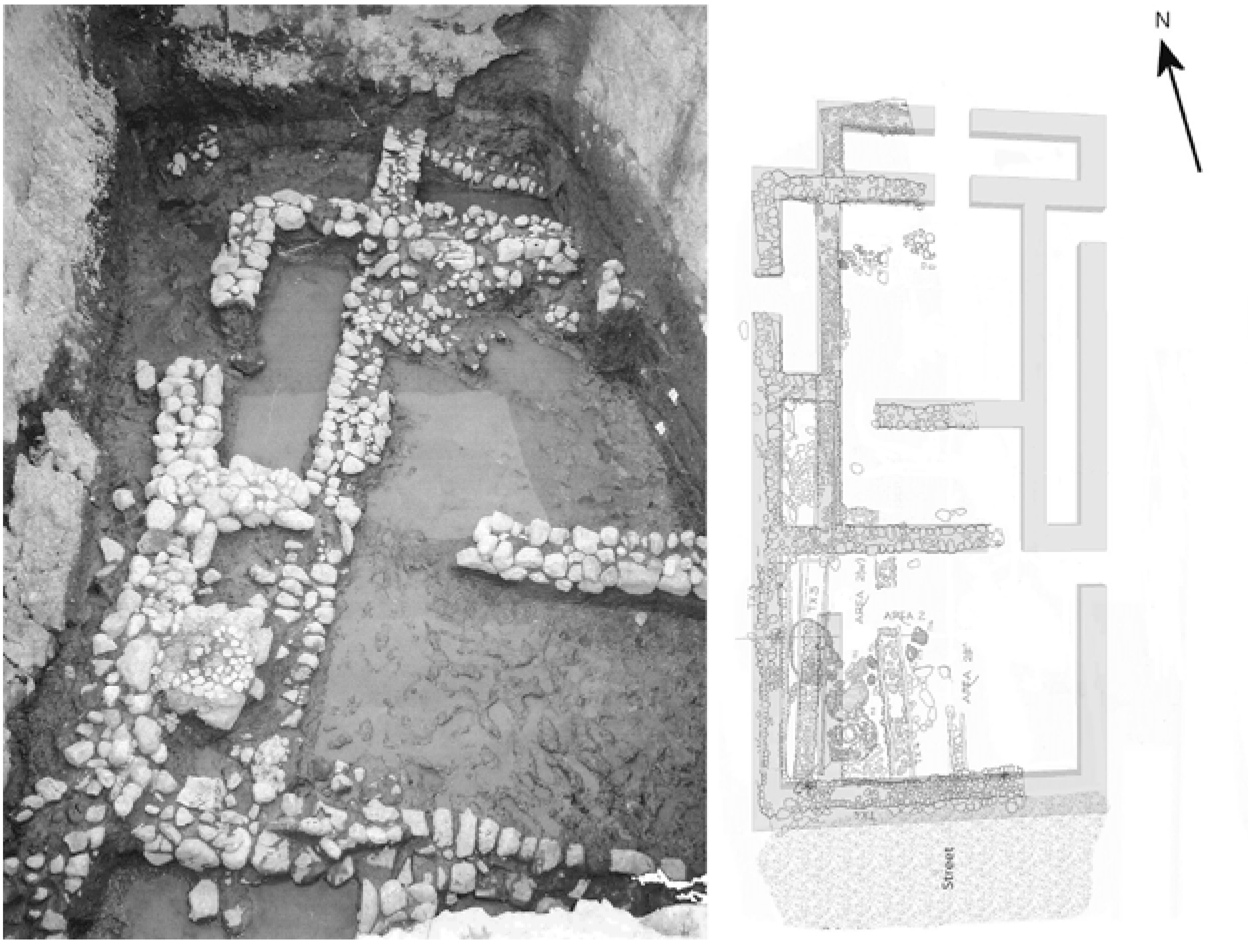


Fig. 2. Left: view of the north western part of the HCH during fieldwork in 2003; right: full drawing of the ground plan.

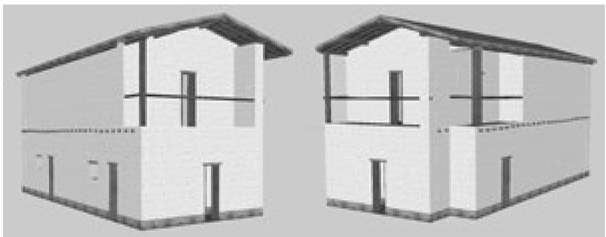


Fig. 3. The 3D model of the HCH, based on the house plan of figure 2.

imported directly into ANSYS Design Modeler providing a full integration into ANSYS Mechanical APDL.

The house plan geometry is derived from accurate measurements of the excavated foundation walls at the EH Helike site. Figure 2 shows part of the excavated foundation walls during the 2003 season and a corresponding drawing of the HCH with added conjectural plan that was used to guide the 3D reconstruction. Figure 3 illustrates two views of the 3D reconstructed house performed in SketchUp.

2.2 Materials Characterisation

The stone foundation walls of the HCH have been buried for the past 4,000 years at a depth of about 3 to 3.50m below present surface. Other structural materials such as complete bricks, wooden structures and roof tiles have not survived. Excavation shows that the house walls were built of adobe (sun dried mud brick), few samples of which have been recovered. Other assumed building materials are wood (*Pinus halepensis* and *Olea spp*) and reed (*Arundo donax*) with mechanical properties characterized as follows.

The Young's Modulus of elasticity is a measure of stiffness of an elastic material when stretched or compressed. The Poisson Ratio is the decrease in lateral measurement to the increase in length in a sample of material that is elastically stretched. The higher the Poisson ratio, the more elastic the material is. The tensile strength is the maximum amount of tensile stress a material can take before failure; it is defined as the ratio of *stress* (force per unit area) along an axis to *strain* (ratio of deformation over initial length). The compressive strength is the capacity of a structure to withstand loads in the elastic region.

The mechanical properties of materials are normally obtained through standardized destructive and non-destructive tests (Hibbeler 2013). In order to determine the compressive and

	Density Kg.m⁻³	Young's Modulus MPa	Poisson Ratio	Compressive Strength MPa	Tensile Strength MPa
Adobe Brick	1,737	54.7	0.17	1.2	0.04
Pinus halepensis	600	10,770	0.17	61	81.6
Olea spp	990	17,770	0.25	62	31
Reed *Arundo donax*	234	9,000	0.25	665	321.7

Tab. 1. Mechanical properties of building materials.

tensile strengths of mud bricks together with their modulus of elasticity and Poisson ratio, it would be necessary to run destructive tests on a number of samples. Since only eroded samples of brick are available from the site, and these certainly cannot be subject to destructive tests, image-based analysis was performed yielding estimated composition of 30% gravel, 53% sand, silt and clay and 17% straw.[1] This led to density estimates and comparison with known properties of ancient mud bricks and other building materials elsewhere for the required mechanical properties (King 1996; Keefe 2005; Houben and Guillaud 1989). The adobe brick mean density was estimated at 1,737kg.m^{-3}. The Young's modulus of elasticity was assumed 54.7Mpa (Adorni *et al*. 2013). The Poisson ratio was 0.17, the compressive strength 1.2MPa and the tensile strength 0.04MPa (Hejazi and Saradj 2014; Academia 2015). Table 1 shows the assumed mechanical properties of adobe brick together with other materials discussed below.

The upstairs floor structure of the HCH was assumed according to interpretations in the literature (Wiencke 2000) to be composed of three layers: a wooden supporting structure, a layer of reed and a layer of mud or rammed earth. The wooden component of the floor discussed in terms of the doorways at the 'House of the Tiles' (Maran and Kostoula 2014) would likely to have been constructed from transversal and longitudinal beams of the local species *Pinus halepensis* with mean diameter of 110mm and 180mm respectively. *Pinus* is also assumed for the construction of stair structure between ground floor and first floor. Evidence for *Pinus halepensis* can be found on the northwestern coast of Peloponnese during the Holocene (Lazarova *et al*. 2012). Radiocarbon analysis of sediment cores indicate that pine communities dominated the landscape during the Neolithic period but, possibly as a result of human intervention, were strongly reduced during the Early Bronze Age (Lazarova *et al*. 2012). The mechanical properties of *Pinus halepensis* quoted in Table 1 were determined by mechanical testing (Correal-Modol 2012; Zanne *et al*. 2009) and by similarity to related species (Ozkaya 2013).

Pollen diagrams also show evidence for cultivation of *Olea spp* in the northern Peloponnese in the Holocene (Lazarova *et al*. 2012). The use of *Olea spp* in the form of reinforcing beams above doors and window frames inside the upper floor wooden component is observed at the Cycladic Bronze Age settlement of Akrotiri, Thera, Greece (Palyvou 2005). In the HCH we may equally consider the possible use of reinforcing longitudinal beams from *Olea spp* beneath the *Pinus halepensis* floor structure, and also in the construction of the steps in the stair structure. The assumed mechanical properties (The Wood Database) are quoted in Table 1.

Reeds are a building material widely used since ancient times mainly to support and hold mud or clay on floor and roof structures and fences. They are well adapted to saline environments (Koutsios and Kontopoulos 2011) and exist in abundance in the area of Helike to this day. It is assumed that the local species *Arundo donax* (Cartwright and Taylor 2011) is the mostly likely to have been used in the floor substructure. Its mechanical properties (Barreca 2012; Spatz *et al*. 1997) are quoted in Table 1.

The roof structure of the HCH is also conjectured as being of similar construction and materials as the upstairs floor: a wooden structure made out of supporting *Olea spp* beams overlaid by *Pinus halepensis* beams followed by a layer of reed *Arundo donax*. A layer of rammed earth would cover the reeds. The roof would have an added topmost layer of tiles. The mechanical properties of the roof structure were not tested as such; instead their equivalent weight acting on the supporting wall structure was used in the simulations reported in the next section. The total weight of the roof structure was calculated from the density of each material multiplied by their volume. The volume was directly obtained from the solid models generated in SketchUp.

3 Structural Integrity Simulation Settings and Results

Figure 4 shows the top level ANSYS schematic program to perform static structural analysis followed by linear buckling. In order to build a simulation model, one must work the way down from the top by first specifying engineering data. These are the mechanical properties for each material as defined in Section 3, which are added to the standard ANSYS database of material properties. The solution to static structural analysis is then used as input to linear buckling analysis as shown in figure 4.

Following *Engineering Data*, the *Geometry* of the structure is specified. All 3D geometries developed in SketchUp were exported as solid models in IGS, which is a data format designed to exchange 3D information. These were then directly imported into ANSYS. The 3D models were divided into groups as follows: 1) Foundations, 2) Walls, 3) Floor: wooden structure, 4) Floor: reed structure, 5) Floor: mud layer, and 6) Stair structure.

Figure 5 top shows the SketchUp model with two walls removed so that the interior floor and stairs could be visualized. Figure 5 bottom shows the imported geometric structures into

[1] Iliopoulos, I., *Image Analysis, Samples H61 and H21* [email]. Message to: Katsarou, S. 29 October 2014.

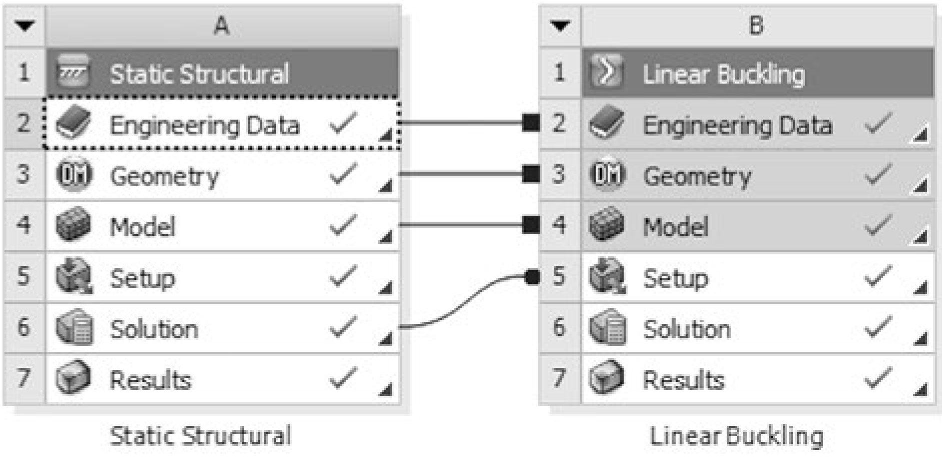


FIG. 4. ANSYS SCHEMATIC PROGRAM.

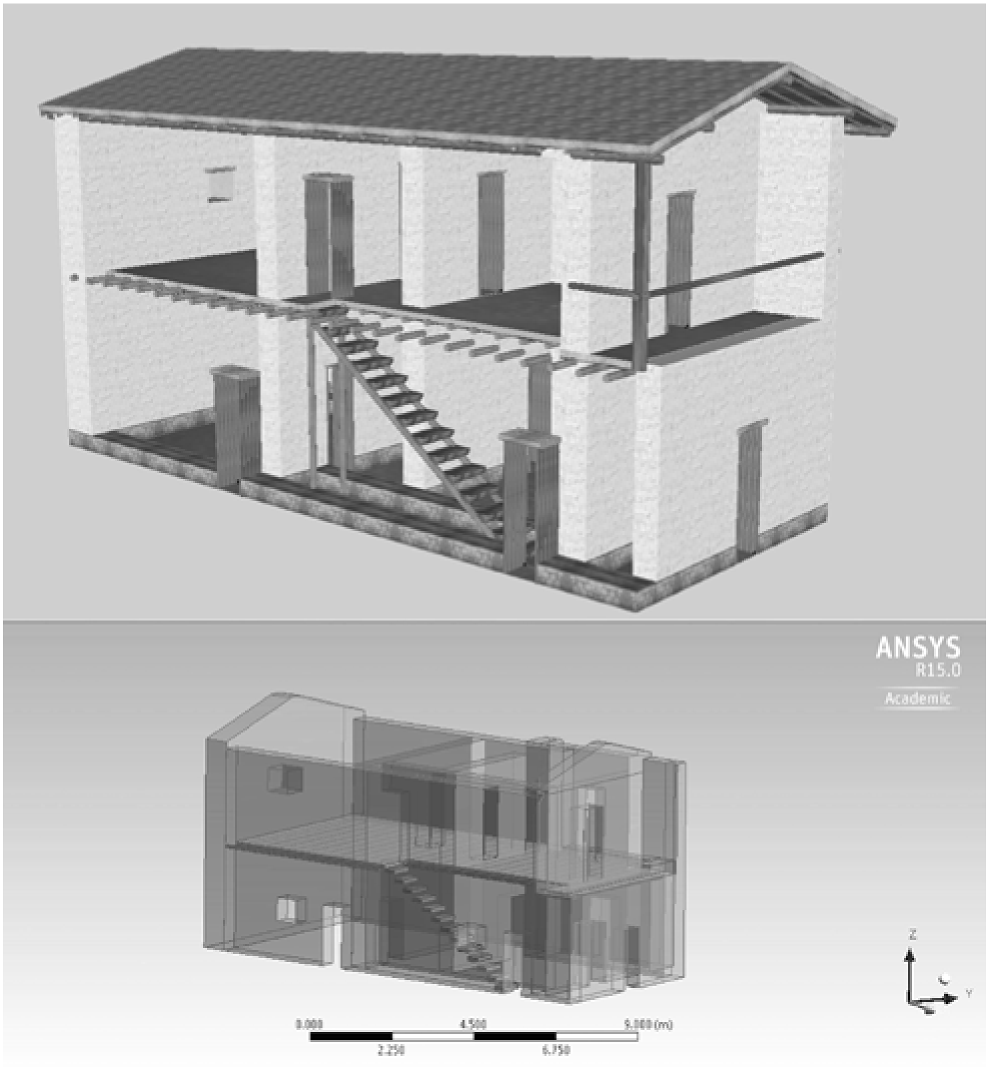


FIG. 5. TOP: VISUALIZATION OF THE 3D MODEL (WITH SOME WALLS REMOVED TO SHOW INTERIOR); BOTTOM: ANSYS MODEL WITH ROOF REMOVED.

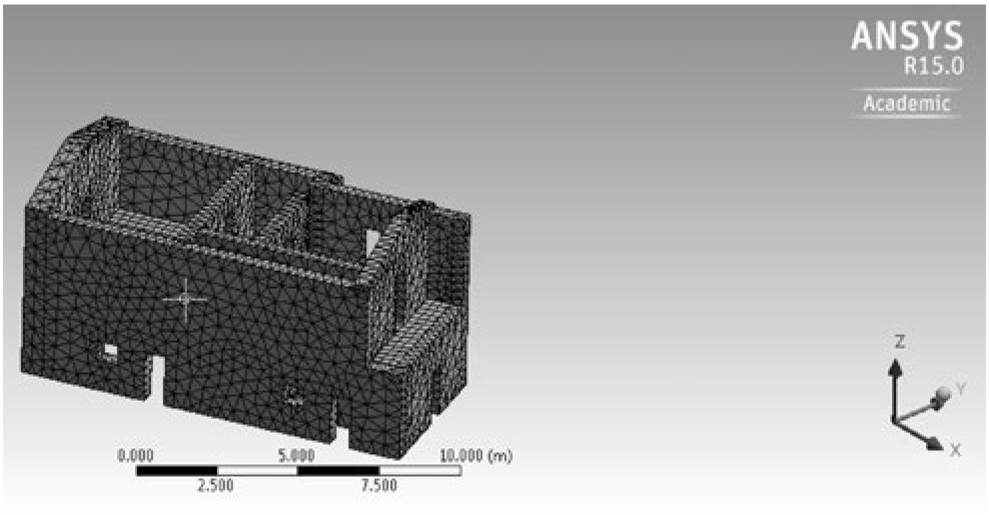


FIG. 6. TETRAHEDRAL MESHING OPERATION ON THE 3D STRUCTURE.

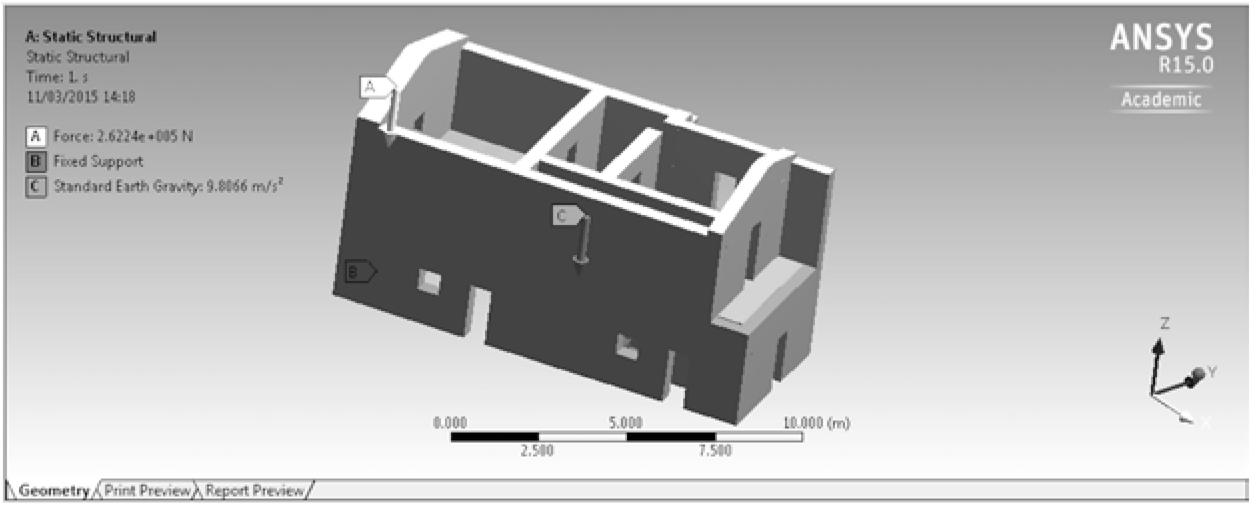


FIG. 7. LOAD SETUP SHOWING DOWNWARD FORCES ACTING ON THE SURFACES IN WHITE (A).

ANSYS. It is necessary to specify the bonding of various structures before the physically based simulation, that is, whether the various walls are allowed relative motion or not. In the simulations of the HCH we specified that all structures are bonded together and no relative independent motion is allowed.

Having imported the geometry, the mechanical *Model* is specified starting from meshing the 3D structure and assigning materials to their respective geometries. ANSYS has a range of meshing tools and mesh refinements to ensure simulations will accurately validate the physical model. We used tetrahedral meshing as depicted in figure 6. ANSYS has a 'physics preference setting' to ensure the most appropriate mesh is generated for each simulation. The size of each element of the mesh can be controlled by the user: the smaller the (finite) element, the more precise the answer, but the price to pay is that of higher computational costs.

In the *Setup* step the parameters of the analysis, namely all loads, forces and support acting on the structure are specified. Only a single compression force is required given as the total weight of the roof plus the live load. The weight of the roof is carefully calculated from the geometry of its various components using their respective densities. A live load is added equivalent to 1ton (~9,800N) to represent people and furniture, yielding a total downward force of 262,244N acting on the surfaces indicated in red in figure 7. Inertial forces were also included using the standard gravity acceleration, so the weight of the wall acting on every element is also taken into consideration. When considering compression forces due to weight integration effects, note that the bricks at the bottom of the wall near to the ground are placed under considerably higher compression than the ones touching the roof.

Finally, a fixed support is added to ensure that wall structures are fixed to the foundations and are constrained in all directions, that is, the bottom surfaces of the walls are not allowed to slide or move along the *x, y* or *z* axes. ANSYS then solves the analysis (the *Solution* step) using the Finite Element Method by applying the specified loads and constraints propagated to each

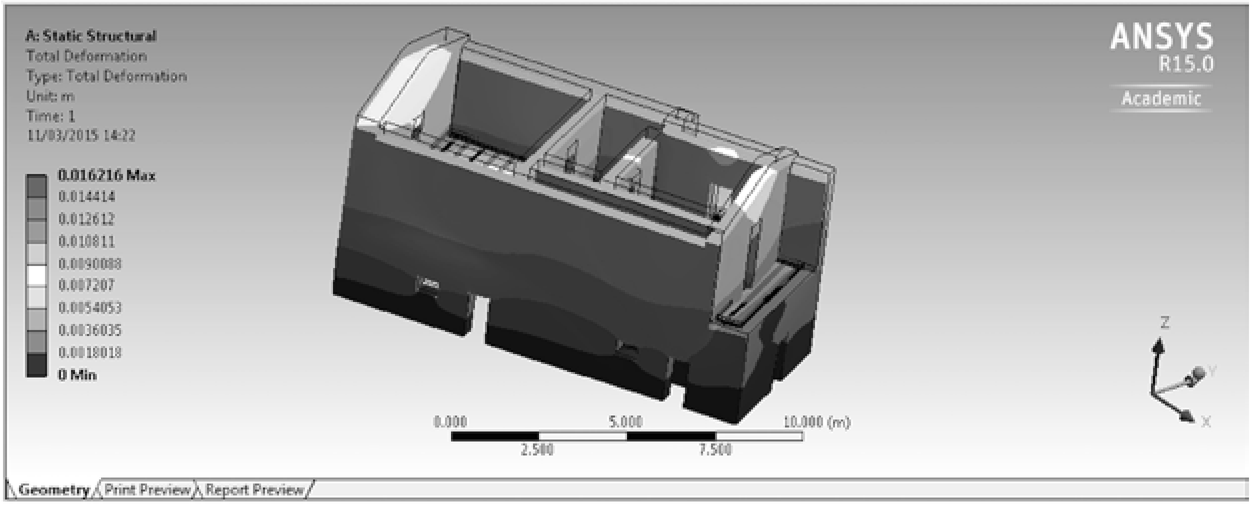


Fig. 8. Total deformation in static structural analysis (exaggerated for visualization).

element of the mesh and then integrating the results, which can be reviewed using a range of graphical tools and tabular formats. The results for total deformation from static structural analysis are depicted in figure 8. The maximum deformation for the applied load is 16mm. This would be difficult to show on a 6m tall wall, so the deformation relative to the original outline in figure 8 is exaggerated for the purposes of visualization.

Buckling analysis is used to determine the buckling loads, or the loads in which the structure becomes unstable (Hibbeler 2013). It is justified and widely used to test slender structures such as walls and columns. The technique seeks to determine the load level at which the structure becomes unstable, and this is achieved by gradually increasing the load. The classic Euler formulation for a column is defined as:where *F* is the allowable load, *n* is the number of end conditions, *E* is the modulus of elasticity, *L* is the length of the column, and *I* is the moment of inertia. At the onset of instability (buckling) the structure will have a very large change in displacement with no change in applied load. To estimate this condition, the linear buckling analysis predicts the theoretical buckling strength by solving for the load multiplier as a function of the applied load:where *K* and *S* are constant and the response based on the loading {} is a linear function of . The critical load specified through the load multiplier must be treated only as a prediction as the load multiplier is not a safety factor. In order to find the actual critical load, a non-linear analysis would be required. The research reported in this paper focuses on linear buckling only and thus, uses the load multiplier as a prediction of structure stability.

Simulations were performed on the HCH 3D model by including or removing various elements of its structure resulting in three relevant what-if scenarios as follows.

1. The house structure as defined by external and internal walls only.

2. The house structure with the addition of the upper floor components including the wooden structure, and the layers of reed and mud.

3. The house structure with the addition of the NNE long side stairway.

Figure 9 depicts the results of linear bucking analysis for the three cases considered. It can be seen that the weakest area of the house is the external wall of the corridor containing the staircase. The respective buckling load multipliers are 28, 30 and 39 where normally the higher the multiplier the more rigid and stable the structure. The simulations clearly demonstrate the relative importance of the stairs as a structural element as is evident in the highlighted areas of the model and by the change in load multiplier: by adding the upstairs floor, the multiplier goes from 28 to 30 but when stairs are added it goes from 30 to 39. Although these are rough predictions, it is clear that the structure would not collapse under the applied loads in normal circumstances – i.e., in the absence of large external disturbances such as an earthquake.

The interpretation of the results leads to the following assertions:

- The design inferred from the foundation walls is capable of supporting a second floor.

- The wall most susceptible to buckling is the outside wall to the stairs, along the NNE side of the house.

- The addition of the upper floor structure provides the HCH with the advantageous side effect of making the external NNE wall more rigid, and thus reducing the magnitude of buckling.

- The addition of the stairway makes the external NNE wall even more rigid and totally removes the probability of buckling on the ground floor.

- The designers have solved structural buckling issues by adding internal transverse walls at 90 degrees to the double NNE wall and to the west façade corridors, which made the structure more rigid and less susceptible to buckling. Instead of providing access to the second floor, these

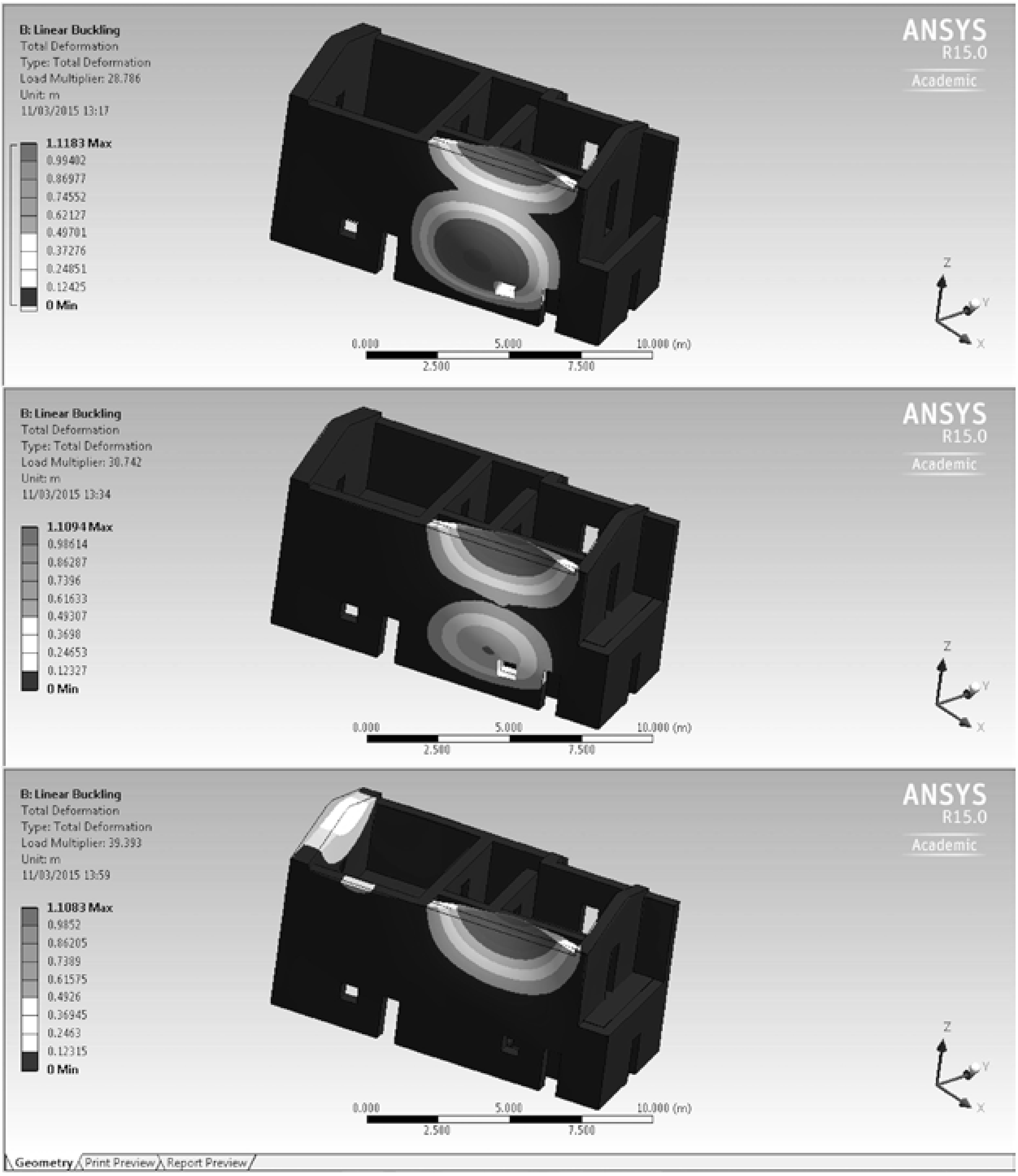


Fig. 9. Top: buckling of the HCH structure defined by the walls only; middle: buckling with addition of the upstairs floor; bottom: buckling with the addition of upstairs floor and stairs.

corridors may have accommodated supplementary rooms in the periphery of the ground floor and a more complex entrance, and had possibly supported one or more upper floor balconies.

- The wall on the south façade was built thicker than any other wall (700mm against 470mm and 400mm of other walls), which also has the effect of reducing its susceptibility to buckling. Had it been built with the same thickness as the other walls, our simulations show that it would be as prone to buckling as the NNE external wall.

4 Discussion and Conclusions

The present project has created a 3D model of the HCH from the measurements and plan inferred from its excavated foundation walls. The house plan was compared with the plans of corridor houses at Lerna and Aegina to enable interpretation of missing components. The model was exported as a 3D solid and loaded into ANSYS for structural analysis. All construction materials were carefully defined concerning their dimensions and respective mechanical properties, namely density, Young's modulus of elasticity, the Poisson ratio, compressive and tensile strengths. These parameters were used to perform finite element-based structural simulations to study the behaviour of the structure and to verify whether or not it would be able to support a second floor.

The models have proved that the modification of an earlier EH II rectilinear ground floor house into a corridor type of building by transforming its sides into the form of double walls or corridors to accommodate the stairway access to the upper floor and auxiliary peripheral rooms, would have met perfectly the structural prerequisites for the HCH to achieve increased space and a monumental height. The suitability of the assumed building materials has been validated by successful structural integrity tests for their loads under normal circumstances. A static structural model followed by linear buckling analysis revealed the areas of the building more susceptible to buckling. It however verified that linear buckling would not develop under the imposed static loads, and the structure would be able to support a second floor thanks to the added 'corridors' and more subtle architectural choices.

Our research points to the specialization of Helike builders on planning and creating architecture. It is interesting to note the number of similarities between the HCH and the 'Weisses Haus' at Aegina, and the 'House of the Tiles' at Lerna. The scale is intriguing: the 'Weisses Haus' is about 1.5 times larger than the HCH while the 'House of the Tiles' is twice as large. This scale applies to length, width, and wall thickness. The HCH measures 6.25x12.50m with wall thickness ranging from approximately 0.45-0.55m, 'Weisses Haus' 9x18.5m with wall thickness of 0.60m while the 'House of the Tiles' measures 12x25m with wall thickness of 1m. The analogy looks too coincidental and may suggest that the sites shared architectural plans as suggested by Shaw (2007) in terms of size and internal arrangements. This may also strengthen the argument for similar engineering practices and construction materials, as half the size would call for half as thick wall as observed in the three houses. The observation may also account for the scenario according to which the plan and building techniques were optimized and then re-used across the region.

The HCH project suggests rapid architectural changes and technological advances through modifications of an earlier design into a monumental corridor house. The employment of standardized architecture such as the corridor type structure at Helike and the broader EH region is the result of social changes such as the need for accommodating a rising number of residents, an administrative centre, an assembly hall, a kin group or communal storage place. Such a social context would lead to the development of larger households and other buildings for public use.

The EH settlement of Helike was destroyed by an earthquake accompanied by fire resulting in its immediate abandonment, leaving the contents of its buildings intact and sealed under mixed terrestrial, marine and lagoonal deposits. Further research will address the structural weaknesses of the adobe brick walls of the free standing, two storeys HCH to the effects of an earthquake (Varum *et al*. 2014) as well as palaeo-seismological data to determine the magnitude of the earthquake that would have been sufficient to destroy the house. These are working hypotheses to be tested in the next stage of our research.

Bibliography

Academia.edu. (2015). *Some Useful Numbers on the Engineering Properties of Materials (Geologic and otherwise)* Angle of Internal Friction. [Online] Available at: http://www.academia.edu/4156626/Some_Useful_Numbers_on_the_Engineering_Properties_of_Materials_Geologic_and_Otherwise_Angle_of_internal_friction [Accessed: 3 November 2014].

Adorni, E., Coisson, E., Ferreti, D. 2013. In situ characterization of archaeological adobe bricks. *Construction and Building Materials* 40, March 2013: 1-9.

Aravantinos, L. 1986. The EH II Fortified Building at Thebes: Notes on its Architecture. In Hägg, R. and Konsola, D. (eds.), *Early Helladic Architecture and Urbanization*. Göteborg, Paul Åströms - Förlag.

Barreca, F. 2012. Use of giant reed *Arundo donax* L in rural constructions. *Agricultural Engineering International, CIGR Journal* 14, 3: 46-52.

Cartwright, C. and Taylor, J. 2011. Investigating technological and environmental evidence from plant remains and molluscs in cuneiform tablets. *The British Museum Technical Research Bulletin* 5: 67-72.

Correal-Modol, E. 2012. Properties of clear wood and structural timber of *Pinus halepensis* from northeastern Spain. *World Conference on Timber Engineering*. Auckland, New Zealand.

Dowling, D. 2004 Adobe housing in El Salvador: Earthquake performance and seismic improvement. In I. Rose, J. J. Bommer, D. L. López, M. J. Carr, J. J. Major (eds.), *Geological Society of America Special Papers*: 281-300.

Goodrick, G. and Gillings, M. 2000. Constructs, simulations and hyperreal worlds: the role of Virtual Reality (VR) in archaeological research. In G. Lock and K. Brown (eds.), *On the Theory and Practice of Archaeological Computing* 51: 41-58. Oxford, Oxford University Committee for Archaeology Monograph.

Hägg, R. and Konsola, D. (eds.) 1986. *Early Helladic Architecture and Urbanization*. Göteborg, Paul Åströms - Förlag.

Harrison, S. 1995. Domestic Architecture in Early Helladic II: Some Observations on the Form of Non-monumental Houses. *British School at Athens* 90: 23-40.

Heath, M. C. 1958. Early Helladic Clay Sealings from the House of the Tiles at Lerna. *Hesperia* 27: 81-120.

Hejazi, M., Saradj, F. M. 2014. *Persian Architectural Heritage: Structure*. Southampton, WIT Press.

Hibbeler, C. R. 2013. *Mechanics of Materials*. N. J., Prentice Hall.

Houben, H. and Guillaud, H. 1994. *Earth Construction, A comprehensive guide*. Rugby Warwickshire, Practical Action Publishing.

Kalogerakou, P. 1999. 'Ta protoelladika II 'Oikodomimata me diadromous': protaseis gia ti leitourgia kai ti simasia tous' In I. Kilian-Dirlmeier (ed.), *Eliten in der Bronzezeit: Monographien des Römisch-Germanischen Zentralmuseums* 43: 87-101. Mainz.

Katsarou-Tzeveleki, S. 2011. Morphology and distribution of pottery at the Early Helladic settlement of Helike, Achaia. In D. Katsonopoulou (ed.), *Helike IV. Ancient Helike and*

Aigialeia. Protohelladika: The Southern and Central Greek Mainland: 89-126. Athens, The Helike Society.

Katsonopoulou, D. 1998. The first excavation at Helike: Klonis field. A preliminary report. In D. Katsonopoulou, S. Soter, D. Schilardi (eds.), *Helike II. Ancient Helike and Aigialeia*, Aigion, 1-3 December 1995: 125-45. Athens, The Helike Society.

Katsonopoulou, D. 2005. Test excavations in the Helike Delta in 2000. In D. Katsonopoulou, S. Soter, I. Koukouvelas (eds.), *Helike III. Ancient Helike and Aigialeia. Archaeological Sites in Geologically Active Regions*, Nikolaiika, Diakopton, 6-8 October 2000: 33-65. Athens, The Helike Society.

Katsonopoulou, D. 2011. A Proto-urban Early Helladic settlement found on the Helike Delta. In D. Katsonopoulou (ed.), *Helike IV. Ancient Helike and Aigialeia. Protohelladika: The Southern and Central Greek Mainland*: 63-86. Athens, The Helike Society.

Keefe, L. 2005. *Earth Building. Methods and materials, repair and conservation*. New York, Taylor and Francis.

King, B. 1996. *Buildings of Earth and Straw*. Vermont, Chelsea Green Publishing Company.

Koutsios, A. and Kontopoulos, N. 2011. Middle to Late Holocene Record of Environmental Changes in the Coastal Area of Helike, NW Peloponnese, Greece. In D. Katsonopoulou (ed.), *Helike IV. Ancient Helike and Aigialeia. Protohelladika: The Southern and Central Greek Mainland*: 185-98. Athens, The Helike Society.

Lawrence, K. L. 2012. *ANSYS Workbench Tutorial Release 14*. SDC Publications.

Lazarova, M., Koutsios, A., Kontopoulos, N. 2012. Holocene vegetation history of the Kotihi lagoon (northwest Peloponnesus, Greece). *Quaternary International* 261: 138-45. Elsevier.

Lock, G. 2003. *Using computers in archaeology. Towards virtual pasts*. London, Routledge.

Maran, J. 1998. Kulturwandel auf dem griechischen Festland und den Kykladen im späten 3. Jahrtausend v. Chr. Studien zu den *kulturellen Verhältnissen in Südosteuropa und* dem *zentralen sowie* östlichen *Mittelmeerraum in derspä*ten *Kupferund frühen Bronzezeit*. Universitätsforschungen zur prähistorischen Archäologie. Bonn, R. Habelt.

Maran, J. and Kostoula, M. 2014. The spider's web: innovation and society in the early Helladic 'Period of the Corridor Houses'. In Y. Galanakis, T. Wilkinson, J. Bennet (eds.), ΑΘΥΡΜΑΤΑ. C*ritical Essays on the Archaeology of the Eastern Mediterranean in Honour of E. Susan Sherratt*: 141-58. Oxford, Archaeopress.

Miles, J. 2014. Integration of laser scanning, photogrammetry and building surveying within the virtual reconstruction of Winchester Cathedral and its precinct buildings. *CAA 2014 Paris. Book of Abstracts.* [Online] Available at: http://caa2014.sciencesconf.org/conference/caa2014/pages/BOACAA_2016.pdf [Accessed: April 2014].

Ozkaya, K. 2013. Determination of some physical and mechanical properties of Calabrian pine (*Pinus brutia* Ten.) trees grown in the Denizli area of Turkey. *International Journal of Physical Sciences* 8, 46: 2063-8.

Palyvou, K. 2005. *Akrotiri Thera: An Architecture of Affluence 3,500 Years Old*. Philadelphia, INSTAP Academic Press.

Peperaki, O. 2004. The House of the Tiles at Lerna: Dimensions of Social Complexity. In J. C. Barrett And P. Halstead, *The Emergence of Civilisation Revisited* (ed.), *Sheffield Studies in Aegean Archaeology* 6: 214-31. Oxford, Oxbow.

Pullen, D. 2008. The Early Bronze Age in Greece. In C. W. Shelmerdine (ed.), *The Cambridge Companion to the Aegean Bronze Age*: 19-46. Cambridge, Cambridge University Press.

Pullen, D. J. 1986. A 'House of Tiles at Zygouries'? The function of monumental Early Helladic architecture. In R. Hägg and D. Konsola (eds.), *Early Helladic Architecture and Urbanization*: 79-83. Göteborg, Paul Åströms Förlag.

Ruano, A., Costa, A. G., Varum, H. 2012. Study of the common pathologies in composite adobe and reinforced concrete constructions. *Journal of Performance of Constructed Facilities* 26 4: 389-401. doi 10.1061/(ASCE)CF.1943-5509.0000200.

Shakya, M., Varum, H. Vicente, R., Costa, A. 2012. Structural Vulnerability of Nepalese Pagoda Temples, *15 World Conferences on Earthquake Engineering*. Lisbon. [Online] Available at: www.iitk.ac.in/nicee/wcee/article/WCEE2012_2919. [Accessed: 28 October 2014].

Sharpe, W. N. (ed.) 2008. *Springer Handbook of Experimental Solid Mechanics*. Heidelberg, Springer.

Shaw, J. W. 1987. The Early Helladic II Corridor House: Development and Form. *The American Journal of Archaeology* 91: 59-80.

Shaw, J. W. 1990. The EH II 'Corridor House': problems and possibilities. In P. Darque and R. Treuil (eds.), *L'Habitat* égéen *préhistorique BCH* 19: 231-54. Paris.

Shaw, J. W. 2007. Sequencing the EH II Corridor Houses. *British School at Athens* 102: 137-51. Athens.

Soter, S. and Katsonopoulou, D. 2011. Submergence and Uplift of Settlements in the Area of Helike, Greece, from the Early Bronze Age to Late Antiquity. *Geoarchaeology* 26 4: 584-610.

Spatz, H. C., Beismann, H., Bruchert, F., Emanns, A., Speck, T. 1997. Biomechanics of the giant reed *Arundo donax*. *The Royal Society* B, 352: 1-10. London.

THE WOOD DATABASE. (2008) [Online] http://www.wood-database.com/lumber-identification/hardwoods/olive/. [Accessed: 10 February 2015]

Walter, H. and Felten, F. 1988. *Alt*-Ägina *Felten III.1: Die vorgeschichtliche Stadt: Befestigungen, Häuser, Funde.* Mainz, Verlag Philipp von Zabern.

Themelis, P. G. 1984. Early Helladic monumental architecture. *Athenische Mitteilungen* 99: 335-51.

Wiencke, M. 2000. Lerna, a Preclassical Site in the Argolid; The Architecture, Stratigraphy, and Pottery of Lerna III. *Results of Excavation by the American School of Classical Studies at Athens* 4. Princeton.

Wiencke, M. 1989. Change in Early Helladic II. *American Journal of Archaeology* 93: 495-509.

Wiersma, C. 2013. *Building the Bronze Age. Architectural and Social Change on the Greek Mainland During Early Helladic III, Middle Helladic and Late Helladic I.* Oxford, Archaeopress.

Varum, H., Figueiredo, A., Silveira, D., Martins, T., Costa, A. 2011. Outputs from the research developed at the University of Aveiro regarding the mechanical characterization of existing adobe constructions in Portugal. *Informes de la Construcción*: 63, 523: 127-42. doi: 10.3989/ic.10.016.

Varum, H., Tarque, N., Silveira, D., Camata, G., Lobo, B., Blondet, M., Figueiredo, A., Rafi, M. M., Oliveira, C., Costa, A. 2014. Structural Behaviour and Retrofitting of Adobe Masonry Buildings. In A. Costa *et al*. (eds.), *Structural Rehabilitation of Old Buildings*. *Building Pathology and Rehabilitation* 2: 37-75. Heidelberg, Springer-Verlag.

Zanne, E., Lopez-Gonzalez, G., Coomes, A., Ilic, J., Jansen, S., Lewis, L., Miller, B., Swenson G., Wiemann, C., Chave, J. 2009. Global Wood Density database. *Dryad Digital Repository.* [Online] Available at: http\://dx.doi.org/10.5061/dryad.234. [Accessed: 8 November 2014].

Discovering Prehistoric Ritual Norms. A Machine Learning Approach.

Stéphanie Duboscq[(1)]
duboscqstephanie@gmail.com

Joan Anton Barceló Álvarez[(2)]
juanantonio.barcelo@uab.cat

Katia Francesca Achino[(2)]
katiafrancesca@libero.it

Berta Morell Rovira[(2)]
morell.berta@gmail.com.

Florence Allièse[(3)]
florence.alliese@gmail.com

Juan Francisco Gibaja Bao[(4)]
jfgibaja@imf.csic.es

[1] Departament de Prehistòria, Universitat Autònoma de Barcelona
[2] Quantitative Archaeology Lab (LaQu). Departament de Prehistòria, Universitat Autònoma de Barcelona
[3] Université de Paris 1 Panthéon-Sorbonne, UMR 7041
[4] Institución Milà y Fontanals - Consejo Superior de Investigaciones Científicas (IMF-CSIC), Grupo Agrest and Icarehb

Abstract: In this paper we propose a computational approach, based on the application of supervised learning techniques, in order to understand prehistoric funerary practices. In particular we focus on the understanding of relevant ritual patterns from North-Eastern Iberian Peninsula Middle Neolithic burials.

We compare standard statistical multidimensional approaches with machine learning methods based on a supervised learning approach in which the relevant category to be formally induced is the sex of the individuals. Different analysis will be explored, as Cluster and Correspondence analysis and Decision Trees to show how we can define social norms in the archaeological record based on detecting relevant differences between controlled categories. Of special relevance for our purposes is the comparison between 'classical' Confirmatory Factor Analysis of burial similarities and the machine learning approach to conceptual induction.

Keywords: Funerary practices, Ritual Patterns, Statistics and Supervised Learning, 'Sepulcres de Fossa'.

Introduction. Archaeological problem solving as reverse engineering

Archaeologists usually deal with the so-called 'reverse problems'. This means that our aim is to infer the causal mechanisms that produced the observable archaeological record from their preserved material traces. For instance, the broken sherd of animal bone of species S, with shape X that we have found at the location Z may be produced by hunting practice. Nevertheless, we have to take into account that various social actions carried out during the past can lead to the same material result. In light of this fact, our reconstruction assumes a probabilistic nature, since we cannot observe the past directly. The only chance we have to solve the archaeological problem is relying on the observed regularity of material outcomes of social action and using it in a heuristic way to build an input-output mapping. In this condition, the initial state of the problem is the input (archaeological description of a material consequence of a social action) and its solution (the causing social action) will be the output. This task is best described as inverse/reverse engineering (Hensel 1991; Kirsch 1996; Woodbury 2002; Sabatier 2000; Pizlo 2001; Kaipio and Somersalo 2004; Barceló 2005; Tarantola 2005; Bunge 2006; Barceló *et al*. 2015). In particular, in our case study we have been dealing with the possibility to identify ritual patterns whereby the analysis of material evidences recovered in the archaeological record; in other words, we are trying to reconstruct the ritual (output) through the presence/absence and variability of some known variables (such as sex of individuals, grave goods, funerary structures etc.) (input) attested in certain archaeological context. However, the available information does not allow reconstructing the entirety of the ritual. Only the subset of ritual norms carried out during the past in a repetitive way has left traces in the archaeological record. In this paper we focus on the Middle Neolithic burials so-called 'Sepulcres de Fossa' from the northeast of the Iberian Peninsula; we intend to detect the possible existence of ritual norms at a global, cultural scale, whereby the analysis of similarities at a macro-scale.

1 The archaeological context of 'Sepulcres de fossa'

In the NE of the Iberian Peninsula, Neolithic was a long period that lasted from the middle sixth to the third millennium cal. BC. Except for the Early Neolithic (second half of the sixth - first half of the fifth millennium cal. BC), habitat structures are almost unknown: they were very affected by natural and anthropogenic erosion, unlike the negative structures that are the graves, on which we have focused in this work (Gibaja 2004; Roig Buxó *et al*. 2010: 60).

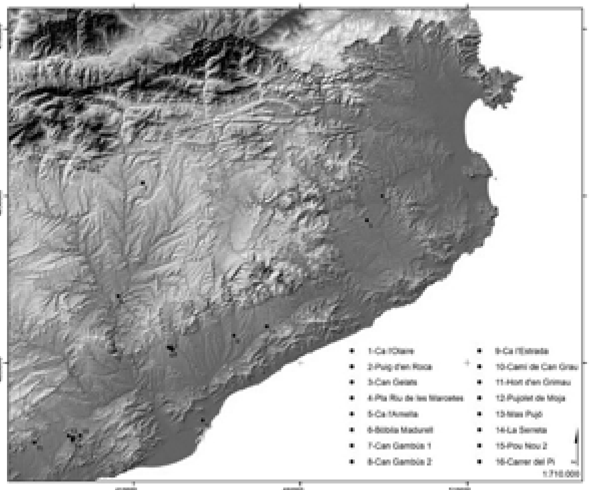
Regarding the economic context, herding and agriculture were main activities of the society. Harvesting was still an important activity (Antolín and Jacomet 2015), whereas hunting become unusual (Antolín *et al*. 2014; Gibaja and Clop 2012; Saña Seguí 1998).

For this study and in order to infer ritual practices, we have focused on the Middle Neolithic (late fifth - early fourth millennium cal. BC), because the Early Neolithic funerary practices were not well known, particularly because there is not a lot of evidence.

The Middle Neolithic was marked by the culture of the 'Sepulcres de Fossa' characterized by burials often individuals, sometimes doubles or plurals. They were usually carried out in a funerary purpose, although in some cases they could be a reuse of silos or pits (i.e. Pujolet Moja or Hort to Grimau, Alt Penedès, Barcelona: Mestres Mercadet *et al*. 1997; Mestres Mercadet 1988-89; some structures of Bobila Madurell: Martín *et al*. in press). These graves did not correspond to a homogeneous morphological model but showed structural differences. Some of them were simple pits dug in the ground; others were sealed on the top by flagstones, pebbles or perishable materials such as trunks. Some certainly had a kind of signalling system of the tomb; others were monumental structures, consisting of a lateral access and burial chambers. Finally, this culture also embraced quadrangular, trapezoidal or rectangular cists (Gibaja 2004; Roig Buxó *et al*. 2010). During this period also the emergence of a few large necropolis as San Pau del Camp (Quarhis 2008), Camí de Can Grau and Bòbila Madurell-Can Gambús (Barcelona) was attested.

The individuals buried in these tombs were men, women and children, generally accompanied by grave goods that varied in quantity and quality. Some structures contained little furniture, but normally the stone tools were numerous, as well as ceramics, bone industry and ornaments.

Some graves had furniture that stands out, such as 'bocca quadrata' pottery (Bernabò Brea, 1946) with probable Italian and / or Chassey influence (Clop and Alvarez 2009), stone tools developed on allochton rocks, as blond flint that would come probably from the SE of France, very few cases of obsidian from Sardinia and some axes coming from Alpes (Vaquer and Léa 2011; Terradas *et al*. 2014; Gibaja *et al*. 2014; Vaquer *et al*. 2012).



Hort d'en Grimau: E1-E2; **La Serreta:** E60-E5; **Mas Pujó:** E14-E16; **Pujolet de Moja:** E25-E26-E27; **Pla del Riu de les Marcetes:** 5-6-7; **Ca l'Oliaire:** E6; **Ca l'Arnella**: CCA2-CCA3; **Ca l'Estrada:** SF501; **Camí de Can Grau:** CCG19-20-23-26-30-33-48-53 ; **Can Gambús 1:** E70-110-111-113-115-116-122-130-137-161-162-163-166-167-175-176-179-180-184-186-208-221-223-243-246-441-442-516-532-534-664-665-668-693
Can Gambús 2: UF1-UF16; **Bòbila Madurell:** G5-G9-G10-G12-G13-G17-G18-H10-11.4-M8-M9-M11-M25-7.7-B6-B16-MS8-MS16-MS20-MS69-MF3-MF10; **Can Gelats:** EF3; **Carrer del Pí:** Ind.1-ind.2; **Pou Nou 2:** E3; **Puig d'en Roca:** 5-16.

Fig. 1. Localization of the settlements.

Among the most interesting aspects of this group, the similarities with other contexts with same chronology in Europe, as Chassey in France, Cortaillod in Switzerland or Lagozza in the North of Italy stood out. Although the archaeological phenomenon under study transcended regional scale, in this paper we are going to focus only on the NE of the Iberian Peninsula.

2 The case-study

2.1 The Sample

As we stated before, our objective is to document possible ritual patterns through the analysis of material evidences from the archaeological context of 'Sepulcres de Fossa': a sample of the sites belonging to this group has been analysed. The structures that we chose for our case-study had been dated in the frame of a project of investigation led by the IMF-CSIC: 'Aproximación a las primeras comunidades neolíticas del NE peninsular a través de sus prácticas funerarias'. The period covers slightly more than a millennium (4th-5th millennium cal BC), and the dating was carried out on human bones. We are working with a total of 84 individuals: 55 males and 33 females, divided into 16 sites, in an area of approximately 93000m^2 (Fig. 1).

We present here only the information coming from individual graves; since in the double and plural burials it is generally difficult to assign grave goods to one individual, we have decided to exclude them. Later, they will require a specific analysis. We have also observed only the information associated with sexed individuals, which are all adults, considering that in this special case we have worked with the variables of sex and grave goods.

Regarding the funerary pits, we have decided to exclude those with missing information or from sites excavated in the first half of the twentieth century. The information obtained from these old excavated structures was often incomplete or approximate, or it just disappeared. In other cases, we were in the presence of badly preserved structures, as having suffered from erosion, agricultural or former looting activities. This damage often involved a displacement of the skeleton, its partial or total alteration, or expulsion of the structure. The grave goods could also be partially or totally lost. Regarding the individuals themselves, they were often poorly preserved, which made it difficult to attribute gender and age, as well as observation of possible pathologies or markers of activities. We have also decided to remove certain suspicious structures, in general whose funeral purpose was not certain or if the number of individuals could not be determined reliably. Furthermore, there was also a lack of dating for many burials: few C14 dating was available, and they were realized on artefact or ecofact samples discovered in the burial and not on the individual itself.

Thus, this analysis started with the only dated burials, although it was a short sample of all available data. Indeed, we have considered that a defined temporal scale could be useful to start the first statistical tests, due to the above mentioned issues related to the archaeological evidence.

2.2 Definition of the variables

In addition to the sex of the individuals, we have used the grave goods as variables for our analysis. These grave goods were objects or perishable materials left to the dead when they had been buried. An eventual recurrence in the type of objects and in their disposition in the tomb could indicate a funerary practice in a specific community. Thus, we have created a database that listed all the preserved artefacts associated with the dead; among them, we have chosen to focus on some particular markers. We divided them into 3 main categories: ceramic vessel, lithic artefacts and faunal remains. For each category, the artefacts are organized as we can see in the table (Fig.2). The presence of 'Bocca Quadrata' pottery as well as the blond flint and the obsidian have suggested long-distance relationships and communication network. They are demonstrated as distant origin of some artefacts or raw material (like obsidian and blond flint) or the cultural transmission of ideas and traditions (such as, probably, in the case of the vases 'bocca quadrata').

2.3 How can we infer a ritual pattern from this special case-study?

In our modern western society, *rite* or *ritual practice* has often been associated to an established, sacred or religious act (Smith 2010: 630). However they cannot be restrained to these aspects.

French ethnographer and folklorist Arnold Van Gennep (1873-1957) was the first to make an important contribution to the study of rituals with the identification of the so-called 'rites of passage' (Van Gennep 1909). Since the 1960s, authors like V. W. Turner (1920-1983) sought for the expressions of sociological and psychological functions of rituals (Turner 1953).

Ceramic Vessel: "Bocca Quadrata" Ceramic and No "Bocca Quadrata" ceramic.

Lithic Artefacts: Blond Flint blades, Obsidian blades, Flint blades, Blond flint flakes, Flint flakes, Blond flint geometrics, Flint geometrics, Blond flint arroheads, Flint arrowheads, Blond flint cores, Quartzite cores, Mill element, Axes, Stone, Blond flint knapped, Variscita beads, Talc, Black stone and Shist muscovite.

Fauna Remains: Awls, Spatulas, Tablets, Phalanx/Metapodials, Bone beads, Malacofauna, Fauna, Tusks and Horns.

Fig. 2. Artefact categories.

Due to diverse nature of the rite, defining this term is not easy, but according to Jean-Pierre Albert and Albert Piette, it could be described as a sequence of actions pragmatically unjustifiable: « le rite est une séquence temporelle conventionnellement définie comportant au moins un acte élémentaire de nature rituelle, c'est-à-dire appris, stéréotypé, sans cohérence pragmatique avec son contexte, qui en tant que moyen est supposé avoir sur la fin visée une action empiriquement non certifiable.» (Albert and Piette 2010: 1104-5).

P. Smith (2010: 632) defines four dimensions that must be kept in mind when working with the notion of *rituals*. First, he distinguishes the *periodic* rites, linked to a calendar and to a community (i.e. seasonal rites) or to biological events and then to the individuals (i.e. birth, death). On the contrary, the *occasional* rites are related to special events and can also concern the community (i.e. drought, epidemic) or the individuals (i.e. illness).

He insists on remembering these four dimensions when analysing rituals: the society and the individual as well as the recurrence and the singular occurrence.

To resume, rites are collective and codified practices that may be repeated at regular rhythms or be associated with occasional occurrences. They can contribute to forge the identity of a community, to build a collective memory and to set up social norms. They may be cultural creations, particularly elaborated and part of the social life.

In an archaeological perspective, we have ruled out the possibility of exploring the occasional occurrences, since their traces have hardly been preserved. On the contrary, we may explore the practices that implied repetitions. Higher is the frequency of their performance, higher is the possibility that they can leave traces in the archaeological record.

In this paper we enlighten funerary rituals: they may be realized with the aim to tame the death, resolving the *future* of the dead (that is what to do with the body and also how to situate the deceased in the group) and supporting the survivors. In fact, funerary rituals would be only addressed to the livings (Thomas 1985: 120-1; Leclerc 1990: 4). Archaeologically, repeated ritualized practices involving the dead body may translate into recognizable patterns, in the temporal frequency of mortuary features.

However, we should not forget that the observation of archaeological evidences is limited to the preserved materials (i.e. the skeleton and the grave goods in non-perishable material). Indeed, organic residues may have disappeared as well as attributes of immaterial practices (such as ceremonies, songs, dances, etc.). Therefore, an eventual absence of ritual pattern in the observation of funerary contexts would not mean an absence of ritual; but might correspond to practice(s) that have not left archaeologically observable traces, as the above mentioned occasional once.

How can we infer ritual practices from our special case study?

3 Methodology

3.1 Theoretical background

The actions that took place during the past left traces in the archaeological record, as material evidences. The repetition of these actions might produce the so-called 'archaeological pattern'. As we mentioned above, in the case of funerary practices the same mechanism could work. Whether this is the case, we can study these ritual patterns through the analysis of the resemblance (Barceló, 2010; Achino *et al.*, in press). Resemblance is defined in terms of properties or characteristics shared by two or more entities. Two entities are similar because they share some properties, so the resemblance between two or more objects depends on the parameters whereby we compare them. Different set of variables lead to apparently different 'resemblances'; it depends on the context. Our goal is to analyse the ritual pattern quantifying the similarities between the burials. In broad terms, similarity could be defined from a symmetrical or asymmetrical point of view (Vosniadou and Ortony 1989). According to the first perspective, similarity is defined as the measure of resemblance, what corresponds to the number of elements shared by two or more entities. The higher this number is, the higher the similarity. Contrary to this definition, from an asymmetrical point of view the mathematician Tversky (1977) argues that similarity is not only a function of shared characteristics, but it also depends on the characteristics that are unique to each object. However, despite this the model seems to be more realistic, yet it still does not have a statistical application. Therefore in this work we analysed the similarity in symmetrical terms; i.e. we only took into account the shared variables between the different burials.

Traditionally, the statistical analysis of ritual patterns under this perspective has been realized evaluating all variables as equally valued. This means that the burial is considered as a close context and the associated variables as independent between them. Furthermore, whether the relationships are considered, they are limited to only certain variables, such as architecture or grave goods.

In our case-study at first we tested this classical approach through a cluster analysis. It can be defined as the task of grouping a set of objects in a sample according to their similarity; the objects in the same group (cluster) are more similar (in some sense or another) to each other than to those in other groups. Whereby a hierarchical clustering, applied in this context, the objects are connected between them to form clusters based on their distance. The variables are joined together in hierarchical fashion from the closest, i.e. the most similar, to the furthest apart, i.e. the most different. The derived matrix of distances provides the actual distances, which reveals the similarities computed for any pair of observations and variables. It is graphically represented by a dendrogram or tree that lists all samples and indicates at what level of similarity any two clusters were joined.

Since we are studying qualitative variables (as grave goods, sex, age, architecture, etc.) we in particular applied the Jaccard index (Jaccard 1912). It is a statistic used for comparing similarity and diversity of sample sets and it is also known as the Jaccard similarity coefficient. The problem of this type of analysis is that they build classes of similar categories without discerning the resemblance. The results of the clustering analysis only confirmed the extreme width variability of the data, but do not shed light on our archaeological issues.

Furthermore, in order to explore the associations between our set of categorical variables we performed a correspondence analysis (Bénzécri 1973). It is a descriptive and exploratory technique designed to analyse tables containing some measure of correspondence between rows and columns. The results provide information that allows the exploration of the structure of categorical variables included in the table, summarised in a set of data in two-dimensional graphical form. Nevertheless, its application in our case-study confirmed the results provided by the clustering analysis.

In light of this outcome and in order to obtain a deeper understanding of our archaeological data, we decided to apply a different approach based on machine learning.

3.2 Machine Learning Approach

We could define 'learning' as a wide range of situations in which someone or something increases their knowledge or skills to accomplish a task. Different mechanisms of learning exist: imitation, introduction of innovations, interchange of knowledge and teaching, for example. Machines can 'learn', in the same way as children and adults. There are two main types of computational learning: non-supervised and supervised (Thorthon 2002; Douglas *et al*. 1991; Moreno Ribas, Armengo Voltas, Bejar Alonso 1991). The former consists of algorithms which develop new knowledge through the discovery of regularities in data (data-driven). On the other hand, supervised learning is similar to learning with a teacher. These kinds of algorithms need examples provided as input in order to meet the learning goals. Thereafter they solve problems making decisions based on their experiences – cases resolved earlier – to improve their performance from a probabilistic point of view. In this case, learning is equivalent to experiment analysis: generalising some individual instances where the explicit relationship *explanans-explanandum* is already known. This is what has traditionally been called inductive reasoning. Once the examples have been provided to the machine, solving the inverse problem is no more than making a probabilistic causal inference, such as 'If A, then B', based on the above cases.

In our case-study we focused on supervised learning in order to analyse the similarity relationship between the different variables. Specifically we used the C4.5 and ID3 Decision Trees algorithms. Decision Trees are predictive algorithms used in the field of Artificial Intelligence. These algorithms build logical construct diagrams from a database to represent and categorize a series of conditions occurring in succession and in order to solve a problem. Decision trees are based on some entrances, which can be an object or a situation described by

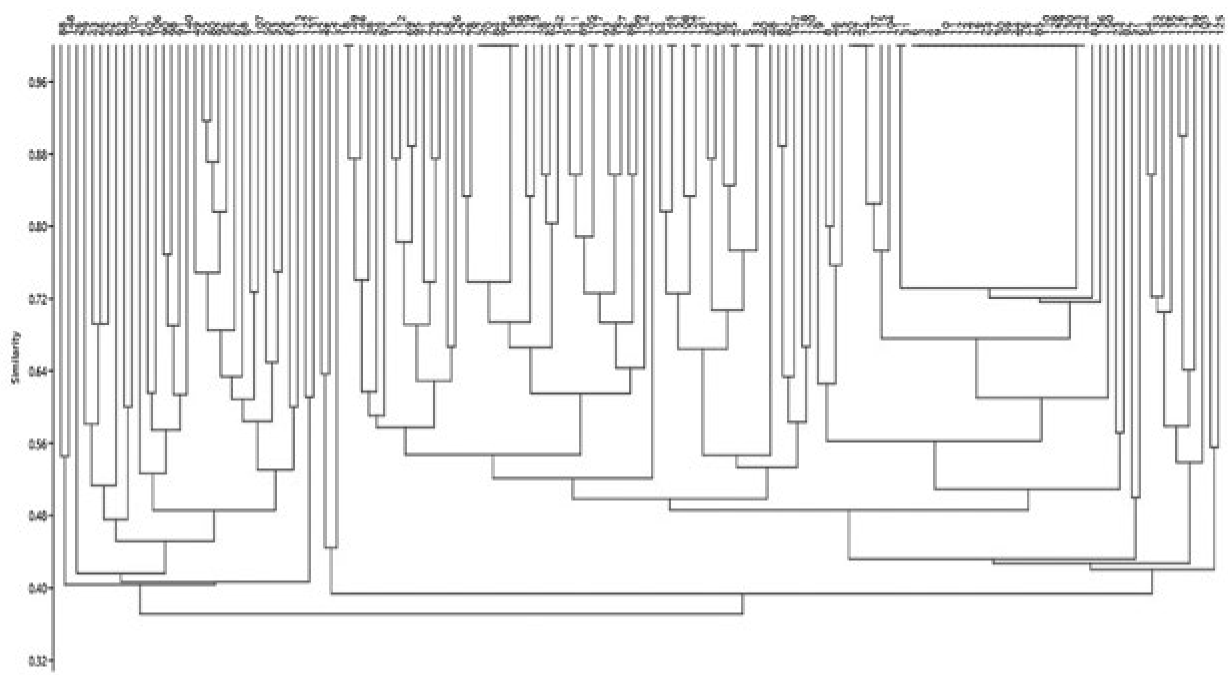


Fig. 3. Hierarchical clustering analysis using the Jaccard Index. The 'y' axis shows the value of similarity in the Index between the qualitative variables related to each analysed grave ('x' axis).

a set of attributes. From this, the algorithms return a response, which ultimately is a decision that is taken from the entries. The values that can take the inputs and outputs can be discrete or continuous values. From here, the decision trees perform a test as this is walking towards the leaves to reach a decision in this way, in order to obtain the optimal course of action.

In this paper we explored in particular the ID3 and C4.5 Decision Trees Algorithms. They were invented by Ross Quinlan (1986; 1993) and they work according to a similar mechanism. However, the ID3 was precursor to the C4.5 algorithm. From an original training dataset S (group S with examples already qualified), on each iteration of the algorithm, it selects the attribute that has the smallest entropy value H(S) or the largest information gain IG (A). Sub-lists of the dataset S are created according to a selection of the attribute with minimum value of entropy using split function. In other words, the attribute with the highest normalized information gain is chosen as decision parameter. Furthermore, the C4.5 algorithm showed a number of improvements to ID3. For instance, it allows the introduction of training data with missing attribute values marked as '?'. They are simply not used in gain and entropy calculations. Moreover, the attributes can be handled in the model with differing costs. Finally, after the trees are built, the algorithm removes branches that do not help by replacing them with leaf nodes.

Then we explored the methodological possibilities of supervised learning algorithms to recognize patterns, using generalized association rules. To carry it out we worked with the WizWhy program (http://www.wizsoft.com/index.php/products/wizwhy). This is an innovative data mining software that reveals patterns, trends and summarizes data. In particular, it reveals interesting phenomena in the data (unexpected rules), points out unexpected cases for auditing purposes and issues predictions for new cases. At the first stage WizWhy applies an association-rules algorithm that reveals all the if-then and if-then-not rules. From here the program is able to develop predictions about new cases based on the above ones.

4 Results

In order to explore the possibility of reconstructing ritual patterns, whereby the analysis of particular variables found in a selected samples of Neolithic 'Sepulcres de Fossa' from the NE of Iberian Peninsula, some statistical analysis were performed. First of all, with the aim to explore the similarity/dissimilarity between qualitative variables, we applied a classical approach based on the hierarchical clustering analysis with the use of the Jaccard index. The results showed an extremely wide variability of ritual patterns as observed in figure 3. Indeed, the dendrogram indicates the presence of many clusters with a large inter-site distance (in particular from 0.56 in the y-axis) which joined few variables. The majority of clusters identified in the graph display such relationships between variables. This scenario, therefore, does not clarify our archaeological data.

Consequently, a correspondence analysis was performed, hoping that the associations between our set of categorical variables could be highlighted. However, the result confirmed the extreme data variability (Fig.4). Through the statistical perspective, the results do not show a significant pattern. Indeed, the variables are not distributed according to a specific model, otherwise they are distributed around all the analysed region. Thus there are not significantly strong relationships between two or more variables.

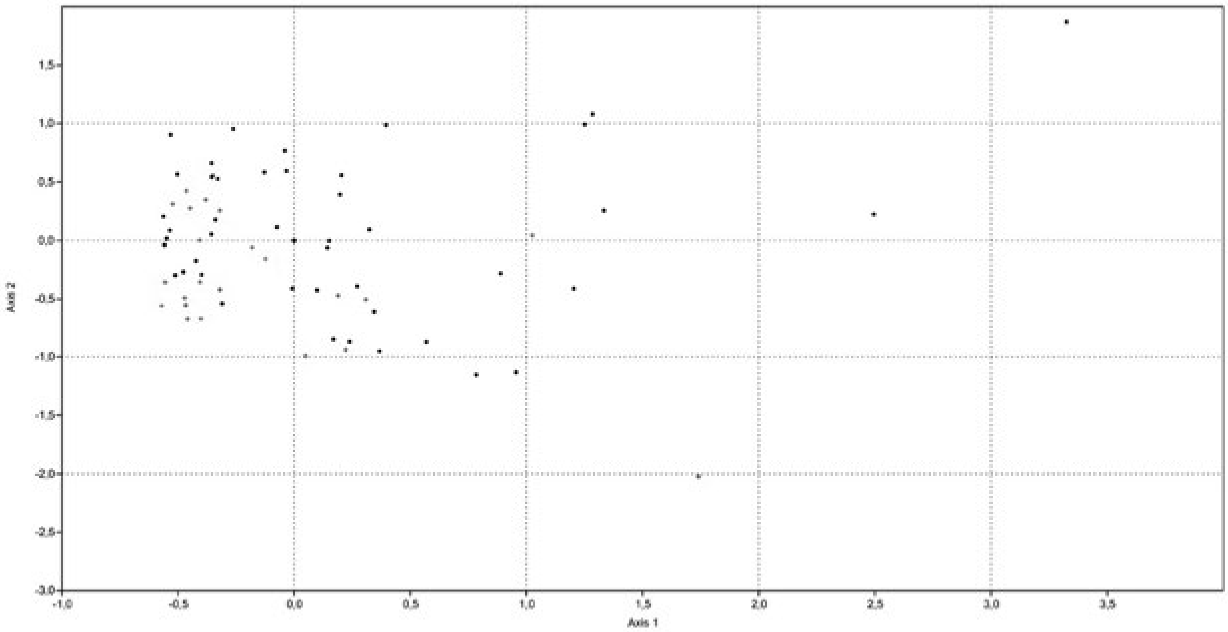


Fig. 4. Correspondence Analysis. Men (cross) and Women (point). The spatial distribution of the studied burials by sex is represented in the Axis 2 (women in black and men in grey). Axis 1 represents the distribution of the shared artefacts between the different burial grave goods.

This extremely variability did not allow us to explain the data so we decided to introduce a machine learning approach. In particular we tested the methodological possibilities offered by decision trees algorithm. We used the C4.5 and ID3 algorithms that we have above explored.

In order to perform this analysis we used the Tanagra-Sipina software (Tanagra: http://eric.univ-lyon2.fr/~ricco/tanagra/. Sipina: http://eric.univ-lyon2.fr/~ricco/sipina.html). First of all we built a decision tree through all the variables. As we can observe in the graph (Fig. 5) also this analysis confirms the strong variability of the data. However the most relevant percentage is associated with geometrics flint. Our data show that in less than 0.5% of the cases the geometrics are associated with men in 54% of the sample and with women in 46%. On the contrary, in more than 0.5% of the cases, the geometrics are only associated with men. This assumption has already been observed by one of the authors (Juan Gibaja). In his doctoral thesis (Gibaja 2002) he noticed that in the necropolis of Bòbila Madurell and Camí de Can Grau geometrics were well represented and more often associated to men, in a context where hunting is no longer a dominant activity. Moreover, it seems that many of these artefacts where not used before being deposited in the grave, or at least that they were repaired. Did they have a more symbolic than utilitarian function? (Palomo and Gibaja 2004)

Only in the case of male individuals we can observe a recurrence of some archaeological markers (such as mostly geometric flint, and also arrowheads and axes) although their percentages are not statistically significant.

Finally, as mentioned above, through the Wizwhy software we have tried to infer ritual patterns. The most statistically significant rules that the software found were generally the same recognized through the decision trees. First the software calculated the statistically significant patterns in the database taking sex as a dependent variable. As in the previous cases, the software only considered the presence of geometric associated with male individuals as a more or less significant pattern. The second step would have been trying to predict new cases (the sex of indeterminate individuals, for example) thanks to the previous cases. The absence of statistically significant patterns, however did not allow us to do it.

5 Discussion: what reflects this lack of visibility of ritual patterns?

The aim of this research was to explore and explain the material evidence of the ritual pattern preserved in the archaeological record of 'Sepulcres de Fossa'. This means that we could only explore a fragmented part of the funerary practices' integrity. However, if we cannot observe an archaeological ritual pattern through this limited sample, it does not mean that it did not exist. Perhaps it is caused by different reasons, linked to grave goods or the structure itself. For example, the architecture of the tomb (some of them are simple pits but others are very complex structures, with access and chamber) could testify to specific funerary practices. Furthermore, the way the deceased was buried (decubitus supino, decubitus prono, foetal position, etc.) could be a part of the ritual practice. Therefore in the future, to present a more complete investigation about ritual pattern, we should also take into account these elements.

Moreover, some ritual behaviours might not leave traces on the archaeological record, for taphonomical reasons or due to the immateriality of some activities, such as ceremonies for instance.

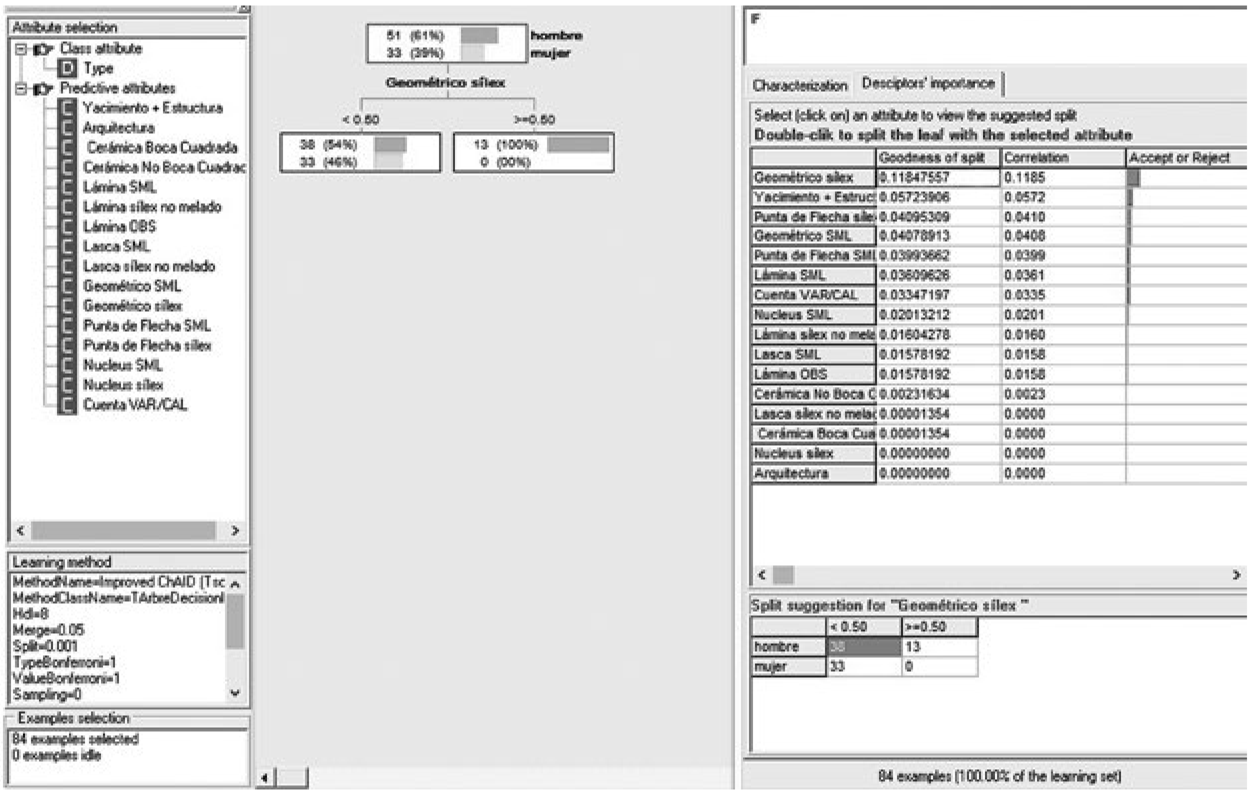


Fig. 5. Screenshot of an ID3 application realized through Tanagra Software (http://eric.univ-lyon2.fr/~ricco/tanagra/)

The lack of visibility of ritual pattern in our case-study could also be linked to the sample itself. Since it is defined by a specific chronological range of 1000 years (almost 40 generations), the ritual patterns might change during this time span in a way that it is visible and statistically significant. Furthermore, our choice could affect the reliability of the data: we reduced the data set to the structures which showed some features, such as the presence of grave goods and gender identification. What about the other structures, such as the ones with unidentified individuals? The fact that we worked only with dated individuals also reduced the sample and then the possibilities to identify patterns. On the other hand, the classification of the variables should be improved in order to obtain more information. For example, the general definition of 'Bocca Quadrata' pottery seems to be too simplistic, because it does not provide information about the category. Moreover, in the case of lithic artefacts their functional analysis can shed some light on their utility. In this context the results of functional analysis of the instruments, when it has been done, would be included. On the other hand, in a future perspective we also should include the burials of individuals with undetermined sex, in order to obtain a more accurate sample. Furthermore we should look for possible different patterns in function of the age of the individuals (immature, adult, and mature). From this we hope to find out more significant rules that explain the ritual patterns and then allow the prediction of new cases.

As this work is a first approach to the problematic of machine learning, we firstly use the most common three decision algorithms available. As above highlighted, these methods do not provide useful results due to the wide variability. As suggested by previous archaeological study (Fernández and García 1991), ID3 algorithm could generate too much clusters with low discrimination percentage. Moreover, the data could produce statistical noise that can obscure the original relationships. Although this algorithm had been improved by Ross Quinlan with C4.5, in our case-study neither provided clusters of the variables with high discriminatory potential.

Probably the implementation of these algorithms or the exploration of others, as well as the extension and improvement of the sample could lead to recognizable ritual patterns taking sex and age as dependent variables.

We believe that in the future it will be interesting to extend the analysed sample adding more contexts, in order to confirm if there is a pattern or if this possibility should be disproved. On the other hand, we consider that this methodology can be extrapolated to other similar cases of study, such as other funerary rituals from other geographical areas and chronologies, as well as, for example, to analyse the depositional processes that occur in all archaeological contexts from a probabilistic point of view.

Bibliography

Aa. Vv. 2008. Estudi del jaciment neolític de la caserna de Sant Pau (Barcelona). *Quarhis*. Epoca II, 4. Barcelona.

Achino, K., Duboscq, S., Morell, B., Barceló, J. A., Gibaja, J. (in press). Comparing in Archaeology through a quantitative approach: dealing with similarity and dissimilarity issues. Cambridge Scholars Editions.

Albert, J. P. and Piette, A. 2010. Rite (Rituel, ritualité). In R. Azria and D. Hervieu-Leger (dir.), *Dictionnaire des faits religieux*. Paris, Presses universitaires de France.

Antolín, F., Buxó, R., Jacomet, S., Navarrete, V., Saña, M. 2014. An integrated perspective on farming in the early Neolithic lakeshore site of La Draga (Banyoles, Spain). Environmental Archaeology 19, 3: 241-55.

Antolín, F. and Jacomet, S. 2015. Wild fruit use among early farmers in the Neolithic (5400-3200 cal. BC) in the north-east of the Iberian Peninsula: an intensive practice? Vegetation History and Archaeobotany 24, 1: 19-33.

Barceló, J. A. 2010. Clasificación, inducción y teoría de la evolución. Algoritmos Adaptativos en Arqueología Cuantitativa. In J. L. Escacena, D. García Rivero, F. García Fernández (eds.), *Clasificación y Arqueología. Enfoques y métodos taxonómicos a la luz de la evolución darwiniana*: 95-124. Sevilla, Secretariado de Publicaciones de la Universidad de Sevilla.

Barceló, J. A. 2005. Multidimensional spatial analysis in archaeology. Beyond the GIS paradigm. In *Reading the Historical Spatial Information in the World Studies for Human Cultures and Civilizations based on Geographic Information System*. Kyoto, International Institute for Japanese Studies: 47-62.

Barceló, J. A., Achino, K. F., Bogdanovic, I., Capuzzo, G., Del Castillo, F., Moitinho De Almeida, V., Negre, J. 2015. Measuring, Counting and Explaining: An Introduction to Mathematics in Archaeology. In J. A. Barceló and I. Bogdanovic, I. (eds.), *Mathematics and Archaeology*: 3-64. Boca Raton, CRC Press.

Benzécri, J.-P. 1973. *L'Analyse des Données. Volume II. L'Analyse des Correspondances*. Paris, Dunod.

Bernabò Brea, L. 1946. *Gli scavi della Caverna delle Arene Candide* 1. Bordighera (Imperia).

Bunge, M. 2006. *Chasing Reality: Strife over Realism*. Toronto, University of Toronto Press.

Clop, X. and Alvarez, A. 2009. Estudi de caracterització petrogràfica d'un vas de boca quadrada neolític de la mina 83 de Gavà. *Intervencions arqueològiques a les Mines de Gavà (sector serra de les Ferreres). Anys 1998-2009.* Rubricatum. *Revista del Museu de Gavà.* 4: 85-91.

Douglas, H., Fisher, J. R., Pazzani, M., Langley, P. 1991. *Concept formation knowledge and experience in unsupervised learning*. United States, Morgan Kaufmann Publishers.

García de la Fuente, M., Fernández Martínez, V. M. 1991. El tratamiento informático de datos funerarios cualitativos: Análisis de Correspondencias y algoritmo ID3 de Quinlan. *Complutum* 1: 123-32.

Gibaja, J. F. 2002. *La función de los instrumentos líticos como medio de aproximación socio-económica. Comunidades del V-IV milenio cal BC en el noreste de la Península Ibérica*. Unpublished PhD thesis, Universitat Autònoma de Barcelona.

Gibaja, J. F. 2004. Prácticas funerarias durante el Neolítico en Cataluña. *Mainake* 26: 9-27.

Gibaja, J. F. and Clop, X. 2012. Síntesis Regional: Cataluña. In M. A. Rojo Guerrera, R. Garrido Pena, I. García-Martínez de Lagrán (eds.), *El Neolítico en la Península Ibérica y su contexto europeo*. Madrid, Ediciones Cátedra.

Hensel, E. 1991. *Inverse Theory and Applications for Engineers*. Englewood Cliffs, Prentice Hall.

Jaccard, P. 1912. The distribution of the flora in the alpine zone. *New Phytologist* 11: 37–50. [Online] Available at: doi:10.1111/j.1469-8137.1912.tb05611.x.

Kaipio, J. and Somersalo, E. 2004. *Statistical and Computational Inverse Problems*. Berlin, Springer.

Kirsch, A. 1996. *An Introduction to the Mathematical Theory of Inverse Problems.* Berlin, Springer.

Leclerc, J. 1990. La notion de sépulture. *Bulletins et Mémoires de la Société d'anthropologie de Paris, Nouvelle Série* 2, 3-4: 13-8.

Mallory, J. P. and Mair, V. H. 2000. *The Tarim Mummies: Ancient China and the Mystery of the Earliest Peoples from the West*. London, Thames & Hudson.

Martín, A., Blanch, R. M., Albizuri, S., Alaminos, A., Mercadal, O., Vives, E., Lázaro, P., Bosch, J., Colomer, S., Miret, J., Enrich, R., Aliaga, S. (in press). El paraje de Bòbila Madurell (Sant Quirze del Vallès, Vallès Occidental, Barcelona). In J. F. Gibaja, M. E. Subirà, A. Martín, M. Mozota, J. Roig (eds.), *Mirando a la Muerte: Las prácticas funerarias durante el neolítico en el noreste peninsular*, E-ditArx - Publicaciones Digitales.

Mestres Mercade, J. 1988-1989. Les sepultures neolítiques de l'Hort d'en Grimau (Castellví de la Marca, Alt Penedès). *Olerdulae*, *Revista del Museu de Vilafranca* 1, 4: 97-129.

Mestres Mercade, J., Nadal, J., Senabre, M. R., Socias, J., Moragas, N. 1997. El Pujolet de Moja (Olèrdola, Alt Penedès), ocupació d'un territori durant el neolític i la primera edat del ferro. *Tribuna d'Arqueologia* 1995-1996: 121-48.

Moreno Ribas, A., Armengo Votass, E., Bejar Alonso, J. 1991. *Aprendizaje automático.* Barcelona, Edicions Universitat Politécnica de Catalunya.

Nilsson Stutz, L. 2010. The way we bury our dead. Reflections on mortuary ritual, community and identity at the time of the Mesolithic – Neolithic transition. *Documenta Praehistorica* XXXVII: 33-42.

Palomo, A. and Gibaja, J. F. 2004. Geométricos usados como proyectiles: implicaciones económicas, sociales e ideológicas en sociedades neolíticas del VI-IV milenio CAL BC en el Noroeste de la Península Ibérica. *Trabajos de Prehistoria* 61, 1: 81-97.

Pizlo, Z. 2001. Perception as viewed as an inverse problem. *Vision Research* 41, 25: 3145-61.

Quinlan, J. R. 1986. Induction of Decision Trees. *Machine Learning* 1, 1: 81-106.

Quinlan, J. R. 1993. C4.5: *Programs for Machine Learning*. San Mateo, Morgan Kaufmann Publishers.

Roig Buxó, J., Coll Riera, J. M., Gibaja, J. F., Chambon, P., Villar, V., Ruiz, J. Terradas, X., Subirà, E. 2010. La necrópolis de Can Gambús-1 (Sabadell, Barcelona). Nuevos conocimientos sobre las prácticas funerarias durante el Neolítico medio en el Noreste de la Península Ibérica. *Trabajos de Prehistoria* 67: 59-84.

Sabatier, P. C. 2000. Past and Future of Inverse Problems. *Journal of Mathematical Physics* 41: 4082–124.

Saña Seguí, M. 1998. Arqueozoologia i faunes neolítiques a Catalunya. Problemàtica plantejada entorn a la dinàmica del procés de domesticació animal. *Cypsela* 12: 99-110.

Smith, P. 2010. Le Rite. In M. Izard and P. Bonte (eds.), *Dictionnaire de l'ethnologie et de l'anthropologie. Qaudrige 2000*: 630-3. Paris, Presses universitaires de France.

Tarantola, A. 2005. *Inverse Problem Theory*. Philadelphia, Society for Industrial and Applied Mathematics.

Terradas, X., Gratuze, B., Bosch, J., Enrich, R., Esteve, X., Oms, F. X., Ribé, G. 2014. Neolithic diffusion of obsidian in the western Mediterranean: new data from Iberia. *Journal of Archaeological Science* 41: 69-78.

Thomas, L. V. 1985. *Rites de mort: pour la paix des vivants*. Paris, Fayard.

Thorthon, C. 2002. *Truth from Trash: How Learning Makes Sense (Complex Adaptive Systems*). Cambridge, Paperback.

Turner, V.W. 1953. *Lunda rites and ceremonies*. Rhodes-Livingstone Museum Occasional Paper No. 10. Livingstone, The Rhodes-Livingstone Museum.

Tversky, A. 1977. Features of Similarity (PDF). *Psychological Reviews* 84, 4: 327-52.

Van Gennep, A. (1909) *Les rites de passage: étude systématique des rites,* Ed. 1981. Paris, E. Nourry.

Vaquer, J. and Lea, V. 2011. Diffusion et échanges au Néolithique en Méditerranée nord-occidentale**.** In A. Blasco, M. Edo, M. J. Villalba (eds.), La cova de Can Sadurní i la prehistòria de Garraf. Recull de 30 anys d'investigació. *Actes de les Jornades Internacionals de Prehistòria 'El Garraf, 30 anys d'investigació arqueològica', celebrades a Begues del 5 al 7 de desembre de 2008.* Milano, Hugony Editore.

Vaquer, J., Martín, A., Pétrequin, P., Pétrequin, A. M., Errera, M. 2012. Les haches alpines dans les sépultures du Néolithique moyen pyrénéen: importations et influences. In P. Petrequin *et al*., *Jade, grandes haches alpines du néolithique européen, Ve et IVe millénaires avant J C*: 872-911. Ledoux, Presses Universitaires de Franche-Comté.

Vosnidau, S. and Ortony, A. 1989. Similarity and Analogical reasoning. Cambridge, Cambridge university press.

Woodbury, K. A. 2002. *Inverse Engineering Handbook*. Boca Raton, CRC Press.

Application of the 'Bag of Words' Model (bow) for Analysing Archaeological Potsherds

Diego Jiménez-Badillo
diego_jimenez@inah.gob.mx
National Institute of Anthropology and History (INAH, Mexico)

Edgar Roman-Rangel
edgar.romanrangel@unige.ch
CVMLab, University of Geneva, Switzerland

Abstract: We propose the application of the bag-of-words model (BoW) for the description and classification of archaeological potsherds.

BoW was developed to statistically analyse text documents with purposes of classification and retrieval. The idea is that text documents can be represented by a histogram that models the distribution of the most discriminative words in their contents (i.e. words that are important to recognize the text subject and topics). In the last decade the BoW model gained popularity in the computer vision community as a method to compare images and 3D models in applications of object recognition, classification and content-based retrieval. This has given rise to the bag-of-visual-words approach, where instead of words, visual patterns and local geometric features are analysed. This development offers great opportunities to analyse 3D shape data in many fields, including archaeology.

We provide an intuitive explanation of the BoW model as applied to the analysis of 3D surface models, and give details of some experiments with a sample of potsherds.

Keywords: Potsherds categorization, Bag-of-words, 3D shape descriptor

Introduction

The analysis of pottery sherds constitutes one of the most significant tasks in archaeology. It provides cultural information of past societies at multiple scales, from the identification of human activity areas to the determination of site chronology and/or the elucidation of regional economic systems.

Unfortunately, a detailed examination of ceramic fragments is also one of the most cumbersome and time-consuming activities for archaeologists. This is due not only to the long learning curve involved in mastering a ceramic classification system but also to the vast quantity of potsherds normally recovered from the field. A typical excavation in Central Mexico, for example, produces tens of thousands of fragments. Moreover, a single site may contain ceramics dating from a very long period, encompassing occupations of the Teotihuacan, Toltec and/or Aztec civilizations, this means potsherds dating from approximately 100 BC to 1521 AD.

A very relevant property in ceramic analysis is shape. Archaeologists are expected to reconstruct the profile of a whole vessel by examining the form of a surviving fragment. A traditional method to accomplish this has been a visual comparison of potsherds with manual drawings of the silhouette and diameter of vessels already known. However, this approach requires arduous training and is time consuming. A common practice to reduce the complexity of the task is selecting only fragments that are considered diagnostic to identify important ceramic types. These include certain body-parts, rims, legs, handles, etc., which are then used in a more detailed typological analysis to deduce chronology, cultural style, etc.

During the past decade, some professionals have been experimenting with digital technologies oriented to reducing learning curves and improving the quality of the classification process. One of the most interesting proposals has been the acquisition of digital 3D models of potsherds, with the purpose of applying mathematical, computer vision and/or machine learning techniques designed to perform classifications in an automatic or semi-automatic way. The extraction of 3D digital data has also brought extra benefits, such as the possibility to undertake new types of content analyses, as well as an easier sharing of information among professionals, the design of better ceramic documentation and archiving systems, and the performance of virtual reconstruction of vessels.

In this paper we present preliminary results of an on-going project focused on finding better methods to deal with ceramics classification. Our focus is on exploiting the descriptive power of local shape 3D descriptors, and combining them to create efficient representations using the so-called bag-of-words model (BoW), an approach that has proven to be very useful in content-based retrieval and classification of different kinds of digital documents, such as texts, 2D images, videos, and 3D models.

1 Related work

Computer-aided classification and reconstruction of ceramics has been a subject of research for at least 30 years, with pioneering work by Hall and Lafling (1984), who created a software package called NEWTS for drawing, archiving and editing ceramic profiles using B-spline functions.

Since then, the focus has continued to be the acquisition of 2D profiles, either from potsherds or from complete vessels, which can then be classified by archaeologists using curvature functions. A notable example of these efforts is the creation of the so-called profilograph, a device to draw profiles from 3D objects (i.e. potsherds).

Others researchers have developed methods to extract 2D profiles automatically (Adler *et al*. 2001; Kampel and Sablatnig 2002; 2003; 2007; Leymarie 2001; Melero 2004; Razdan *et al*. 2001; Sablatnig and Menard 1996; Shurmans *et al*. 2001). These works are based upon the assumption that the majority of vessels studied by archaeologists are axially symmetric. Indeed, for perfectly symmetric vessels the profile corresponds to a cross section in the direction of the rotational axis. Thus, by calculating the rotational axis, different methods are able to draw the profile of the vessels with different levels of success. Karasik and Smilansky (2008) have made great progress because their method takes into account the many possible deviations in the axis of symmetry. Unfortunately, many archaeological vessels are not perfectly symmetric, especially if they were hand-crafted as opposed to thrown-wheel manufactured. Therefore, extracting the rotational axis possesses serious challenges (Karasik 2005).

Perhaps the most complete and sophisticated approaches under the paradigm of profile extraction are due to Gilboa *et al*. (2004) as well as to Hörr, Brunner and Brunnett (2007). The latest paper proposes a series of mathematical algorithms for profile segmentation, feature extraction and, more importantly, clustering of potsherd descriptions using algebraic functions. This in turn allows performing queries and hierarchical classifications. The method, however, has been applied only to complete or semi-complete vessels and to the best of our knowledge results for potsherds are not available yet.

The calculation of the axis of symmetry also requires a pre-processing stage of orientation and alignment of the potsherds, which is normally a time consuming task. Our analytic approach is invariant to rotation and scale and therefore avoids the need of normalizing orientation and scale.

Another drawback of the current approaches is that they require a whole model of the potsherd. This involves scanning the potsherd from several viewpoints and merging the partial scans together in order to complete the model. Our method does not rely on capturing a whole model. Instead, it uses only surface information from the frontal and/or back views of the potsherd, which expedites the process significantly.

As for the comparison of potsherds for classification, some methods compare the shape of potsherds using a point-to-point matching process. As we explain in the following section, our method compares histograms (i.e. bag-of-visual-words) that represent the statistical frequency of local descriptors, namely the Local Depth Scale Invariant Feature Transform (LD-SIFT) (Darom and Keller 2012), the Scale Invariant Spin Image (SISI) (Darom and Keller 2012), and a newly proposed local descriptor based on spherical orientations called Histogram of 3D Lines (H3DL) (Roman-Rangel, Jimenez-Badillo, Marchand-Maillet 2015).

Recently, two papers have proposed the use of BoW for automatic analysis of potsherds. One reported the results of an initial exploration of the potential that bag-of-words representations have for categorizing potsherds using seven different taxonomic criteria. This trial obtained very good categorization performance – above 81% in the best case scenario (Roman-Rangel, Jimenez-Badillo, Aguayo-Ortiz 2014).

The other successful implementation – due to Sfikas *et al*. (2014), presented a method for partial matching and retrieval of 3D objects based on range images. This too achieves very good performance – above 70% of precision in their best scenario. This paper computes SIFT descriptors enhanced with depth information on a 2D panoramic projection of the 3D model (Sfikas *et al*. 2014), while the former work seeks to avoid such projections in order to exploit the real 3D information of the model as much as possible (Roman-Rangel, Jimenez-Badillo and Aguayo-Ortiz 2014). Both approaches also differ in the kind of dataset. One uses 16 well-defined classes of vessels and the 3D surfaces correspond to sections ranging from 25% to 40% of the complete piece in the best scenario (Sfikas, 2014). The other paper focuses on much smaller fragments (Roman-Rangel, Jimenez-Badillo and Aguayo-Ortiz 2014).

2 The bag of words model

The bag-of-words model was initially proposed in the field of Natural Language Processing (NLP) for addressing the challenge of determining the content of written documents automatically; more specifically for tackling the problem of text retrieval (Salton and McGill 1983).

In its simplest formulation, BoW analysis focuses on quantizing the frequency of words found in the document of text corpus without considering their order, grammar or syntactic rules. Thus, a document is represented by a frequency histogram of words, where each of its bins indicates the number of times a given word happens within the document. This histogram is precisely the BoW representation of that particular text.

Following this strategy, a set of documents can be classified, ranked and retrieved by simply comparing their corresponding frequency histograms. The intuition is that similar documents will have similar frequency histograms. For instance, two documents about Politics are expected to have large counts of certain key words, such as parliament, bill, debate, policy, etc. Likewise, the histograms of documents about Biology would show large counts of specific terms, such as life, plant, photosynthesis, DNA, etc. In general, the more relevant two documents are to each other, the more similar their corresponding histograms will be. Note that by using this approach it is also possible to rank text documents according to their degree of relevance (e.g. a document about Geography might be relevant to both History and Geology, whereas a document about Politics will probably have very little relevance to Botany).

It is worth noticing that not every word in a corpus of documents has the same potential to produce discriminative bag representations. For this reason, a base dictionary of the

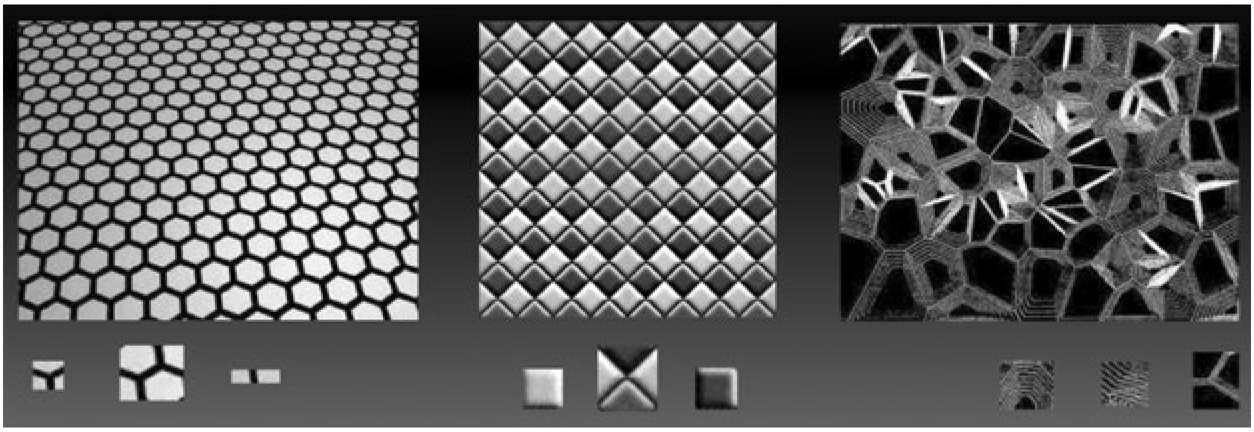


Fig. 1. Visual examples of 2D local features from texture images.

most relevant terms must be assembled and only words in this dictionary must be considered for constructing the frequency histograms. The construction of such a dictionary represents a critical step in the application of this model. For instance, stop-words such as articles, prepositions, conjunctions, etc., are found in all classes of documents; thus, including their counting in the BoW modeling would produce bag representations with several bins that are equally probable for all documents and therefore would not very useful for classifying their contents. A more discriminative representation can be obtained by excluding such stop-words, as well as any other term of very high and very low frequency within the corpus (i.e. very common words and words that are unique for single documents, respectively) (Roman-Rangel and Marchand-Maillet 2014).

Also, in practice a large corpus of documents normally includes texts of different lengths. Therefore, for the BoW model to be robust and to perform a proper comparison a normalization procedure is necessary; this is done by dividing the value in each bin of the histogram by the sum of the complete histogram, thus converting the bag representation into a probability density function (PDF) in which the sum of all its bins equals 1. In other words, each bin in the histogram represents the proportional contribution of its corresponding word to the whole document representation.

2.1 Bag-of-Words in 2D images and 3D models

After many successful applications in text analysis, the BoW model was adopted in the field of Computer Vision, where it was renamed bag-of-visual-words (Sivic and Zisserman 2003), bag-of-visual-features (Quelhas *et al*. 2007), or bag-of-visterms (i.e. visterm meaning 'visual term') (Quelhas *et al*. 2007). For simplicity, we continue using BoW to refer to the bag-of-visual-words approach through the rest of this document.

The BoW model is often used for content-based image analysis, where no text labels are attached to pictures. Instead, images are compared merely by the automatic analysis of low level visual features extracted with algorithms for shape description (Wang, Ronneberger, Burkhardt 2009; Lowe 2004; Dalal and Triggs 2005; Bay *et al*. 2008; Belongie, Malik, Puzicha 2002; Roman-Rangel *et al*. 2011). Figure 1 illustrates a very basic example of how these features look like in a simple 2D texture image.

More recently, the BoW model has also been adapted to content-based analysis of 3D data. In this case, local shape descriptors are computed at sampled regions of the 3D surface models. Mathematically speaking, these descriptors are vectors in high dimensional space.

In this context, a visual word is defined as a group of local shape features that are very similar among themselves and at the same time show high dissimilarity with respect to other groups. Therefore, the process of building a dictionary of 3D visual words (i.e. visual shape features) consists in clustering the set of local features found in a training corpus of 3D surface models. The appropriate quantity of words varies according to each data corpus. Thus, one may want to try different dictionary sizes to adjust the clustering to any particular application. The integer number K represents the number of clusters and therefore the quantity of visual-words in the dictionary. Visual words are thus labeled k = 1, 2, ..., K; and the centroid of each cluster is consider the prototype of that particular visual word, such that these K prototype descriptors (i.e. K visual-words in the dictionary) are used as reference for labeling local descriptors of new 3D surface models, i.e. models that are queried or added to the corpus. Mathematically, the label assignment for a visual word is given by:

$$label(d) = \underset{k}{argmin}\{dist(d, c_k)\}$$

Equation 1. Label assignment for a visual word.

Where, d is an example local descriptor (SISI, LD-SIFT, or H3DL); ck is k-th centroid, i.e. the prototype of the k-th cluster; and dist() is a function that computes the Euclidean distance between to vectors. For instance, the Euclidean distance between vectors a and b is computed as:

$$dist(a, b) = \sqrt{\sum (a_i - b_i)^2}$$

Equation 2. Euclidean distance between two vectors.

Where, i indicates each of the N dimensions of vectors a and b.

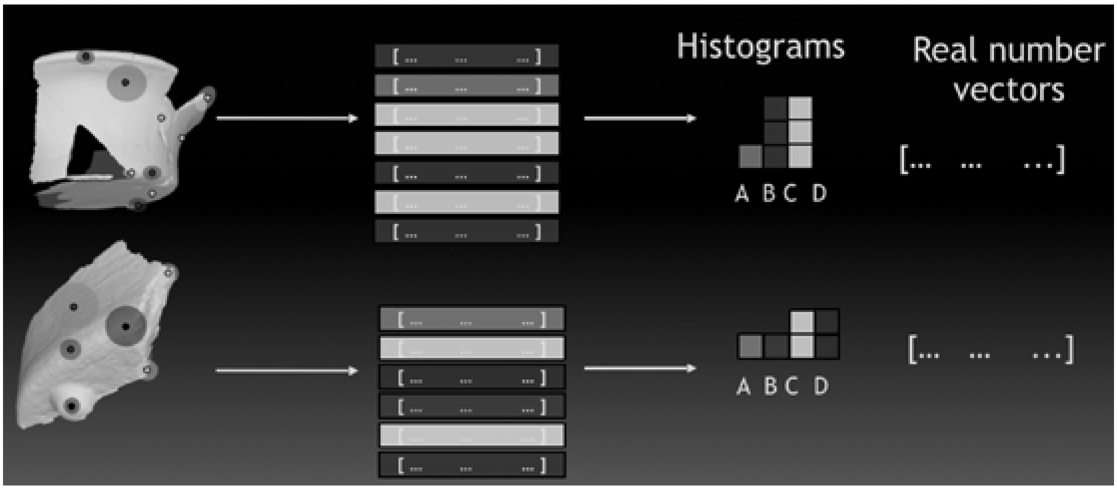


Fig. 2. Visual example of the construction of BoW representations.

Once the visual dictionary has been compiled, each 3D model in a data base can be represented as a set of visual words. More precisely, each local feature of the 3D model is labeled using the indices k = 1, 2, …, K of the centroid to which it is the closest (i.e. the characteristic centroid with the minimum distance).

After each local feature has been labeled, the histogram of frequencies can be computed counting the number of times each visual word of the dictionary occurs within each 3D model. This final step is also conducted for representing new models that are introduced into a previously constructed system. Figure 2 shows a visual intuition of the bag of words representation for a set of 3D models.

Note that applying the BoW approach allows us to take advantage of the descriptive potential of local descriptors, as this collects more detailed shape information that is highly relevant for recognizing form variations in 3D models, whereas global descriptors compress that information into a single description (Quelhas *et al*. 2007).

Also, implementing the BoW approach allows generating document representations that can be easily compared, even when they correspond to sets of points of different size. This represents a significant advantage with respect to other approaches, such as the point-to-point comparison of two sets of local descriptors (two 3D models), because the latest is a very time-consuming process (Belongie, Malik, Puzicha 2002). Moreover, point-to-point comparison is not straightforward when dealing with two 3D surface models of different size (Roman-Rangel *et al*. 2011).

3 Our Approach

In this work, we implement a classification system for 3D surfaces of potsherds using the BoW approach. In particular, our system works as follows:

3.1 Input Description

The input of our system consists of 3D surfaces representing the external face of potsherds. These were acquired using a Minolta Vivid 910 scanner. This is an approach that we propose for fast modeling, as scanning a single view is a much faster process than scanning the complete potsherd, yet it produces enough information for automatic classification of potsherds. Figure 3 shows examples of the 3D surfaces used in this work.

More precisely, all surfaces in this dataset are composed by a set of 3D point and their corresponding edges that connect them to form a mesh in the 3D space. However, our methodology neglects the information of the edges, and relies on the relative position of the 3D points with respect to each other. On average, a point cloud has around 9782±833 vertices. A potsherd represents from 5% to 20% of the complete ceramic piece.

For characterizing the 3D surfaces of our data base, we used two state-of-the-art methods that compute local descriptors for a set of interest points of 3D models. Namely, the Scale Invariant Spin Image (SISI) (Darom and Keller 2012; Johnson and Hebert 1999) and the Local Depth Scale Invariant Feature Transform (LD-SIFT) (Darom and Keller 2012; Lowe 2004). In practice, the set of points of interest is defined using a 3D approximation of a Difference-of-Gaussian approach that detects inflection points (Darom and Keller 2012). After the detection of these points, the 3D information around each point is projected onto a 2D space to generate a depth image, which is finally used for computing the local descriptor. The main difference between these two methods is that, while SISI creates a histogram of the relative positions of the neighboring points around the point of interest (Johnson and Hebert 1999), LD-SIFT creates a histogram of the local orientations of the neighborhood of the point of interest (Lowe 2004).

We also implemented the Histogram of 3D Lines (H3DL) (Roman-Rangel, Jimenez-Badillo, Marchand-Maillet 2015), which is a recently proposed 3D shape descriptor, that directly exploits the 3D information instead of projecting it onto 2D images, thus minimizing potential risks that the projection might cause of losing important visual cues. More precisely, this method selects points of interest by a uniform random sampling procedure, and describes each of these points by a histogram of their local spherical orientations. It has been

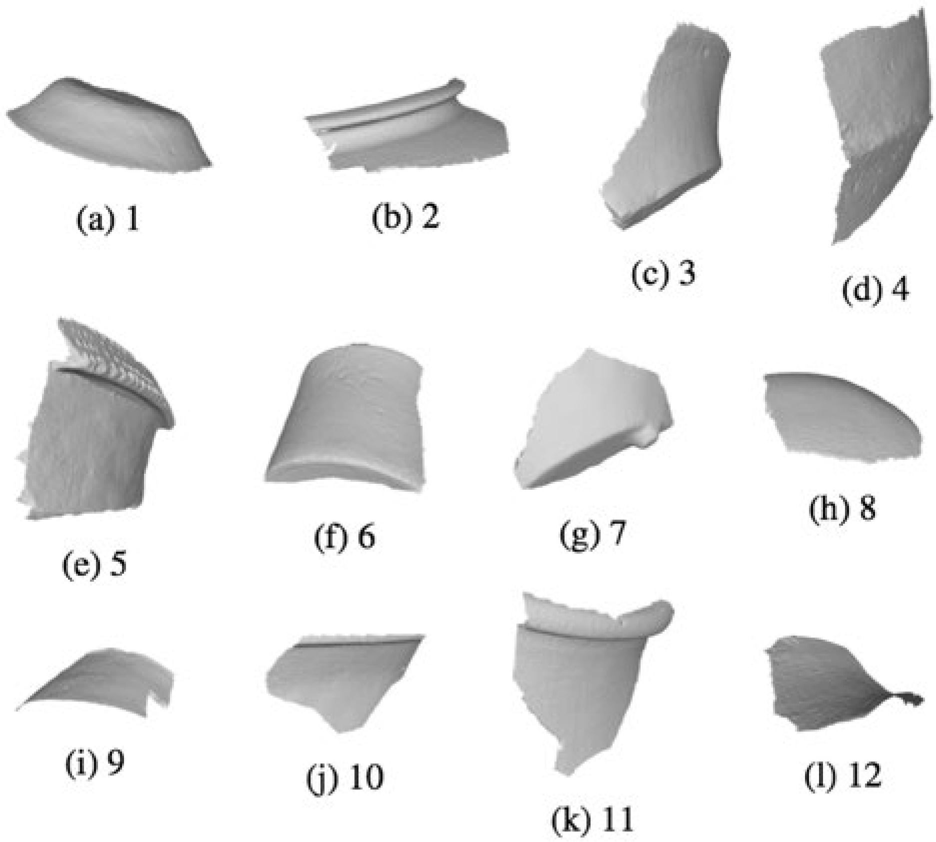


FIG. 3. EXAMPLES OF 3D SURFACES USED IN THIS WORK.

shown that the resulting descriptors are more robust than traditional methods for 3D description.

Note that, besides their technical differences, all three methods generate a set of local descriptors based on statistics of the local geometry around each point of interest.

3.2 Training: Dictionary Learning

To learn the dictionary of visual features we relied on the well-known k-means clustering algorithm (Lloyd 1982). We randomly sampled 20,000 local features (SISI, LD-SIFT, or H3DL) and clustered them into K clusters. In practice we estimated visual vocabularies of different size, as this is a good heuristic way to find the dictionary that provides the best performance. Namely, we tried six different visual dictionaries with size K = [100, 250, 500, 1000, 2500, 5000].

Note that this process was performed independently for each of the three local descriptors, i.e. SISI, LD-SIFT, or H3DL.

3.3 3D surface representation

After estimation of a particular dictionary, the 3D surfaces were represented using the quantization approach explained in section 3. 1. This step produced bag representations than can be compared using distance metrics, e.g. Euclidean distance. Figure 4 shows an example of the comparison of two BoW representations with 8 and 14 local features, respectively, and using a dictionary of 10 visual words.

3.4 Classification

We relied on a k-NN approach, with k = 1, for classifying 3D surfaces represented as bag models. This is, using the 3D surfaces as queries, one at the time, we classify it as belonging to the same class of its nearest exemplar in the data base.

Note that both the representation and the classification steps were performed independently for each of the three local descriptors, and for each of the six visual dictionaries. The classification accuracy results of these evaluations are presented in section 6.

4 Experiments

This section presents details of the experiments that we performed and the data base that we used.

4.1 Data base

We performed a series of classification experiments on a data base of 207 3D surfaces. These surfaces correspond to potsherds of ceramics pieces of the Teotihuacan culture.

67 of the 207 surfaces correspond to diagnostic potsherds; this is ceramic fragments whose type is easily recognizable to the naked eye, e.g. the neck of a pot, the supports of a vase, etc. Namely, they correspond to 7 classes: (1) plate, (2) pot, (3) cajete, (4) crater, (5) censer, (6) vase, and (7) vase with support.

	BoW 1										
frequency	0	2	1	1	0	3	0	0	1	0	
word	A	B	C	D	E	F	G	H	I	J	Distance
											0.539
	BoW 2										
frequency	2	0	4	0	0	1	2	3	1	1	
word	A	B	C	D	E	F	G	H	I	J	

Fig. 4. Visual example of the Euclidean distance between two bag representations.

The remaining 140 surfaces are not diagnostic potsherds and therefore we called them 'generic potsherds'. This means that they are not easily recognizable as belonging to known ceramic types, mainly because they came from body regions, as opposed to rims, bases, etc. Therefore they represent a bigger test for the application of the BoW model. We split these 140 surfaces by degree of curvature into the following 6 classes:

(8) Curved potsherd: this class corresponds to 3D surface models of concave fragments.

(9) Highly curved potsherd: this class contains highly pronounced concave curved potsherds.

(10) Curved potsherd with slight border: in these 3D surface models the border of the vessel is barely visible.

(11) Curved potsherd with clear border: it contains potsherds with clearly visible border.

(12) Convex potsherd: different from the previous curved potsherds, this class consists of potsherds whose curvature is convex. These instances often correspond to the neck of a jar or a pot, but have no diagnostic sections.

(13) Flat potsherd: this class includes all potsherds with almost no curvature.

In the analysis of results, we might refer to each class by its name for easy reading, but images and tables might refer to them by their numbers in the previous lists for visualizations purposes. Figure 5 shows the amount of instances in each of these classes.

4.2 Protocol

We evaluated the BoW representation by comparing its classification performance using different vocabulary sizes in a series of four experiments. Namely, the four experiments consist of:

1. Analyzing the surfaces of all the 207 potsherds from all the 13 classes in the data base.

2. Analyzing only 67 surfaces corresponding to the 7 classes of diagnostic potsherds, that is: plate, pot, cajete, crater, censer, vase, and vase with supports.

Tab. 1. Classification accuracy obtained using Bag-of-Words representation of different sizes for different local descriptors.

	Vocabulary size					
Method	100	250	500	1000	2500	5000
All classes in the dataset						
SISI	29.47	28.50	26.57	26.09	21.74	19.32
LD-SIFT	37.68	33.82	31.40	27.05	27.05	22.71
H3DL	**53.62**	53.14	48.31	44.93	47.34	46.86
Only classes with diagnostic potsherds						
SISI	28.36	34.33	29.85	28.36	22.39	22.39
LD-SIFT	47.76	38.81	40.30	37.31	38.81	32.84
H3DL	58.21	**64.18**	55.22	53.73	50.75	53.73
Only classes with at least 10 instances						
SISI	34.12	33.53	29.41	28.82	24.71	21.76
LD-SIFT	45.88	40.59	39.41	35.88	33.53	30.00
H3DL	60.59	**61.18**	56.47	53.53	54.71	56.47
Only classes with diagnostic potsherds and 10 instances						
SISI	36.17	40.43	36.17	31.91	25.53	25.53
LD-SIFT	51.06	46.81	53.19	51.06	53.19	46.81
H3DL	76.60	**80.85**	74.47	80.85	70.21	76.60

3. Analyzing only 170 surfaces of those classes that are represented by at least 10 potsherds. That is: pot, cajete, censer, vase with support, curved potsherd, potsherd with slight border, convex potsherd, and flat potsherd.

4. Analyzing only 47 surfaces from diagnostic classes that are represented in the data base for at least 10 instances. That is: pot, cajete, censer, and vase with support.

5 Results

Table 1 shows the average classification accuracy for the four sets of results.

The first observation from table 1 is that small dictionaries suffice for good representations of the 3D surfaces. Namely, dictionaries of 100, 250, and 500 words obtained the highest classification accuracy for all three shape descriptors in the four experiments. This observation means that there exists only a few local 3D structures present in the potsherds, and that different combinations of them result in the various types of 3D surfaces that represent all the potsherds. Furthermore,

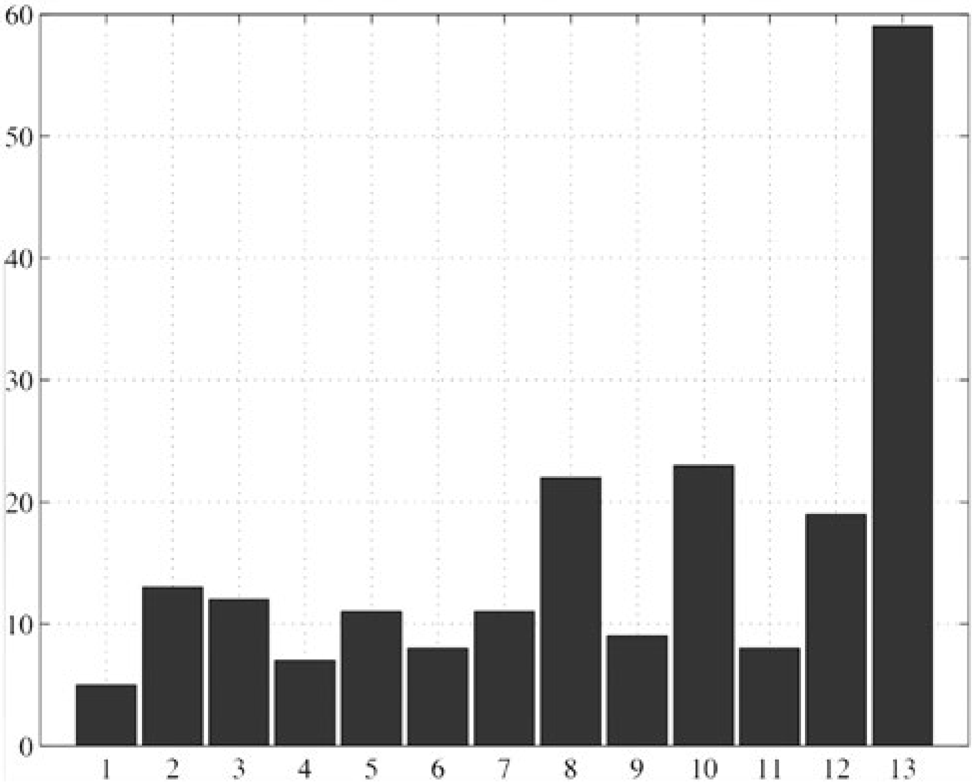


Fig. 5. Distribution of the 207 3D surfaces over the 13 classes defined in this work.

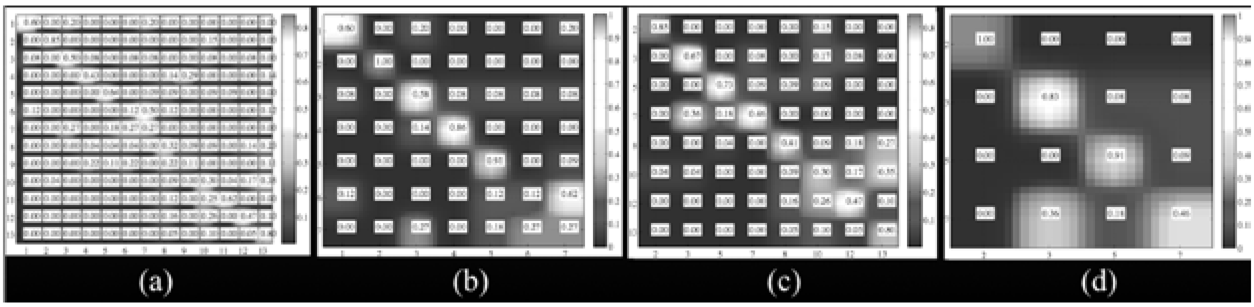


Fig. 6. Confusion matrices obtained with the four classifications experiments, using H3DL and the dictionary of 250 visual words.

the small amount of visual words required for representations has two advantages: (1) it is relatively efficient to estimate the visual vocabularies in terms of computational loads; and (2) comparing bag representations of only 250 dimensions is very fast, i.e. classification and retrieval of 3D models is also fast, even in data bases in the order of thousands of instances.

A second observation from table 1 is that measuring local orientations (i.e. H3DL) is a promising way to obtain better classification results. Notice that LD-SIFT performs better than SISI, but H3DL outperforms them both. Therefore, working directly with local orientations of 3D surfaces (H3DL) seems to be a better method than using descriptors that depend on 2D projection of 3D data.

Finally, note that classification performance is strongly impacted by the level of control there is about the data base itself. More precisely, the results of the first experiment, where all data are evaluated, remain only above 53% of classification accuracy, whereas the performance increases when only the sample of diagnostic potsherds is analyzed. The reason for this is that non-diagnostic (generic) potsherds are easily confused, both with diagnostic potsherds and among themselves. Besides, classification performance improves when we remove from the analysis classes that contain fewer than 10 potsherds, which – as expected – indicates that as the data sample grows higher classification rates can be obtained.

Figure 6 shows the confusion matrices of the four classification experiments using H3DL. Each row of a confusion matrix

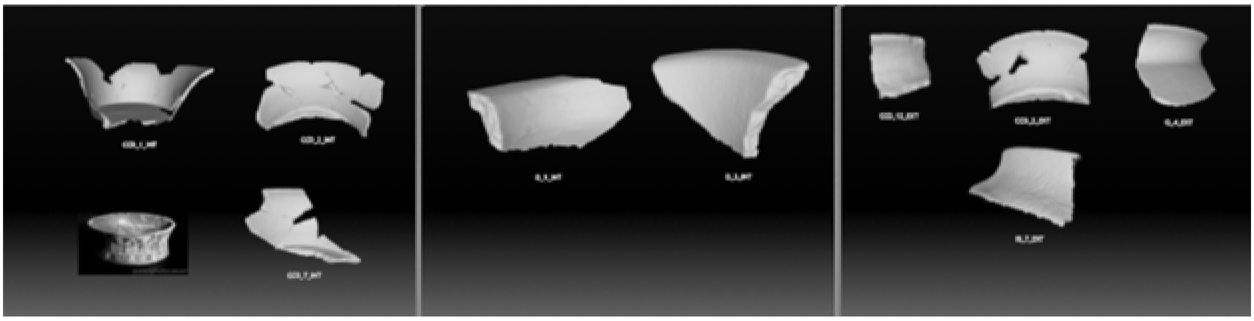


Fig. 7. Most similar surfaces that our methodology identifies as the most similar models for certain 3D surfaces used as queries.

refers to one class of the data base when its instances are used as query, and each column refers to the class to which the query was assigned. Such that each entry in the matrix indicates the average probability of classifying a query of a class (rows) as a member of a certain class (columns). For example, the entry of the 1st row and 3rd column indicates the probability of erroneously classifying a member of class 1 as belonging to class 3; and the entry of the 2nd row and 2nd column indicates the probability of correctly classifying a member of class 2. In this context, a perfect classification methodology would generate a confusion matrix with '1's along the main diagonal and '0's elsewhere.

Note that good classification results can be easily obtained for some classes, such as pot, censer, and flat fragments, even when the complete data base of 207 potsherds (i.e. both 'diagnostic' and 'generic' potsherds) is included in the model (Figure 6(a)). However, some other classes are easily confused, like vase and vase with support, as well as highly curved and curved potsherds. We believe that this type of miss-classification is acceptable as the only difference between the former two classes are the supports themselves, likewise, the threshold between curved and highly curved potsherds is subjective.

On the other hand, when we only use classes of diagnostic potsherds with at least 10 instances (Figure 6(d), which constitutes a very controlled scenario, there is very little miss-classification. For instance, vase with support is often confused with cajete. This, however, is somehow expected, since both shapes share many visual similarities and even experts sometimes fail to distinguish both.

To show some visual examples, in Figure 7 we shows some 3D surfaces that our methodology considers to be the most similar for certain 3D surfaces used as queries.

6 Conclusions

We proposed the application of the Bag-of-Visual-Words (BoW) for addressing the problem of automatic classification of potsherds, and more precisely, of potsherds represented as 3D surfaces. We combined the BoW approach with three local descriptors for 3D shapes.

Two of these descriptors (SISI and LD-SIFT), which are based on projecting 3D information onto 2D spaces, achieved competitive classification performance – above 40% and 50% respectively. And both of them where outperformed by a recently proposed descriptor (H3DL) that exploits geometric information of the 3D point clouds, and that achieves more than 80% of classification accuracy.

Our results also demonstrate that a methodology based on the use of 3D surfaces, instead of complete 3D models, is capable of capturing enough visual information for accurate description of potsherds. We also noticed the importance of properly defining visual classes in a data base for achieving high rates of classification performance. Overall, we noticed two important restrictions to be addressed when building a system for automatic classification of potsherds: (1) to be aware of generic potsherds as they are far more difficult to classify than their diagnostic counterparts; and (2) the need of having classes with enough instances, such that more visual variability is learnt by the system, and therefore, higher classification accuracy can be obtained.

Future efforts on this problem will focus on shortening the dimensionality of the H3DL descriptor, such that a more efficient system could become available. Also, we plan to gather data from several archaeology groups for further evaluation of our methodology.

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Bibliography

Adler, K., Kampel, M., Kastler, R., Penz, M., Sablatnig, R., Schindler, K., Tosovic, S. 2001. Computer aided classification of ceramics. Achievements and problems. In W. Börner and L. Dollhofer (eds.), *Proceedings of 6th International Workshop on Archaeology and Computers, Vienna, Austria*: 3-12.

Bay, H., Ess, A., Tuytelaars, T., and Van Gool, L. 2008. SURF: Speeded up robust features. *Computer Vision and Image Understanding* 110, 3: 346-59.

Belongie, S., Malik, J., Puzicha, J. 2002. Shape matching and object recognition using shape contexts. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 24, 4: 509-22.

Dalal, N. and Triggs, B. 2005. Histograms of oriented gradients for human detection. In *Proceeding of the IEEE Conference* *in Computer Vision and Pattern Recognition*: 886-93. San Diego, USA.

Darom, T. and Keller, Y. 2012. Scale-invariant features for 3-D mesh models. *IEEE Transactions on Image Processing* 21, 5: 2758-69.

Gilboa, A., Karasik, A., Sharon, I., Smilansky, U. 2004. Towards computerized typology and classification of ceramics. *Journal of Archaeological Science* 31, 6: 681-94.

Hall, N. S., and Laflin, S. 1984. A Computer aided design technique for pottery profiles. In S. Laflin (ed.), Proceedings of the Conference in Computer Applications in Archaeology 1984. Centre for Computing and Computer Science, University of Birmingham: 178-88.

Hörr, C., Brunner, D., Brunnett, G. 2007. Feature extraction on axially symmetric pottery for hierarchical classification. *Computer-Aided Design and Applications* 4: 375-84.

Johnson, A. and Hebert, M. 1999. Using spin images for efficient object recognition in cluttered 3D scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 21, 5: 433-49.

Kampel, M. and Sablatnig, R. 2002. Computer aided classification of ceramics. In F. Niccolucci (ed.), *Proceedings of the VAST 2000 Euroconference, Arezzo, Italy, 24-25 November 2000*, British Archaeological Reports International Series 1075: 77-82. Oxford, Archaeopress.

Kampel, M. and Sablatnig, R. 2003. Virtual reconstruction of broken and unbroken pottery. In *Proceedings of the Fourth International Conference on 3-D Digital Imaging and Modeling (3DIM´03)*. IEEE Computer Society: 318-25.

Kampel, M. and Sablatnig, R. 2007. Rule based system for archaeological pottery classification. *Pattern Recognition Letters* 28, 6: 740-7.

Karasik, A., Mara, H., Sablatnig, R., Sharon, I., Smilansky, U. 2007. Measuring deformations of wheel-produced ceramics using high resolution 3D reconstructions. In A. Figueiredo and G. Leite Velho (eds.), *The world is in your eyes. CAA2005. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 33rd Conference, Tomar, March 2005*: 11-4. CAA Portugal, Tomar.

Karasik, A. and Smilanski, U. 2008. 3D scanning technology as a standard archaeological tool for pottery analysis: Practice and theory. *Journal of Archaeological Science* 35: 1148-68.

Leymarie, F., Cooper, D., Joukowsky, M., Kimia, B., Laidlaw, D.H., Mumford, D., Vote, E, 2001. The SHAPE Lab: A new technology and software for archaeologists. In Z. Stancic and T. Veljanovski (eds.), *Computing Archaeology for Understanding the Past: Proceedings of the XXVIII Annual Conference on Computer Applications and Quantitative Methods in Archaeology*. British Archaeological Reports International Series 931: 79-89. Oxford, Archaeopress.

Lloyd, S. 1982. Least Squares Quantization in PCM. *IEEE Transactions in Information Theory* 28, 2: 129-37.

Lowe, D. G. 2004. Distinctive Image Features from Scale-Invariant Keypoints. *International Journal of Computer Vision* 60, 2: 91-110.

Melero, F. J., León, A. J., Contreras, F., and Torres, J. C. 2004. A new system for interactive vessel reconstruction and drawing. In K. Fischer-Ausserer, W. Börner, M. Goriany, L. Karlhuber-Vöckl (eds.), *Enter the Past. The E-way into the four Dimensions of Cultural Heritage. CAA 2003. Computer Applications and Quantitative Methods in Archaeology*, British Archaeological Reports International Series 1227: 78-81. Oxford, Archaeopress.

Quelhas, P., Monay, F., Odobez, J. M., Gatica-Perez, D., Tuytelaars, T. 2007. A thousand words in a scene. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 29, 9: 1575-89.

Razdan, A., Liu, D., Bae, M., Zhu, M., Farin, G., 2001. Using geometric modeling for archiving and searching 3D archaeological vessels. In *Proceedings of the International Conference on Imaging Science, Systems, and Technology CISST 2001*, Las Vegas.

Roman-Rangel, E., Jimenez-Badillo, D., Aguayo-Ortiz, E. 2014. Categorization of Aztec potsherds using 3D local descriptors. In *Proceedings of 3rd Workshop on e-Heritage, in the 12th Asian Conference on Computer Vision*. Singapore.

Roman-Rangel, E., Jimenez-Badillo, D., and Marchand-Maillet, S. 2015. *Retrieving 3D surfaces with histograms of 3D lines*. Research Report, CVMLab - University of Geneve.

Roman-Rangel, E. and Marchand-Maillet, S. 2014. Automatic removal of visual stop-words. In Kien A. Hua, Y. Rui, R. Steinmetz, A. Hanjalic, A. Natsev, W. Zhu, *Proceedings of the ACM International Conference on Multimedia, MM 2014, Orlando, USA, 3-7 November 2014. ACM 2014*: 1145-8. Orlando, USA.

Roman-Rangel, E., Pallan, C., Odobez, J. M., Gatica-Perez, D. 2011. Analyzing ancient Maya glyph collections with contextual shape descriptors. *International Journal of Computer Vision* 94, 1: 101-17.

Sablatnig, R. and Menard, C., 1996. Computer based acquisition of archaeological finds: the first step towards automatic classification. In P. Moscati and S. Mariotti, *Proceedings of the Third International Symposium on Computing and Archaeology, Rome*: 429-46.

Salton, G. and McGill, M. J. 1983. *Introduction to modern information retrieval*. McGraw Hill, New York.

Schurmans, U. Razdan, A., Simon, A., McCartney, P., Marzke, M., Alfen, D. V., Jones, G., Rowe, J., Farin, G., Collins, D., Zhu, M., Liu, D., Bae, M. 2002. Advances in geometric modeling and feature extraction on pots, rocks and bones for representation and query via the Internet. In G. Burenhult and J. Arvidsson (eds.), *Archaeological Informatics: Pushing The Envelope. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 29th Conference, Gotland, April 2001*. British Archaeological Reports International Series 1016: 191-202. Oxford, Archaeopress.

Sivic, J. and Zisserman, A. 2003. Video google: A text retrieval approach to object matching in videos. In *Proceedings of the IEEE International Conference on Computer Vision*. Nice, France.

Skifas, K., Pratikakis, I., Koutsoudis, A., Savelonas, M., Theoharis, T. 2014. Partial matching of 3D cultural heritage objects using panoramic views. *Multimedia Tools and Applications* 73 [Online] Available at: doi 10.1007/s11042-014-2069-0.

Wang, Q., Ronneberger, O., Burkhardt, H. 2009. Rotational invariance based on fourier analysis in polar and spherical coordinates. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 31, 9: 1715-22.

Autonomy in Marine Archaeology

Øyvind Ødegård[(1, 2)]
oyvind.odegard@ntnu.no

Stein M. Nornes[(1)]
stein.nornes@ntnu.no

Martin Ludvigsen[(1)]
martin.ludvigsen@ntnu.no

Thijs J. Maarleveld[(3)]
t.maarleveld@sdu.dk

Asgeir J. Sørensen[(1)]
asgeir.sorensen@ntnu.no

[1] Centre for Autonomous Marine Operations and Systems (AMOS) Department of Marine Technology,
Norwegian University of Science and Technology, Norway
[2] Department of Archaeology and Cultural History, University Museum,
Norwegian University of Science and Technology, Norway
[3] Department of History, Maritime Archaeology Programme,
University of Southern Denmark

Abstract: After what oceanographers have called 'a century of undersampling', the marine sciences are now benefiting from tremendous technological advances in sensors and sensor platforms. Efficient exploration of the deep or remote marine environments depends on the use of underwater robotics, particularly untethered Autonomous Underwater Vehicles (AUVs) that can be sent out on missions covering large areas and return with data from multiple sensors. As technological developments allow AUVs to be deployed on long duration missions (months), the need for robust autonomous guidance, navigation and control systems become evident. For long duration missions in areas that prohibit human involvement (e.g. ultra-deep or under ice), it will be of interest for marine archaeologists to have an AUV that can find as many wrecks or other traces of cultural heritage on the seabed as possible. A hypothetical long duration AUV survey implementing archaeological mission objectives is described and discussed.

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Keywords: Marine archaeology, Underwater robotics, Autonomy, Cybernetics, AUV

Introduction

Climate change and enabling technologies are driving forces for an increased attention to mapping and expanding our understanding of the oceans. Industry and management have common needs for knowledge and data to better exploit marine resources both economically and environmentally. This is also true for management of underwater cultural heritage. The lack of data from the underwater environment has become a major problem for the discipline. True: exemplary research can usefully focus on those sites for which evidence exists. However, the quantitative lack of data affects the way research issues can be resolved and is particularly dramatic in relation to present management schemes. This is the more urgent since management, including cultural heritage management and the management of research funding have become addicted to quantitative control (Anthony and Govindarajan 2007). After a century of undersampling, new technologies show promising potential for mapping larger areas with high temporal and spatial coverage and resolution helping scientists to acquire data relevant and appropriate for questions that previously were difficult nor even impossible to answer (Nilssen *et al*. 2015). The new technologies are sensors such as Synthetic Aperture Sonar (SAS) (Hansen 2011) and Underwater Hyperspectral Imaging (UHI) (Johnsen 2013), advanced sensor platforms, increased processing abilities and progress in research on control methods for autonomy. This development seen in light of the holistic principles behind emerging Ecosystem Based Management models (de la Mare 2005) should enable large scale data gathering operations in the ocean space to integrate archaeological aspects without much ado.

On land, in relation to occupation sites, and in relation to sites of a monumental character a quantitative body of observations has consistently been built up by populations that run in the tens of millions. Subsequently, over more than 200 years, these observations have been systematized by antiquarians and archaeologists who had relatively easy access, and who could make sure that observations were reliably corroborated. Under water and in relation with marine sites this is far less the

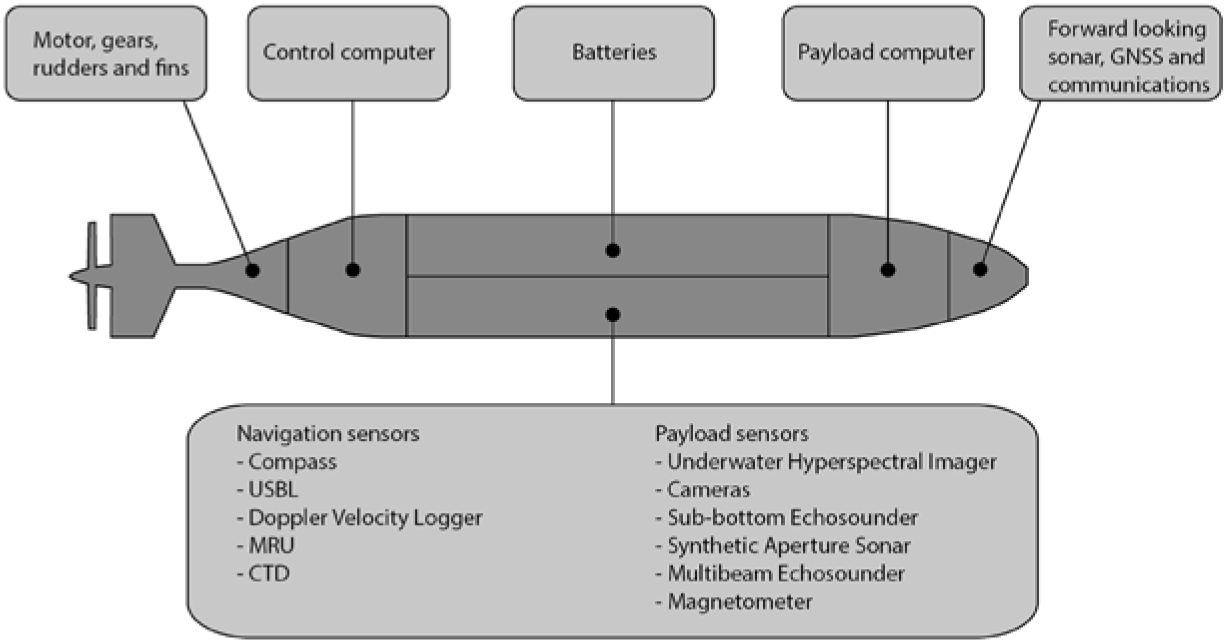

Fig. 1. Outline of AUV anatomy.

case. Even though the last 70 years have seen the discipline of marine archaeology develop, the intensity of observations lags far behind. Apart from systematic survey – and even there – observations are limited to where people go, which stands in no relation to the sheer extent of the underwater landscape. For various reasons many observations never enter the archaeological record (Maarleveld 2010). Moreover, many underwater observations are uncorroborated, as corroboration is relatively impracticable in the underwater environment. However, it begs the question whether vague data is data at all.

While there are considerable advances made in control systems, navigation system and manipulators for remotely operated vehicles (ROVs) that will also benefit ocean space mapping (Sørensen *et al*. 2012) this paper will focus on untethered autonomous underwater vehicles (AUVs). Because of the exponentially growing amount of data new sensors can provide, an important challenge is to reduce the amount of data describing 'uninteresting observations', and on the other hand get as much as possible from 'interesting observations'. This is of course due to storage capacity, processing time and energy budget. Having robots that stop, turn on additional sensors, lights, and do detailed surveying only when they have found something worth investigating, will save energy to do longer missions and cover larger areas.

In this paper we will be discussing future missions to explore the ocean space that are based on certain assumptions. For long duration surveys in deeper waters, the costs of revisiting areas are very high. We will therefore be assuming that these are 'one shot' operations with only one chance to get it right, and revisiting or inspecting objects of interest (OOI) later is not considered an option. Another assumption is that purely archaeological missions are not likely to happen. There probably will be interdisciplinary cruises/surveys with multiple stakeholders involved including archaeology as one of them. As limited available energy is the main constraint for AUV operations, we assume that resources allocated to archaeology must be negotiated, and that a high number of false positives, is a negative argument regarding archaeology.

As technological developments allow AUVs to be deployed on long duration missions (months), the need for robust autonomous guidance, navigation and control systems become evident. Intelligent control command and task execution with obstacle avoidance, fault-detection and diagnosis as a basis for reconfigurable control and re-planning of path and missions will be necessary in order to improve capabilities to operate in an unstructured environment with little or no *a priori* knowledge. In the years to come the field of artificial intelligence and learning systems as driven forward in the field of software science will strengthen the interactions between top-down and bottom-up approaches towards improved autonomy and more intelligent systems and operations. Adaptive planning and strategical and tactical decision making are methods that have already been used successfully by marine sciences and for navy purposes. This paper will present some examples of these methods in a discussion of *if* and *how* they can be adapted to archaeological applications. The paper aims to identify and define some challenges regarding autonomy in marine archaeology, and to demonstrate the importance of debating them.

1 AUV

Autonomous Underwater Vehicles (AUVs) are untethered robots that can operate independent of human operators at different levels of autonomy. AUVs come in many different shapes and sizes. For long duration missions covering large areas, slender bodied torpedo shaped vehicles with one propeller are commonly used (Hobson *et al*. 2012). An AUV typically consists of battery or energy cell for power, a propulsion unit, communication unit, navigation and payload sensors and computers (Fig. 1). Typical navigational sensors

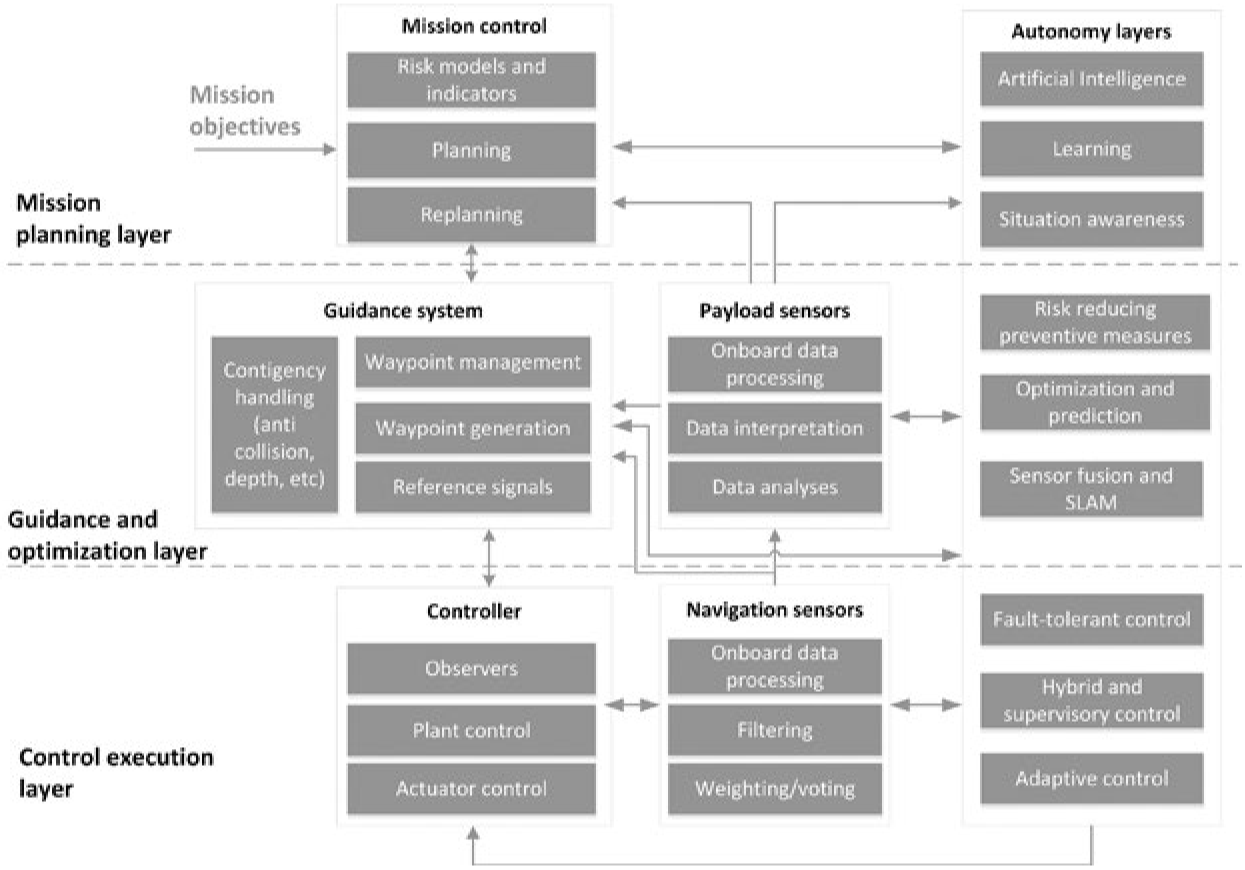

FIG. 2. AUV CONTROL ARCHITECTURE.

are Doppler Velocity Logger (DVL), Current Temperature and Depth (CTD), Compass and Motion Reference Unit (MRU). Typical payload sensors are long range sonar systems like Side Scan Sonar (SSS), Synthetic Aperture Sonar (SAS) and Multi Beam Echo sounders (MBE). Sub Bottom Profilers (SBP), magnetometers, different types of cameras and other instruments are deployed for measuring bio-geo-chemical properties. For a description of typical payload and navigation sensors see Sørensen and Ludvigsen (2015). Even though we distinguish between navigational sensors and payload sensors in the autonomy architecture, it should be mentioned that data from several sensors can be used for multiple mission objectives, and are not exclusive for one particular purpose.

1.1 Control system

In addition to hardware an AUV is completely dependent on a control system to operate. The control system is the 'brain' of the robot, and commands and coordinates every single part of the AUV to make it behave in accordance with a mission plan. Complex mission plans may require many parallel or sequential tasks to be performed interdependently, often with conditional choices for the next action. If an AUV is to operate in an environment with many unknowns and uncertainties, which typically characterizes the marine environment, an intelligent control system will increase the chances for success in performing its mission. Since the late 1980s there have been great advances in the research field of intelligent control. The challenges of introducing Artificial Intelligence (AI) and autonomy into the predominantly mathematical field of conventional control theory was recognized early (Meystel, 1989), and the necessity for multi- or interdisciplinary work efforts were acknowledged (Antsaklis *et al*. 1989; Zeigler 1990). The three layered hybrid architecture emerged as a successful framework for autonomy, and became a standard approach to autonomy for mobile robots (Gat, 1998). Many of the most successful systems today have evolved from these early models, and have similar divisions. The three layers all have important roles to play with regards to autonomy. The following AUV autonomy framework (Fig. 2) is based on the autonomy architecture presented in Sørensen and Ludvigsen (2015). At the top is the mission planning layer where the mission objective is defined and the mission is planned with tasks to fulfil the mission goal(s). Subject to contingency handling, any input from payload sensor data analysis and any other input from the autonomy layer, the mission may be re-planned. This layer also manages and maintains a world model by continuous updating from sensor data. The guidance and optimization layer translates these tasks into sequences of behaviours that are carried out by distributing commands to actuators and sensors in the control execution level.

1.2 Autonomy

Discussing autonomy from an end-user perspective can bring untraditional problems into an established discourse, as concepts can represent different meanings in different disciplines (Bal 2009). The need for precise taxonomy to avoid misunderstandings is important. The terms Autonomy and Level of Autonomy (LOA) are used to describe the relationship between human and machine, and are often expressed along a scale with increasing machine control and less human interference. Different models are used since robot/human relationships can be very diverse and take on quite different forms. Some models are very simplistic with few levels, and short descriptions of each level, while other are more intricate with several dimensions necessary for describing complex relationships, e.g. involving contextual factors like environment and data processing. A good overview of autonomy taxonomy can be found in Vagia *et al*. (in press).

Hagen *et al*. (2009) links levels of autonomy for AUVs to their performance in energy autonomy, navigation autonomy and decision autonomy. To see autonomy in relation to tasks, and not just as a relationship between human and machine, we need to investigate how high level archaeological goals can be formulated in an autonomy layer, but also how marine archaeological practice can be translated into meaningful actions and behaviours for the robot.

For short term missions in relatively known environments, uncertainties can be handled by e.g. simple IF-THEN-ELSE rules (Gat, 1998). The programmer can predict possible events, and have the robot to act based on rules encompassing these events. This can involve multiple conditions, creating a more solid basis for decisions. However, as the number of conditions grows the conditional variations grow exponentially, and the purely logical decision model becomes exceedingly complex very fast. The robot now needs to deliberate combinations of events, both in its environment and regarding its own state, that are beyond practical predictability. This problem is especially relevant for longer missions in unknown environments.

1.3 SLaM

Simultaneous Localization and Mapping (SLaM) addresses the problem of constructing a spatial map of the environment around a mobile robot while simultaneously utilizing this map to calculate the position of the robot relative to this map (Siciliano and Khatib 2008).

Efficient method for SLaM is generally regarded as one of the most important problems to solve in the pursuit of building truly autonomous mobile robots capable of operating unassisted in unknown environments for a prolonged period of time with limited access to external navigation systems such as acoustics of surface based satellite systems. With global position updates such as GPS being unavailable underwater one would often rely on dead-reckoning methods for navigation. In such systems small measurement errors from navigation sensors will accumulate over time causing the estimated position of the vehicle to drift. With SLaM, a vehicle revisiting an area mapped earlier in the mission can use the new position calculated from the map to counteract this time related drift. This is often referred as 'closing the loop' and bound the error drift.

An autonomous vehicle will also be limited by both power consumption and data storage. To map large areas efficiently, it is often beneficial to do an initial coarse resolution mapping and return to smaller areas with features and objects of interest (OOI) for a higher resolution mapping. Doing this on a single dive is known as adaptive replanning (Wiig *et al*. 2012). Obviously, the map built using SLaM will be highly beneficial for relocating the features and OOI for re-examining.

SLaM methods have now reached a state of considerable maturity (Durrant-Whyte and Bailey 2006; Bailey and Durrant-Whyte 2006). Several successful implementations have been demonstrated, ranging from structured man-made environments (Ribas *et al*. 2008) to drowned coral reefs (Williams *et al*. 2009) to visual mapping of the RMS Titanic (Eustice *et al*. 2005). Newer research (Kim and Eustice 2014) is also moving from passive SLaM where the vehicle follows a predetermined path, to active SLaM where the path is modified to improve both map building and localization performance.

The main obstacle for SLaM has traditionally been computational complexity. With continuous improvements in computational power and research into new algorithms, the field has grown considerably the last decade, and is likely to continue improving.

2 Archaeological survey

For long duration missions in areas that prohibit human involvement (e.g. ultra-deep or under ice), it will be of interest for marine archaeologists to have an AUV that can find as many wrecks or other traces of cultural heritage on the seabed as possible. The AUV should return with good data from each site that can serve as a foundation for decision making regarding management issues, or as material for research and knowledge production in case the site will not be revisited again. This is a comprehensive mission objective, and one must expect to make many compromises both in terms of what can be done, and how it can be done. Since an exhaustive high resolution multi sensor mapping of every inch of the seabed is not feasible with current technologies, we must introduce elements of deliberation and choices into the mission plan that will reduce the amount of work to be done, and have the robot only spend time and resources on sites that are likely to be of interest. A high level formulation of this mission objective can be divided into three missions: Mission 1 – Detect; Mission 2 – Verify and Mission 3 – Record (Fig. 3). The missions are sequentially dependent, mission 2 will only be performed if mission 1 produces waypoints, likewise mission 3 will only be performed if mission 2 result in any Objects of interest (OOI).

To see how these missions can best be implemented into the control architecture of an AUV, we must decompose/ deconstruct each mission into tasks that better matches the behaviours AUVs typically can perform. This requires the archaeologist to see marine archaeological praxis independent of the methodological and cognitive constraints typical for the tools commonly available today, and instead adopt and investigate the possibilities offered by the perceptive and operational abilities and constraints of the AUV.

Consider the following as an outline of a hypothetical AUV survey to illustrate how the mission objectives described above could be resolved.

2.1 Mission 1 Detect

The AUV will explore an area of the seabed (Fig. 4 a) of which it has limited if any a priori knowledge. It will keep a constant altitude above the seabed optimal for maximum areal

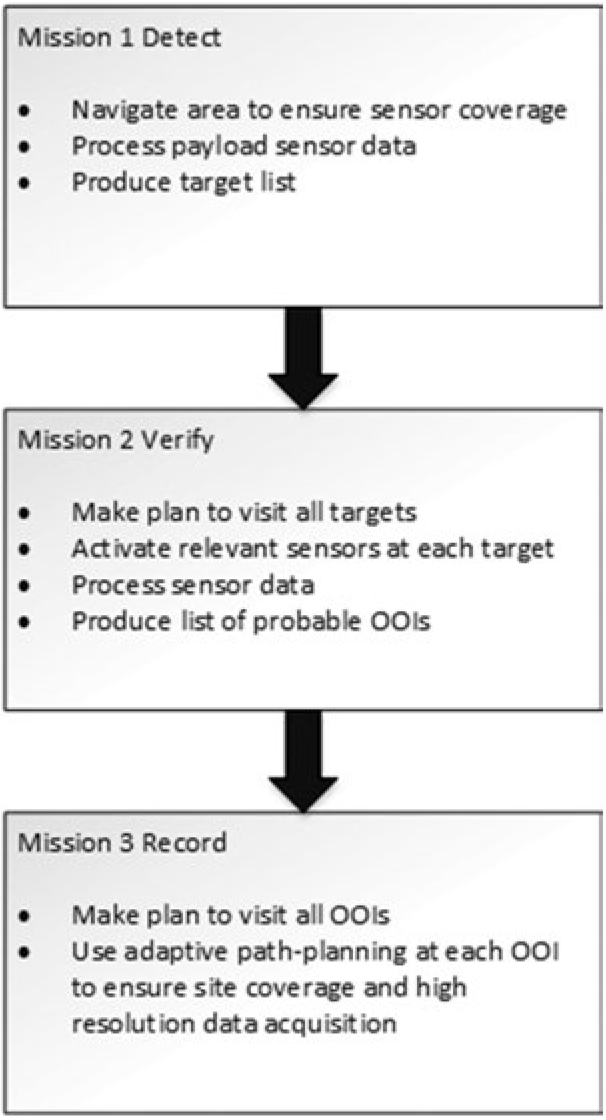

Fig. 3. Tripartite mission plan for an archaeological survey.

coverage, using one or several long range acoustic sensors (e.g. SAS and MBES) while navigating in a lawnmower pattern (Fig. 4 b). The SAS/MBES data is processed in real time producing both imagery and bathymetric data that is used both for safely navigating the environment (SLaM), and for feature detection (segmentation using e.g. computer vision algorithms). Interferometric SAS data can also be analyzed to find the maximum range for a predefined data quality threshold, and thus adjust line spacing to ensure that the whole area is covered (Krogstad and Wiig 2014). Detecting features that could possibly be OOIs (Fig. 4 c), the AUV creates a list of waypoints to be used as input in re-planning as shown in Fig. 3.

2.2 Mission 2 Verify

The AUV re-plans its mission to navigate along a route to visit all the waypoints. To save energy the path planning will involve use of Traveling Salesman Planning (TSP) algorithms to have the new path as short as possible (Krogstad and Wiig 2014; Tsiogkas *et al*. 2014). At every target it activates relevant sensors (UHI, magnetometer, O2-optode etc.) for measuring and sampling (Fig. 4 d). This data is then processed to determine if the targets should be regarded as possible OOIs. The autonomy layer then decides if it should reject the targets and continue with its original mission, or revisit again for full data acquisition (Fig. 4 e).

2.3 Mission 3 Record

Targets determined to be OOIs are revisited and recorded with all relevant sensors to secure optimal data sets (Fig. 4 f). The AUV will plan survey lines with spacing and altitude appropriate for the sensors that are activated (e.g. ensure at least 60 percent image overlap for photogrammetry). In addition the AUV must apply computer vision and machine learning algorithms to sensor data in real time to ensure that the area of interest has been covered completely, and to decide when the operation is finished (Giguere *et al*. 2009).

3 Autonomous detection and recognition of wrecks

Detecting and classifying features in imagery are nontrivial and complex problems. Image segmentation using computer vision and machine learning is a research field given much attention in the last decades, and is currently seeing many breakthroughs – especially within deep learning and artificial neural networking. However, as time and computing power are limited resources for AUVs, simpler algorithms would be preferable for on-board calculations. Imagery produced by acoustic sensors is monochrome, and in principle shows the intensity of echoes for each pixel that represents a specific location on the seabed. In archaeological applications, to recognize features in such imagery as potential OOIs would entail comparison of morphological qualities of the features with an on-board knowledge representation (library) of shapes likely to be found on wreck sites. This approach using learned classifiers for feature or object recognition has been successfully pursued by using Automated Target Recognition algorithms in research on Mine Counter Measures (Petillot *et al*. 2010; Groen *et al*. 2010). While this method could probably successfully detect and classify some features as wrecks, a problem would be that the method is inherently biased towards what is already known and therefore less likely to recognize sites that are disintegrated, decomposed or otherwise scattered in an unprecedented (un-modelled) pattern. Wreck site formation processes are very complex, chiefly determined by the characteristics of the ship, the events causing its deposition on the seabed (how it wrecked), the environment of the wreck site and the time it has spent on the seabed (assuming it has remained undisturbed). Muckelroy's (1978) classic model treats the site formation process almost like a cybernetic system with the ship as input, and loss of integrity and materials as conditional outputs depending on a number of 'extracting filters' and 'scrambling devices'. While this model may seem a bit positivistic today, it nevertheless accounts for the factors influencing a site formation process and describes the variations from structurally intact wrecks like the *Vasa,* to examples like the *Kennemerland* where disintegration and deposition of materials on the seabed happened over a relatively long time and the traces left on the seabed were spread over several hundreds of meters. It can be argued that in deeper waters, wreck site formation processes are more coherent, as a wreck once it is deposited on the seabed is less likely to be mechanically disturbed (Church 2014). However, even

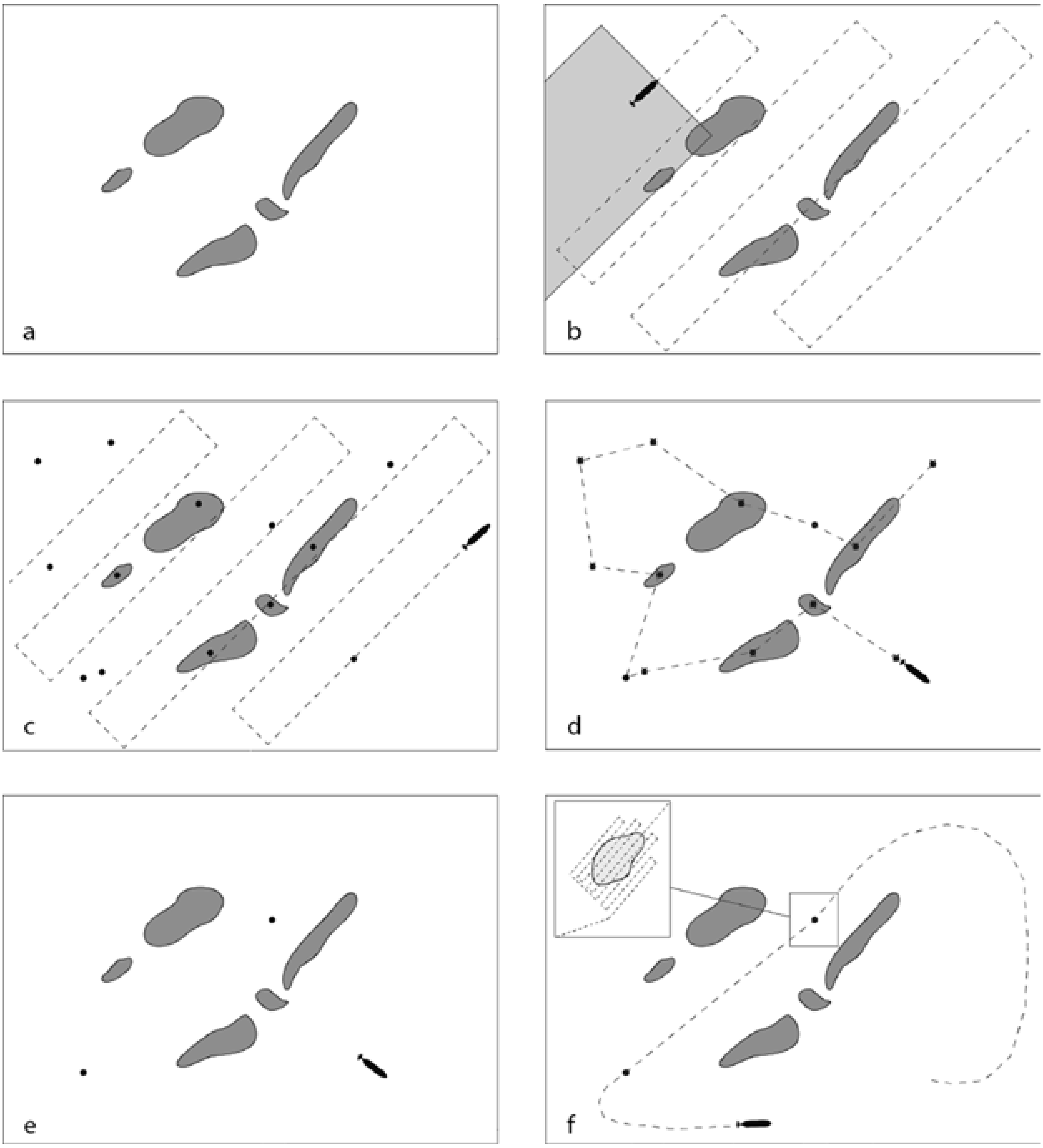

Fig. 4. AUV survey: a) area to survey; b) lawnmower pattern to cover area; c) detect targets; d) visit and inspect targets; e) list of OOI; f) revisit and record OOI.

though intact hull structures could presumably be modelled as variations of some shared qualities regarding shape and size, any typical morphological characteristics would eventually be broken down by biology, chemistry, gravity and time (Björdal *et al*. 2011). The recognition of wreck sites as they appear in sonar imagery is therefore often a heuristic undertaking were the archaeologist will perceive features in the imagery based on his understanding of the technology (Quinn *et al*. 2005), and in the context of knowledge of the sea bed terrain (e.g. aided by additional sensors as described by Sakellariou *et al*. (2007)), empirical experience of probable or possible wrecking processes (Muckelroy 1978), and of course the prevailing currents and other known or assumed environmental conditions in the area.

An alternative approach could be to look for what stands out as different or unusual on the seabed (Girdhar and Dudek 2014). By simply stating that a feature is different from what has been perceived so far, and therefore interesting, this approach sheds the problems of morphological ambiguity discussed above. There would be no need for archaeological knowledge representation and wreck site modeling in mission 1 (the analysis of acoustic data), as the AUV would generate a target list based on its experiences made in the local environment.

This way of shifting the allocation of a problem from the deliberate high-level end of the control architecture towards the more reactive, low-level end could also probably make it easier to adjust and fine tune algorithms as less abstractions and semantic representations are involved.

While this approach will reduce the number of false negatives, it is very likely to include many false positives. Recording will be a very energy and time consuming part of such missions, and to avoid wasting resources on what we can expect to be a high number of uninteresting features, we introduce a mission 2 for verification of targets. While the initial target list in mission 1 was selected to encompass every possible OOI, the purpose of mission 2 is to reduce the final number of false positives. This is done by navigating over all targets found in mission 1 for an inspection with multiple sensors activated. While the morphological variations of wreck sites are almost unlimited, the material composition of the remains of shipwrecks would be easier to delimit. Iron anchors, cannons, and chains are some typical objects that can be found on many wreck sites. An AUV equipped with a magnetometer (e.g. Hugin HUS has a Honeywell HMR 2300 magnetometer) could register magnetic signals near a shipwreck with such objects present. Underwater Hyperspectral Imagers are optical sensors that can record the spectral signature of the seabed with centimeter resolution (Johnsen 2013). The UHI detects light in the spectral range 380-800 nm, with a resolution of 1 nm (Ludvigsen *et al*. 2014). If the AUV carries a library describing the spectral signatures of materials typically present at wreck sites, it could look for matches or close similarities in the sensor data. Methods in sensor fusion can be used to calculate probabilities with many uncertainties involved - see for instance Wu (2002). This means that signals from sensors that acting alone would give very unreliable indications of e.g. a potential wreck site, in combination with each other could yield estimations with higher degrees of confidence. For instance, a magnetometer could register a magnetic anomaly that together with UHI detection of pigments typical for bricks, would indicate a probable wreck site. Targets found in mission 1 that remain unsupported by sensor data from mission 2 will not be considered possible OOIs. By reducing the number of targets to be fully documented in mission 3, a considerable amount of time and energy is saved.

Marine archaeology, as most marine sciences, have used robotics and utilized the technological development both in sensors and platforms to gain access to areas normally not accessible by diving methods. However, the potential for interdisciplinary benefits in the application of robotics has so far largely remained unexplored as a methodologically significant choice by archaeologists as end users. Rather, robots and sensors have been seen as extensions or replacements/proxies for human presence and observation (for some notable exceptions see Bingham and Foley *et al*. 2010 and Allotta *et al*. 2015). When archaeologists inspect a wreck site with an ROV, common for surveys beyond diving range, focus will predominantly be on the visual data acquired by cameras, what the archaeologist sitting next to the ROV-pilot can see, and what can be recognized and classified. This is no wonder, as state–of-the-art HD-cameras now can produce fantastic imagery exceeding the perceptive constraints of the human eye. It seems that the *primacy of vision*, as described by Jonathan Adams (2013), has been transferred to these new methods, and while the diver is no longer situated at the site – with all the cognitive processes that follows – the operation could be seen as an adaptation of traditional marine archaeological diver based practice.

On land the implementation of computer vision and machine learning in archaeological knowledge production has met resistance (Bennett *et al*. 2014). It is different under water. The operational constraints of ultra-deep or ice covered waters make autonomous operations the only way to access certain areas. Even if some will argue that the methods deployed are ill-suited or inappropriate, the alternative would be nothing at all. This doesn't mean that the critiques of these methods are irrelevant, but the outcome of such a discourse would have less practical consequences. The abilities to consider and fruitfully deliberate archaeology will only be developed if archaeologists engage with the inner workings of robotic autonomy. It requires an understanding of how intelligent autonomy frameworks function, and it of course requires an understanding of archaeological praxis – both critical to current methods, and aware of trade-offs in transferring a traditionally humanistic praxis to machines.

4 Conclusion and future work

This paper has proposed a strategy to implement archaeological mission objectives as input to the design of autonomous control systems for AUVs. By dividing the missions into tasks that the AUV can perform with behaviours within given parameters, the abstract goals are moved from the higher deliberative layer to the middle coordination layer and finally can be executed in the lowest control layer with commands and direct reactions to sensor data determining actions.

It has been demonstrated that SAS in terms of resolution and coverage allows detection of relatively indistinct wreck sites at considerable distances (Ødegård *et al*. 2013). Future work at the Centre for Autonomous Marine Operations and Systems (AMOS) will look at how on-board SAS image analysis can best be applied to detect wrecks with a focus on avoiding false negatives. UHI-technology is still a novel tool with a huge potential for the marine sciences, but has already been used to investigate wreck sites with good results (Ludvigsen *et al*. 2014). Ongoing work at AMOS will build a library of spectral signatures for typical materials found at wreck sites. UHI data from wreck sites will be used together with this library to develop methods for aided detection and classification.

Bibliography

Adams, J. 2013. Experiencing Shipwrecks and the Primacy of Vision. In J. Adams and J. Rönnby (eds.), *Interpreting Shipwrecks: Maritime Archaeological Approaches*: 85-96. Southampton, Highfield Press.

Allotta, B., Costanzi, R., Ridol, A., Colombo, C., Bellavia, F., Fanfani, M., Pazzaglia, F., Salvetti, O., Moroni, D., Pascali, M. A., Reggiannini, M., Kruusmaa, M., Salumäe, T., Frost, G., Tsiogkas, N., Lane, D. M., Cocco, M., Gualdesi, L., Roig, D., Gündogdu, H. T., Tekdemir, E. I., Dede, M. I. C., Baines, S., Agneto, F., Selvaggio, P., Tusa, S., Zangara, S., Dresen, U., Lätti, P., Saar, T., Daviddi, W. (in press). The ARROWS project: adapting and developing robotics technologies for underwater archaeology. *IFAC Workshop on Navigation Guidance and Control of Underwater Vehicles (NGCUV 2015), 2015 Girona, Spain*.

Anthony, R. N. and Govindarajan, V. 2007. *Management control systems*. McGraw-Hill Irwin, Chicago.

Antsaklis, P. J., Passino, K. M., Wang, S. 1989. Towards intelligent autonomous control systems: Architecture and fundamental issues. *Journal of Intelligent and Robotic Systems* 1: 315-42.

Bailey, T., Durrant-Whyte, H. 2006. Simultaneous localization and mapping (SLAM): Part II. *IEEE Robotics & Automation Magazine* 13: 108-17.

Bal, M. 2009. Working with concepts. *European Journal of English Studies* 13: 13-23.

Bennett, R., Cowley, D., De Laet, V. 2014. The data explosion: tackling the taboo of automatic feature recognition in airborne survey data. *Antiquity* 88: 896-905.

Bingham, B., Foley, B., Singh, H., Camilli, R., Delaporta, K., Eustice, R., Mallios, A., Mindell, D., Roman, C., Sakellariou, D. 2010. Robotic tools for deep water archaeology: Surveying an ancient shipwreck with an autonomous underwater vehicle. *Journal of Field Robotics* 27: 702-17.

Björdal, C. G., Gregory, D., Trakadas, A. 2011. *WreckProtect: decay and protection of archaeological wooden shipwrecks.* Oxford, Archaeopress.

Church, R. A. 2014. Deep-Water Shipwreck Initial Site Formation: The Equation of Site Distribution. *Journal of Maritime Archaeology* 9: 27-40.

De La Mare, W. K. 2005. Marine ecosystem-based management as a hierarchical control system. *Marine Policy* 29: 57-68.

Durrant-Whyte, H., Bailey, T. 2006. Simultaneous localization and mapping: part I. *Robotics & Automation Magazine, IEEE* 13: 99-110.

Eustice, R., Singh, H., Leonard, J. J., Walter, M., Ballard, R. 2005. Visually Navigating the RMS Titanic with SLAM Information Filters. *Robotics: Science and Systems* 2005: 57-64.

Adams, J. 2013. Experiencing Shipwrecks and the Primacy of Vision. In J. Adams and J. Rönnby

Giguere, P., Dudek, G., Prahacs, C., Plamondon, N., Turgeon, K. 2009. Unsupervised learning of terrain appearance for automated coral reef exploration. *Canadian Conference on Computer and Robot Vision, CRV'09*. *IEEE*: 268-75.

Girdhar, Y., Dudek, G. 2014. Exploring Underwater Environments with Curiosity. *Canadian Conference on Computer and Robot Vision (CRV)*. IEEE: 104-10.

Groen, J., Coiras, E., Williams, D. 2010. False-alarm reduction in mine classification using multiple looks from a synthetic aperture sonar. *OCEANS 2010 IEEE-Sydney*, *IEEE*: 1-8.

Hagen, P. E., Hegrenæs, Ø., Jalving, B., Midtgaard, Ø., Wiig, M., Hagen, O. K. 2009. Making AUVs Truly Autonomous. In A. V. Inzartsev (ed.), *Underwater Vehicles.* InTech.

Hansen, R. E. 2011. Introduction to Synthetic Aperture Sonar. In N. Kolev, *Sonar Systems*, InTech, Croatia. doi: 10.5772/23122. Available at: http://www.intechopen.com/books/sonar-systems/introduction-to-synthetic-aperture-sonar.

Hobson, B. W., Bellingham, J. G., Kieft, B., Mcewen, R., Godin, M., Zhang, Y. 2012. Tethys-class long range AUVs-extending the endurance of propeller-driven cruising AUVs from days to weeks. *Proceedings of the Autonomous Underwater Vehicles (AUV)*. *IEEE*: 1-8.

Johnsen, G., Volent, Z., Dierssen, H., Pettersen, R., Van Ardelan, M., Søreide, F., Fearns, P., Ludvigsen, M., Moline, M. 2013. Underwater hyperspectral imagery to create biogeochemical maps of seafloor properties. *Subsea optics and imaging.* Woodshead Publishing Limited.

Kim, A., Eustice, R. M. 2014. Active visual SLAM for robotic area coverage: Theory and experiment. *The International Journal of Robotics Research*. [Online] Available at: doi: 10.1177/0278364914547893.

Krogstad, T. R. and Wiig, M. S. 2014. Autonomous Survey and Identification Planning for AUV MCM Operations. *UDT 2014*.

Ludvigsen, M., Johnsen, G., Sørensen, A. J., Lågstad, P. A., Ødegård, Ø. 2014. Scientific Operations Combining ROV and AUV in the Trondheim Fjord. *Marine Technology Society Journal* 48: 59-71.

Maarleveld, T. J. 2010. 10. Fish and «Chips of Knowledge»: Some Thoughts on the Biases of the Archaeological Record. In T. Bekker-Nielsen and D. Bernal Casasola (eds.), *Ancient Nets and Fishing Gear. Proceedings of the International workshop on Nets and Fishing Gear in Classical Antiquity: a First Approach, Cadiz, 15-17 November 2007*: 257-71. Universidad de Cadiz and Aarhus University Press.

Meystel, A. 1989. Intelligent control: A sketch of the theory. *Journal of Intelligent & Robotic Systems* 2: 97-107.

Muckelroy, K. 1978. *Maritime archaeology*. Cambridge, Cambridge University Press.

Nilssen, I., Ødegård, Ø., Sørensen, A. J., Johnsen, G., Moline, M. A., Berge, J. 2015. Integrated environmental mapping and monitoring, a methodological approach to optimise knowledge gathering and sampling strategy. *Marine Pollution Bulletin* 96: 374-83.

Petillot, Y., Pailhas, Y., Sawas, J., Valeyrie, N., Bell, J. 2010. Target recognition in synthetic aperture and high resolution side-scan sonar using auvs. In *Proceedings of the International Conference: Synthetic Aperture Sonar and Synthetic Aperture Radar, Institute of Acoustics, Lerici, Italy, September* 2010.

Quinn, R., Dean, M., Lawrence, M., Liscoe, S., Boland, D. 2005. Backscatter responses and resolution considerations in archaeological side-scan sonar surveys: a control experiment. *Journal of archaeological science* 32:1252-64.

Ribas, D., Ridao, P., Tardós, J. D., Neira, J. 2008. Underwater SLAM in man-made structured environments. *Journal of Field Robotics* 25: 898-921.

Sakellariou, D., Georgiou, P., Mallios, A., Kapsimalis, V., Kourkoumelis, D., Micha, P., Theodoulou, T., Dellaporta, K. 2007. Searching for Ancient Shipwrecks in the Aegean Sea: the Discovery of Chios and Kythnos Hellenistic Wrecks with the Use of Marine Geological-Geophysical Methods. *International Journal of Nautical Archaeology* 36: 365-81.

Siciliano, B. and Khatib, O. 2008. *Springer handbook of robotics*. Springer Science & Business Media.

Sørensen, A. J., Dukan, F., Ludvigsen, M., Fernandes, D. A., Candeloro, M. 2012. Development of dynamic positioning tracking system for the ROV Minerva. In G. Roberts and B. Sutton (eds.), *Further Advances in Unmanned Marine Vehicles.* The Institution of engineering and Technology.

Sørensen, J. A. and Ludvigsen, M. (in press). Towards Integrated Autonomous Underwater Operations. *IFAC Workshop on Navigation Guidance and Control of Underwater Vehicles*, *Girona, Spain 2015*.

Tsiogkas, N., Papadimitriou, G., Saigol, Z., Lane, D. 2014. Efficient multi-AUV cooperation using semantic knowledge representation for underwater archaeology missions. In *Oceans-St. John's 2014, 14-19 september 2014*, *IEEE*: 1-6. [Online] doi: 10.1109/OCEANS.2014.7003085.

Vagia, M., Transeth, A. A., Fjerdingen, S. A. (in press). A survey on levels of autonomy during the years. What are the different taxonomies that have been proposed? *Applied Ergonomics*.

Wiig, M. S., Krogstad, T. R., Midtgaard, O. 2012. Autonomous identification planning for mine countermeasures. *Autonomous Underwater Vehicles (AUV), 2012. IEEE*: 1-8.

Williams, S. B., Pizarro, O., Mahon, I., Johnson-Roberson, M. 2009. Simultaneous localisation and mapping and dense stereoscopic seafloor reconstruction using an AUV. *Experimental robotics* 2009: 407-16. Springer.

Wu, H., Siegel, M., Stiefelhagen, R., Jie, Y. 2002. Sensor fusion using Dempster-Shafer theory [for context-aware HCI]. In *Proceedings of the 19th IEEE Instrumentation and Measurement Technology Conference, IMTC/2002, 21-23 May 2002*: 7-12.

Zeigler, B. P. 1990. High autonomy systems: concepts and models. *In Proceedings of AI, Simulation and Planning in High Autonomy Systems*: 2-7. IEEE Computer Society Press, Tucson, AZ.

Ødegård, Ø., Ludvigsen, M., Lågstad, P. A. 2013. Using synthetic aperture sonar in marine archaeological surveys-Some first experiences. In *OCEANS-Bergen, MTS/IEEE, 2013*: 1-7.

Identifying Patterns on Prehistoric Wall Paintings: a New Curve Fitting Approach

Michail Panagopoulos(1)

Dimitris Arabadjis(2)

Panayiotis Rousopoulos(2)

Michalis Exarhos(2)

Constantin Papaodysseus(2)

1 Department of Audio and Visual Arts, Ionian University, Greece
2 School of Electrical and Computer Engineering, National Technical University of Athens, Greece

Abstract: In this paper a curve fitting approach, based on the curvature, is presented and is applied to the wall paintings from Akrotiri, as well as those of Mycenae. The error minimization is calculated by a curvature function and consequently the refined parameters of the prototype curves are provided again by means of data clustering. The fitting error between the original drawn contour parts and the prototype curves is extremely small, namely the average fitting error is 0.02 mm, while the maximum fitting error is 0.06 mm. It is notable that there exist contour parts of length over 15 cm, which fit optimally the prototype curves and that there exist object parts of the same wall painting that perfectly fit to each other. Finally, it is remarkable that the same group of geometric stencils is found to different locations.

Keywords: Stencils, Geometry, Conics, Wall paintings, Prehistoric, Curve fitting, Curvature

Introduction

The excavation of Akrotiri, Thera, Greece, has offered a number of very well preserved wall paintings. The importance of these wall paintings has been analyzed by several scholars, however in this work we are mostly interested in the amazing drawing of the contours of the shapes depicted on them. In this paper, a methodology of general applicability is presented for answering the question whether an artist used a number of archetypes to draw a painting, or if he drew it by free hand. Previous work (Fragoulis *et al*. 2005), (Papaodysseus *et al*. 2006), (Roussopoulos *et al*. 2010) and (Arabadjis *et al*. 2013) has shown that most of the parts of these contours were constructed by prototype geometric stencils and the contribution of the present approach is to test a new curve fitting methodology based on the contour parts curvature. In the bibliography so far, only the problem of semi-automatic attribution of a drawing to its painter has been tackled (Sablatnig *et al*. 1998). On the contrary, curve fitting is a field where quite extensive research has been done in the last decades (Atieg and Watson 2003), (Werman and Keren 2001). The method has, initially, been applied to geometrical shapes, such as spirals, shown on a wall painting drawn c. 1650 BC excavated at Akrotiri, Thera. This wall painting depicts a complex of a number of spirals together with a number of bigger ones. Figure 1 shows one spiral which belongs to this complex. Other wall paintings, which were studied, are the celebrated wall paintings 'Naked Boys' and 'The Saffron Gatherers', (Doumas 1992) initially decorating the internal murals of the austral basin of the edifice 'Xeste 3' excavated at Akrotiri, Thera.

In addition, the method was also applied to Mycenaean civilization frescos e.g. the 'Lady of Mycenae', of the 12th century BC excavated at Mycenae. The so called 'Lady of Mycenae', housed in the National Archaeological Museum in Athens (inv. no 11670), is the best preserved wall painting on the Greek mainland and of the highest quality. It comes from a house, near the fortification wall, in the area of the Cult Centre at Mycenae. It is attributed to a seated goddess who accepts the offerings of the worshipers.

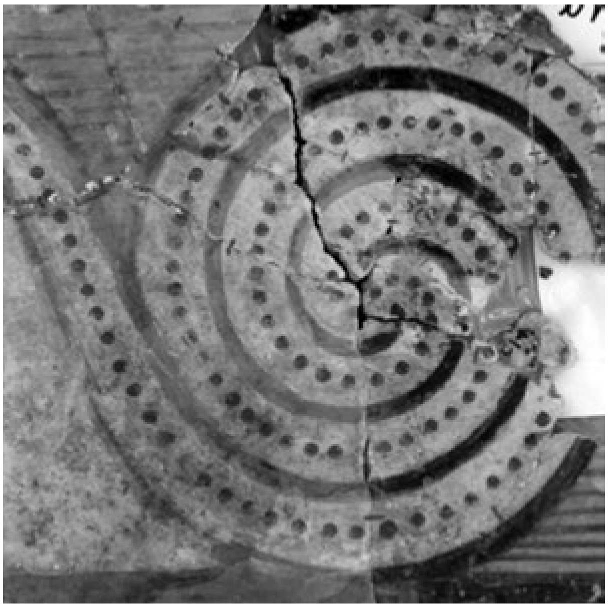

Fig. 1. One of the spirals belonging to the big wall painting of the second floor of Xeste 3.

1 Stating the main hypotheses concerning the method of drawing of prehistoric wall paintings in the Hellenic region

The stability of lines of the contours of the drawn figures in many wall paintings of the prehistoric Akrotiri, Thera town suggested the idea to the authors that guides or stencils might had been used for the drawing of these paintings. In fact, the main hypotheses that have been immerged may be described as follows:

The artist(s), c. 1650 BC, used pre-fabricated stencils or a proper apparatus for drawing parts of the figures' contours. We will adopt the assumption that these parts were drawn by a single continuous stroke of the brush. For this reason, we call each such subject of a figure's contour 'one-stroke part' or alternatively 'object part'.

After drawing a one-stroke part, the artist(s) removed and repositioned the stencil or the apparatus in order to draw the next adjacent object part. For aesthetic reasons the artist(s) was always trying to ensure continuity in the adjacent one-stroke parts; the artist's desire was to ensure both continuity of the line itself, as well as of its tangent. It is very logical to assume that, in this way, the artist wanted to lure the potential viewer towards believing that the contour was made in a uniform manner and probably by hand.

After analyzing the spiral themes initially decorating the internal murals of the upper most floor (see Fig. 2), we have reached the conclusion that these spirals fit a single linear (Archimedes) spiral in an excellent manner. Thus, we have extended this result and we have stated the hypothesis that, probably, geometric stencils and/or apparatuses had been used for the drawing of the contours of arbitrary figures in all considered wall paintings. However, we have made the plausible assumption that the corresponding geometric prototypes should be compatible with the capabilities of an ancient civilization. Consequently, we have considered the following geometric candidates:

A. exponential spiral

B. the spiral generated by unwrapping a thread around a peg, usually called the involute of a circle

C. the linear or Archimedes' spiral

D. the ellipse

E. the parabola

F. the hyperbola

General information about these curves can be found in (Katz 2008) and (Boyer and Merzbach 2011). Concerning spirals, here are infinitely many types of them. More specifically, the involute of a circle and the exponential spiral are encountered in nature: the involute of a circle can be easily generated in everyday life events, while the exponential spiral can be found in various cockleshells. Thus, it is not a surprising fact that rough approximations of these two types of spirals are encountered quite early in various prehistoric civilizations.

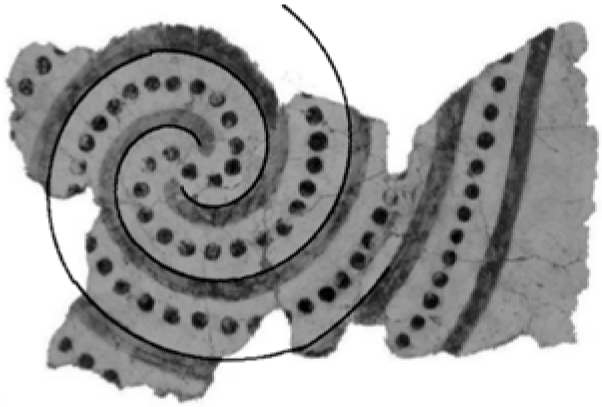

Fig. 2. The linear spiral fitting the drawn one.

On the other hand, the Archimedes spiral seemingly does not exist in nature. Archimedes defines linear spiral and gives many fundamental properties and related theorems. For these reasons, the linear spiral also bears Archimedes spiral.

Conics where not known as mathematical objects at the time that the wall paintings were made, but people at the time of Thera civilization probably had the means to construct them empirically. It seems that the first who actually conceived them as mathematical objects and realized that they result from the intersection of a cone with a plane was Menaichmos, around 350 BC. The first who wrote about conics is Euclid around 300 BC. The names of the three conic types (ellipse, hyperbola, parabola), as well as many complicated theorems, are attributed to Apollonius.

The equations of all candidate prototype curves are shown in Table 1.

2 Testing these hypotheses

It is highly probable and reasonable to assume that the prehistoric artist did not have a rigorous mathematical background to support his methods. Therefore, it is equally logical to expect that at the changing points of positioning the stencil or the apparatus, he did not ensure continuity of the curvature. Actually, he most probably did not know the mathematical concept of curvature. Therefore, we may retrospectively guess the sequence of his actions, employing modern advanced mathematics and computer algorithms. Indeed:

1. One may characterize a one-stroke part of a figure's contour, as a subset of this contour having continuity in the first derivative together with continuity of the curvature.

2. At the points where repositioning of the stencil or apparatus took place, one expects to encounter a considerable discontinuity of the curvature.

3. In order to accomplish steps 1 and 2 above, one must extract the boundaries of the figures of the studied wall paintings, by means of an effective image segmentation algorithm.

4. After successfully extracting the figures' contours of the considered wall paintings, one must properly estimate the

curvature at all points of these contours with the maximum greater accuracy.

5. After evaluating the curvature, one must answer the question whether the sequence of the curvature values at the points of a one-stroke part corresponds to a specific geometric prototype with the greater possible likelihood.

2.1 First stage of processing

In order to obtain the wall paintings' contours at first we have to take high resolution digital images of these paintings. If a wall painting is available for photo shooting, the photographs are being taken following a strict protocol. If not, published images of the wall paintings are scanned in 600 dpi resolution. Image segmentation and edge detection (Roman *et al*. 2001), (Lopez 2013) algorithms are applied to determine the drawn parts contours. The final step of this first stage of processing is to define the stroke part, namely, the most probable different contour parts which consist the whole contour of each figure.

2.2 Determining congruencies between painted contours and geometric prototypes

Suppose that one wants to find out if a specific one-stroke part, symbolized P^{OS}, optimally fits to a geometric prototype of a certain class, e.g. hyperbolae. We have proved (Arabadjis *et al*. 2011) that two parameters are sufficient for the determination of the member of each class. Thus, for example consider the arbitrary conic or spiral given by the implicit form:

$$f(x,y;\ a,b)=0 \qquad (3.1)$$

where (x, y) is the pair of the Cartesian coordinates of each point of the geometric curve and (a, b) the pair of the primary parameters of the curve. For example, for the class of hyperbolae with axes parallel to the coordinate axis, equation (3.1) reads:

$$\frac{(x-x_0)^2}{a^2}-\frac{(y-y_0)^2}{b^2}-1=0.$$

In order to test if the geometric prototype described by equation (3.1) optimally fits the given one-stroke part P^{OS}, we have developed a number of mathematical entities, together with a number of associated propositions and algorithms, which are, very briefly, outlined bellow in the form of steps:

Step 1: we consider all level-sets of the given geometric prototype, namely, the sets of points which satisfy the following equation:

$$f(x,y;\ a,b)=c$$

Evidently, vector $\vec{n}=\frac{\nabla F}{|\nabla F|}$ is perpendicular to the tangents of this level set. Using $\vec{n}$ we can determine the curvature at each point of each such level set by means of the planar function

$$C(x,y)\equiv\nabla\cdot\vec{n}\equiv\mathrm{div}(\vec{n}) \qquad (3.2)$$

which we will call plane curvature. In (Arabadjis *et al*. 2013) it has been shown that the optimal fit of an object part with a prototype P^G of the considered family of curves along vector field can be determined by minimization of the plane curvature discrepancy

$$\eta_c=\int_{P^{OS}}\left|C|_{P^G}-C|_{P^{OS}}\right|ds$$

Step2: in order to deal with simultaneous fit of P^{OS} with prototypes of different parameters (a,b) we will determine how the transformation (x,y) → (ax, by) affects C(x,y). By considering the infinitesimal generator of this transformation

$$A=\begin{bmatrix}1+da & 0\\ 0 & 1+db\end{bmatrix}\begin{bmatrix}1 & -dT\\ dT & 1\end{bmatrix}\Leftrightarrow A=$$

$$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}+\begin{bmatrix}da & -dT\\ dT & db\end{bmatrix}\equiv I_2+dA$$

where dT is the infinitesimal angle of rotation.

We obtain that the resulting deformation of C(x,y) is ruled by the PDE:

$dC=C\cdot\frac{g_a da+g_b db}{\mu^2}$ where

$\mu^2=|\nabla f|^2,\ g_a=3\left(\frac{\partial f}{\partial x}\right)^2-2\mu^2$ and

$g_b=3\left(\frac{\partial f}{\partial y}\right)^2-2\mu^2$

which is resolved by:

$$\frac{C(x,y;a,b)}{C(x,y;a_0,b_0)}=e^{\int_\Delta\frac{g_a da+g_b db}{\mu^2}}$$

It is understood that during this transformation, the pair of scaling factors (a,b) change along a curve Δ in their coordinate system, starting at identity point (a_0,b_0)

Considering this resolution for the change of C(x,y) under the change of parameters (a,b) the fitting error η_c depends on a, b and the starting point of the tested prototype curve's part.

These minimizers of η_c fully determine the prototype curve's part that optimally fits the considered object part P^{OS}.

Step 3: In order to test physical fit between the determined prototypes and the drawn contours the prototypes curves' parts are optimally rotated and translated so as to match the corresponding object parts minimizing the pair wise Euclidian distances (Papaodysseous *et al.* 2006). This error will be the main measure for the quality of the approximation of the painted contours by the determined prototypes.

2.3 Determination of the prototypes that approximate the considered wall painting contours

As described in Section 2, we have defined a set of candidate geometric prototype curves to test their correspondence to the actual figures' contours.

3 Main conclusion: many celebrated prehistoric wall paintings were drawn via the use of accurate geometric guides

Tab. 1. Implicit functions of the tested prototype curves families.

Prototype	Implicit function
Exponential Spiral	$f_{ES}(x,y\|a,b) = x^2 + y^2 - a^2 \exp\big(2b\,\theta(x,y)\big)$ $\theta(x,y) = \arctan\frac{y}{x} + \big(1-\operatorname{sgn}(x)\big)\frac{\pi}{2}$
Spiral of revolution	$f_{IV}(x,y\|a) = x^2 + y^2 - a^3(1+\theta_E(x,y)^2)$ $\theta_E + \arctan\theta_E = \arctan\frac{y}{x} + \big(1-\operatorname{sgn}(x)\big)\frac{\pi}{2}$
Linear Spiral	$f_{LS}(x,y\|\kappa) = x^2 + y^2 - \kappa^2\theta(x,y)^2$ $\theta(x,y) = \arctan\frac{y}{x} + \big(1-\operatorname{sgn}(x)\big)\frac{\pi}{2}$
Ellipse	$f_{EL}(x,y\|a,b) = \left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 - 1$
Hyperbola	$f_H(x,y\|a,b) = \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 - 1$
Parabola	$f_P(x,y\|a,b) = (ax+b)^2 - y$

Tab. 2. Prototype curve parameters.

The parameters of the determined prototypes for the "Lady of Mycenae" wall-painting

Prototype	Color	Parameters (cm)
Hyperbola 1	pink	$a = 11.583,\ b = 12.6025$
Hyperbola 2	brown	$a = 6.75,\ b = 13.7391$
Linear Spiral 1	orange	$\kappa = 0.0592$
Linear Spiral 2	green	$\kappa = 0.3175$

The parameters of the determined prototypes for the "Naked Boys" wall-painting

Prototype	Color	Parameters (cm)
Hyperbola 3	magenta	$a = 14.24,\ b = 20.12$
Hyperbola 4	light green	$a = 4.11,\ b = 6.29$
Hyperbola 5	blue	$a = 7.86,\ b = 17.63$
Hyperbola 6	cyan	$a = 2.09,\ b = 2.52$
Linear Spiral 3	red	$\kappa = 0.169$

We have verified the use of concrete geometric stencils in the drawing of a considerably increased number of prehistoric wall paintings. In fact:

- As far as the wall paintings of the Late Bronge Age excavated at Akrotiri, Thera are concerned, we have supported that at least 30 figures belonging to 9 different wall paintings fit specific geometric prototypes in an excellent manner. We emphasize the fact that these paintings dating c. 1650 BC decorated walls of different buildings such as the 'Xeste 3', the 'House of the Ladies', etc. These geometric prototypes are four distinct hyperbolae and a single Archimedes spiral, the parameters of which are shown in Table 1. The error with which the proper parts of these prototypes fit the corresponding drawn one-stroke contour part is exceptionally low. This fact, together with the particularly high average length of these one-stroke parts, strongly supports the initial hypothesis that the contours of the figures of these wall paintings had been drawn by means of corresponding hyperbolae or Archimedes spiral stencil and/or of an analogous apparatus.

The aforementioned results manifest a highly advanced sense of symmetry, geometric feeling and basic technology in Thera and the related Aegean islands in the 17th century BC at least.

- As far as 'Lady of Mycenae' is concerned, it is equally well supported that this wall painting too, had been drawn by means of similar geometric stencil or apparatuses. More specifically, two hyperbolae and two Archimedes spirals fit the one-stroke parts of the Lady of Mycenae contour in an excellent manner. The parameters of these geometric prototypes are different than those of the Akrotiri, Thera wall paintings. However, the fact that both hyperbolae and spirals had been used for the drawing of this wall painting circa 500 years after the eruption of the Thera volcano, indicates that the aforementioned sense of symmetry, geometry, fundamental technology and Art, had been spread and perpetuated in the expanded Aegean region for many centuries.

We firmly believe that the previously reported results support the following:

TAB. 3. THE ONE-STROKE PARTS FITTING ERRORS OF THE 'NAKED BOYS' WALL PAINTING.

One-stroke parts	Prototype	Mean Error (cm)	Max Error (cm)	Max Length (cm)
Hb3-Hb5, Hb8, Hb9, Hb11, Hb12, Hb14, Hb16, Hb18,Hb23, Hc1-4, Hc8, Hc9, Hc11, Hc12	Hyperbola 3	0.0209	0.0559	14.1541
Hb1, Hb2, Hb6, Hc10, Hc13, Hc14	Hyperbola 5	0.0168	0.0477	6.1036
Hb7, Hb10, Hb13, Hb15, Hb20, Hb21, Hc5 – Hc7, Hc15, Hc16	Hyperbola 6	0.0224	0.0470	7.7096
Hb17, Hb19, Hb22, Hc17, Hc18	Hyperbola 4	0.0193	0.0555	7.1760
Sb1 – Sb8, Sc1 – Sc20	Linear Spiral 3	0.0295	0.0497	15.5649

TAB. 4. THE ONE-STROKE PARTS FITTING ERRORS OF THE 'LADY OF MYCENAE' WALL PAINTING.

One-stroke parts	Prototype	Mean Error (cm)	Max Error (cm)	Max Length (cm)
H1-H11, H15-H19, H23	Hyperbola 1	0.0197	0.0555	16.6597
H12-H14, H20-H22,H24,H25	Hyperbola 2	0.0169	0.0449	9.9723
S1-S3, S5-S10,S18, S19, S31-S34	Linear Spiral 1	0.0107	0.0272	5.2204
S4, S11-S17, S20-S30	Linear Spiral 2	0.0161	0.0374	9.1799

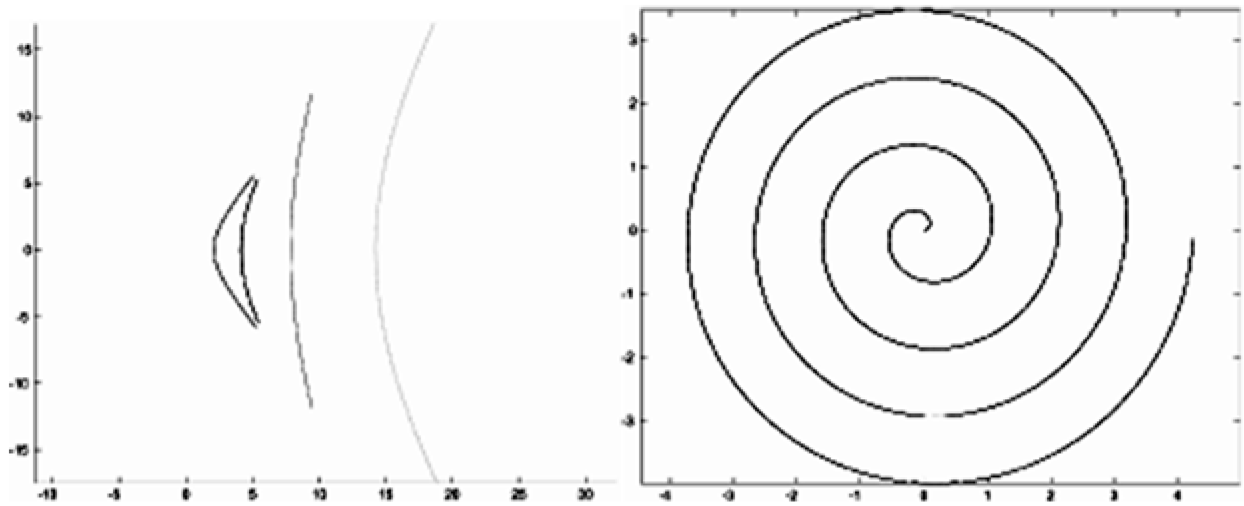

FIG. 3. THE GEOMETRIC STENCILS USED IN THE WALL PAINTING 'NAKED BOYS'.

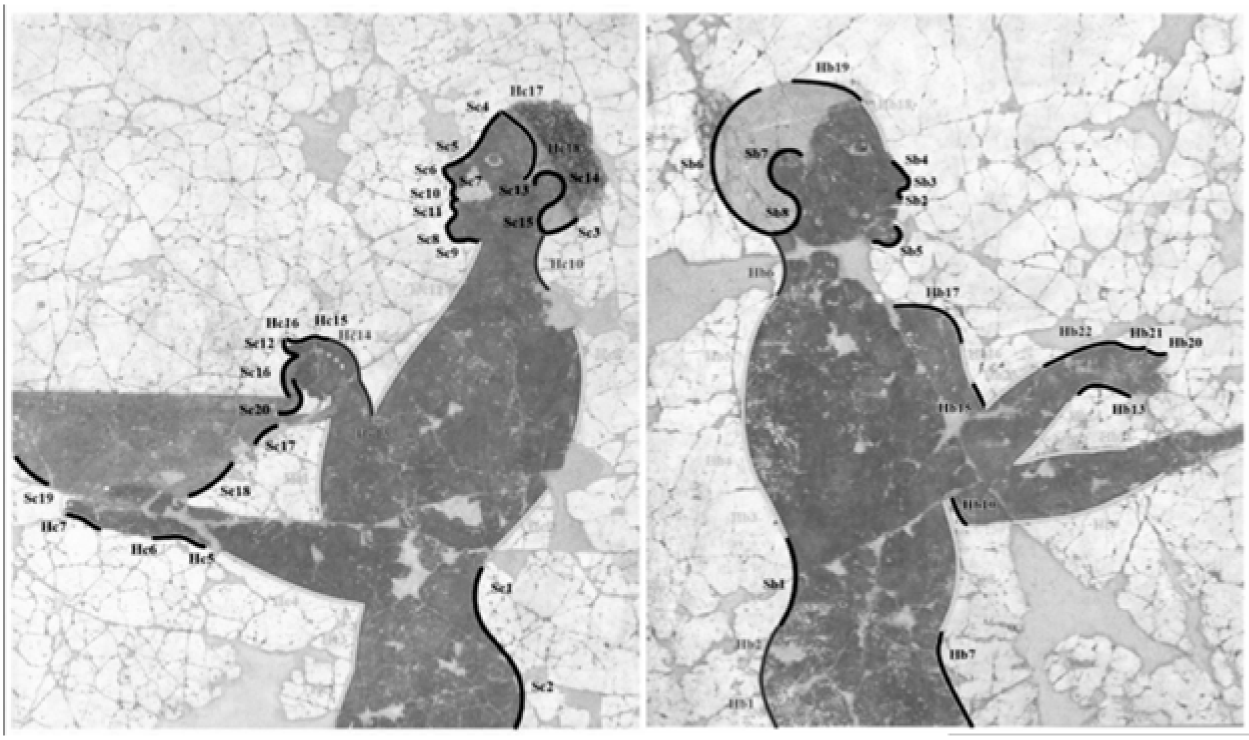

Fig. 4. The fitting of the corresponding stencils to the drawn contour parts.

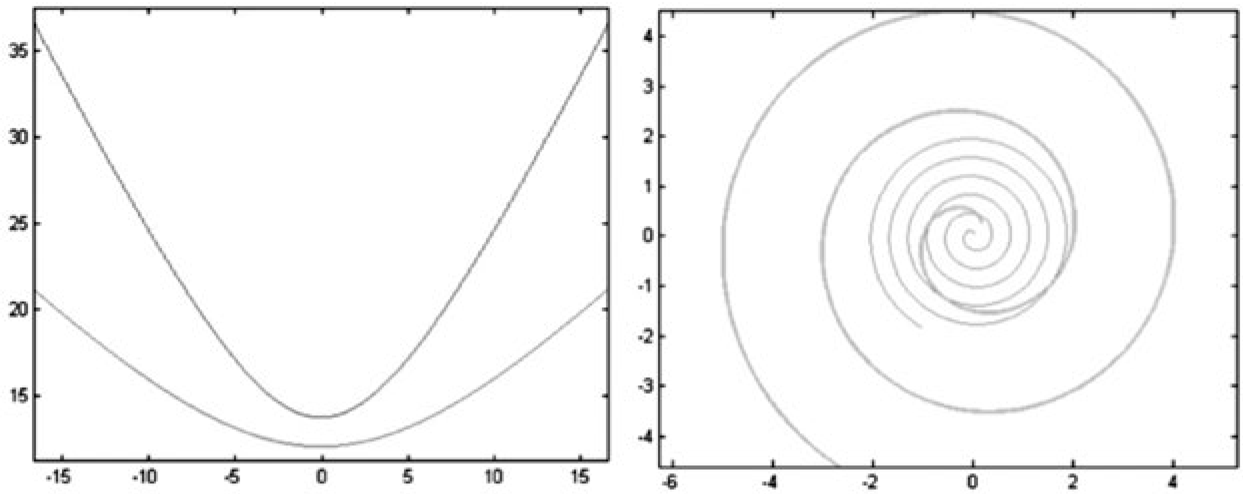

Fig. 5. The geometric stencils used in the wall painting 'Lady of Mycenae'.

1. Inspiration is always ahead of the rigorous foundation. In other words, a subconscious and/or emotional knowledge is necessary to exist before the appearance of a formal theory.

2. Primitive science and technology had been also developed in order to satisfy aesthetic reasons and an immerging need of expression.

3. As far as the specific prehistoric wall paintings which have been studied, it seems that the form of the expression of the esthetic feeling is constrained by the choice or the availability of the means of drawing.

Finally, as far as the contemporary approach is concerned, we would like to point out that the new approach introduced here for testing the hypothesis of section 2, is in full accordance with the results offered by other different methods previously developed by the authors.

Bibliography

Arabadjis, D., Giannopoulos, F., Papaodysseus, C., Zannos, S., Rousopoulos, P., Panagopoulos, M., Blackwell, C. 2013. New mathematical and algorithmic schemes for pattern classification with application to the identification

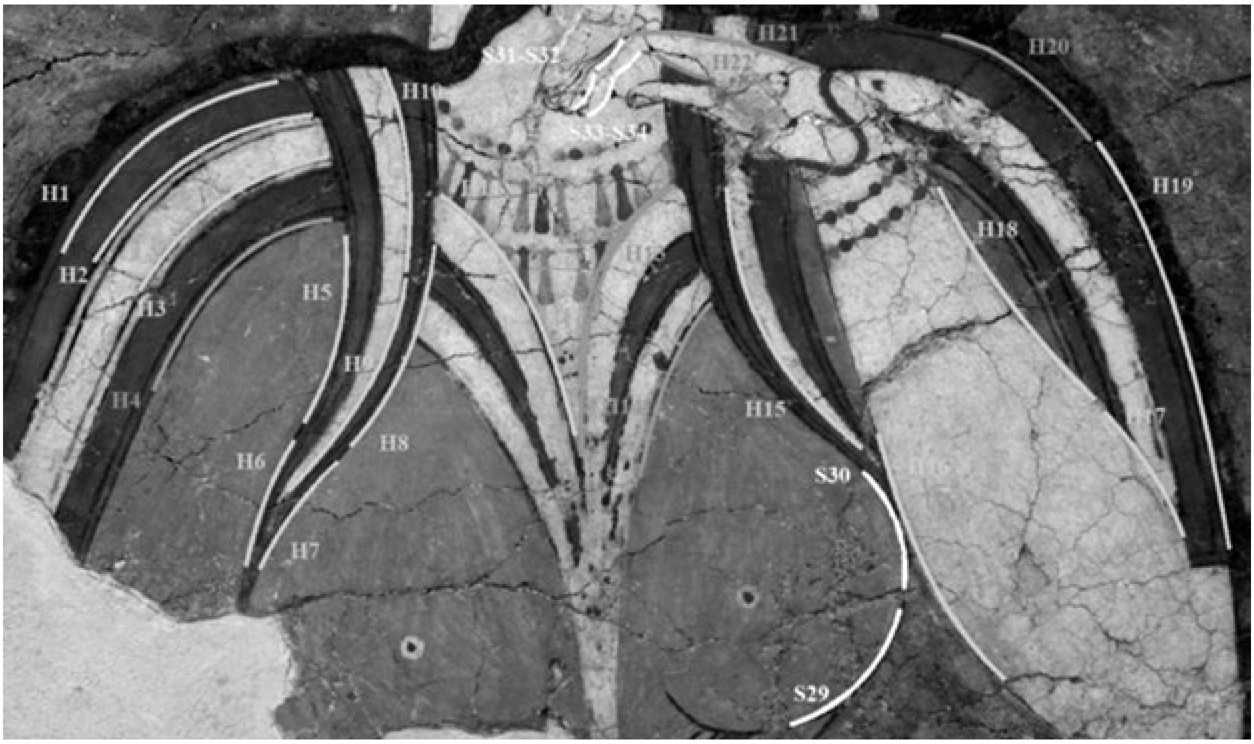

Fig. 6. The fitting of the corresponding stencils to the drawn contour parts.

of writers of important ancient documents. *Pattern Recognition* 46: 2278-96.

Arabadjis, D., Rousopoulos, P., Papaodysseus, C., Exarhos, M., Panagopoulos, M., Papazoglou-Manioudaki, L. 2011. Optimization in Differentiable Manifolds in Order to Determine the Method of Construction of Prehistoric Wall Paintings. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 33: 2229-44. doi:10.1109/TPAMI.2011.65

Atieg, A., Watson, G. A. 2003. A class of methods for fitting a curve or surface to data by minimizing the sum of squares of orthogonal distances. Journal of Computational and Applied Mathematics 158, 277–296. doi:10.1016/S0377-0427(03)00448-5

Boyer, C. B., Merzbach, U. C. 2011. *A History of Mathematics*. John Wiley & Sons.

Doumas, C. 1992. *The wall-paintings of Thera*. Thera Fondation, Athens.

Katz, V. J. 2008. *A History of Mathematics*. Pearson, Boston.

Lopez-Molina, C., De Baets, B., Bustince, H. 2013. Quantitative error measures for edge detection. *Pattern Recognition* 46: 1125-39. doi:10.1016/j.patcog.2012.10.027

Papaodysseus, C., Fragoulis, D. K., Panagopoulos, M., Panagopoulos, T., Rousopoulos, P., Exarhos, M., Skembris, A. 2006. Determination of the method of construction of 1650 BC wall paintings. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 28: 1361-71.

Pintus, R., Pal, K., Yang, Y., Weyrich, T., Gobbetti, E., Rushmeier, H. 2014. Geometric Analysis in Cultural Heritage. In R. Klein and P. Santos (eds.), Eurographics Workshops on Graphics and Cultural Heritage: 117-33. The Eurographics Association.

Román-Roldán, R., Gómez-Lopera, J. F., Atae-Allah, C., Martínez-Aroza, J., Luque-Escamilla, P. L. 2001. A measure of quality for evaluating methods of segmentation and edge detection. *Pattern Recognition* 34: 969-80. doi:10.1016/S0031-3203(00)00052-2

Roussopoulos, P., Papaodysseus, C., Arabadjis, D., Exarhos, M., Panagopoulos, M. 2010. Image and Pattern Analysis for the Determination of the Method of Drawing Celebrated Thera Wall-paintings circa 1650 BC. *Journal on Computing and Cultural Heritage* 3, 2: 1-21. ACM. doi:10.1145/1841317.1841318

Sablatnig, R., Kammerer, P., Zolda, E. 1999. Structural analysis of paintings based on brush strokes. In W. C. McCrone, R. J. Weiss (eds.), *Fakebusters: Scientific detection of fakery in art*: 222-44. Hansen, Stoughton, Massachussetts. doi:10.1117/12.308585

Schäfer, A., Bock, G., Sanday, J., Leitte, H. 2015. Virtually reassembling Angkor-style Khmer temples. *Digital Applications in Archaeology and Cultural Heritage* 2: 2-11. doi:10.1016/j.daach.2014.12.001

Werman, M., Keren, D. 2001. A Bayesian Method for Fitting Parametric and Nonparametric Models to Noisy Data. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 23, 5: 528-34.

Pottery Studies of the 4th-Century Necropolis at Bârlad-Valea Seacă, Romania

Vlad-Andrei Lăzărescu
lazarescu_vlad@yahoo.com
Romanian Academy, Institute of Archaeology and History of Art, Cluj-Napoca, Romania

Vincent Mom
v.mom@kpnmail.nl
DPP Foundation, Rotterdam, Netherlands

Abstract: The Migration period in general and the Early Migration period in particular continue to be among the least studied fields in Romanian archaeology. Pottery from important sites from that period, especially necropolises, was not given much attention and especially the necropolis at Bârlad-Valea Seacă, one of the largest sites, was paradoxically hardly studied. Moreover, the site (that was never before studied in its entirety due to the huge quantity of artefacts) is one of the richest cemeteries suffering little from post-disturbances while covering the complete chronology of the Sântana de Mureș - Černjachov (SMC) culture. The present paper studies the evolution of artefact types, using a clustering machine learning approach through the use of the Secanto software, a sophisticated version of the 'sliced method' introduced by Shennan and Wilcock (1975). The software is both effective and efficient in handling big datasets and generating large distance matrices that constitute the basis for the subsequent statistical analysis and creation of distribution maps. Finally, by using combined artefacts from the closed contexts it was possible to establish a preliminary relative chronology while making also close observations regarding the spatial distribution and chronological evolution of the necropolis which led to interesting archaeological conclusions about the entire site.

Keywords: Romanian archaeology, Migration period, Necropolis, Pottery

Introduction

After decades of scientific studies, the Late Roman and Early Migration period (300 AD - 450 AD) is still one of the least studied fields in Romanian archaeology. Although there are some general studies (e.g. Horedt 1982; 1986; Harhoiu 1998), most of the available publications describe stray finds or singular archaeological features only, ignoring their general context. Also, during the last 20 years several site monographs were published (for example Dragomir 2001; Palade 2004; Șovan 2005; Vornic 2006; Ursachi 2007; 2010) but for the other large sites of the Migration period adequate publications are still missing. And without further publications of such site monographs the elaboration of a general history of this complex epoch cannot continue.

Because of the lack of a good research strategy for this period, the majority of archaeological material comes from rescue excavations and stray finds, while there are only a few systematic excavations that are properly documented. The processing of these larger excavations is difficult due to the huge quantities of finds but also because of the limited documentation of the archaeological contexts. The archaeological research of pottery from this period therefore is much behind and the existing gaps are only just beginning to be filled (Lăzărescu 2011).

Discussions about broader subjects such as the general context of this era and the relations between different communities that inhabited the nowadays territory of Romania are scarce, and, in many cases, ignored by the majority of Romanian archaeologists who are still focusing on cataloguing and analysing individual sites and artefacts without creating theoretical frameworks to integrate their research. Moreover, there is a lack of regional studies highlighting specific patterns of evolution and development of regional tendencies and the national archaeological research strategy has no proper research plan (Stanciu 2010 and for reflections on the manner in which archaeology in Romania was approached at a theoretical level see e.g. Niculescu 2002 and 2004-2005; Anghelinu 2003; Palincaș 2006; Dragoman and Oanță-Mărghitu 2006; Măgureanu 2007; Dragoman 2009; and more recently Dragoman and Oanță-Mărghitu 2013). But many of the complex topics raised by the research of the Early Migration period are of paramount importance for the understanding and contextualising of the phenomena that contributed to the development of the European civilization. Therefore a reassessment of the current theories of this historical period, based on the (re-) interpretation of both old and new discoveries, is highly needed.

Our research is focused on the problems mentioned above, and we attempt to put our analysis results in context, starting with the site at Bârlad-Valea Seacă. We try to find the right position of this site in the general framework of its historical period, hoping that some of the patterns observed for this site will enhance and improve the knowledge of the Early Migration period. To achieve such results the research is conducted at two different levels, a general level to establish the main chronological and spatial characteristics of the period and on the other hand at an interpretative level in line with current archaeological theories.

1 Bârlad-Valea Seacă

The site at Bârlad-Valea Seacă (Vaslui County, Moldavia region) was discovered by Vasile Palade in 1959. The site is located on a relatively narrow valley of the river Periana/ Valea Seacă, being part of the larger area of the Tutovei Hills (geographical coordinates: 46°41' northern latitude and 20°40' eastern longitude). The site is nowadays part of the city of Bârlad (Fig. 1). The next year, performing small scale rescue

Fig. 1. Spatial distribution of the Sântana de Mureș - Černjachov sites in Romania (after Petrescu 2002).

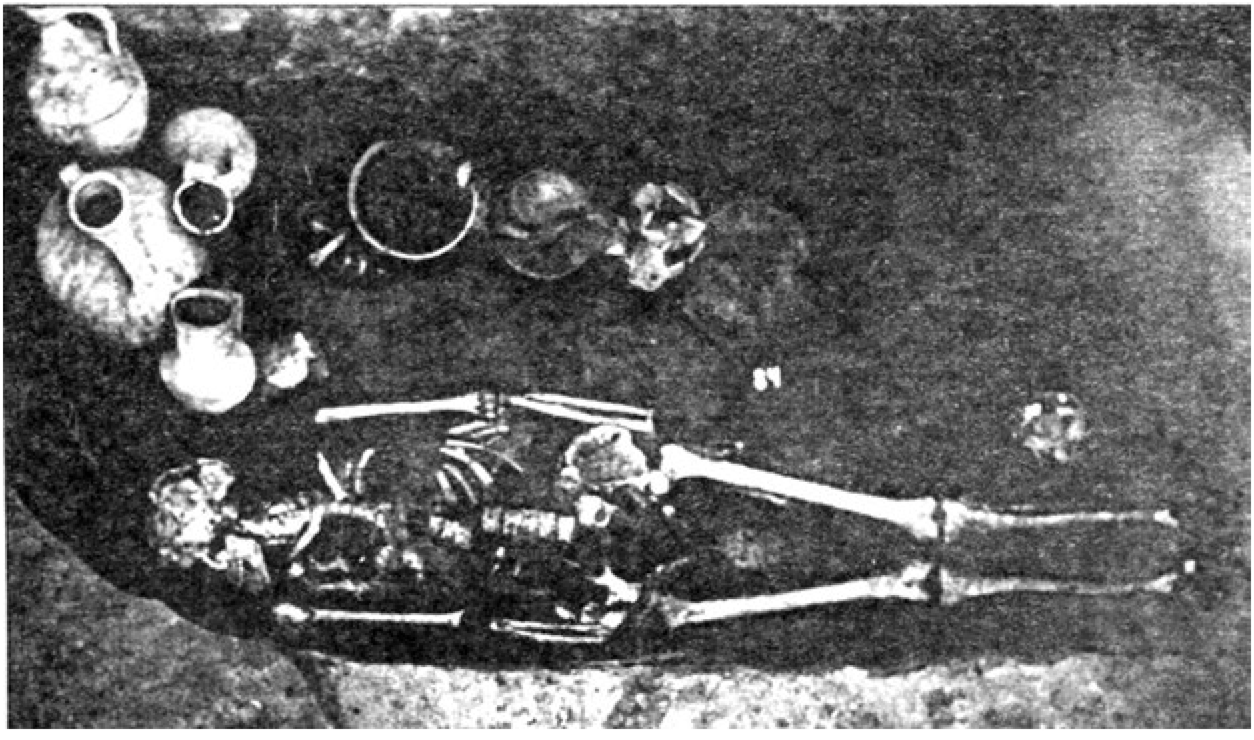

Fig. 2. Grave 84: excavation snapshot (after Palade 2004).

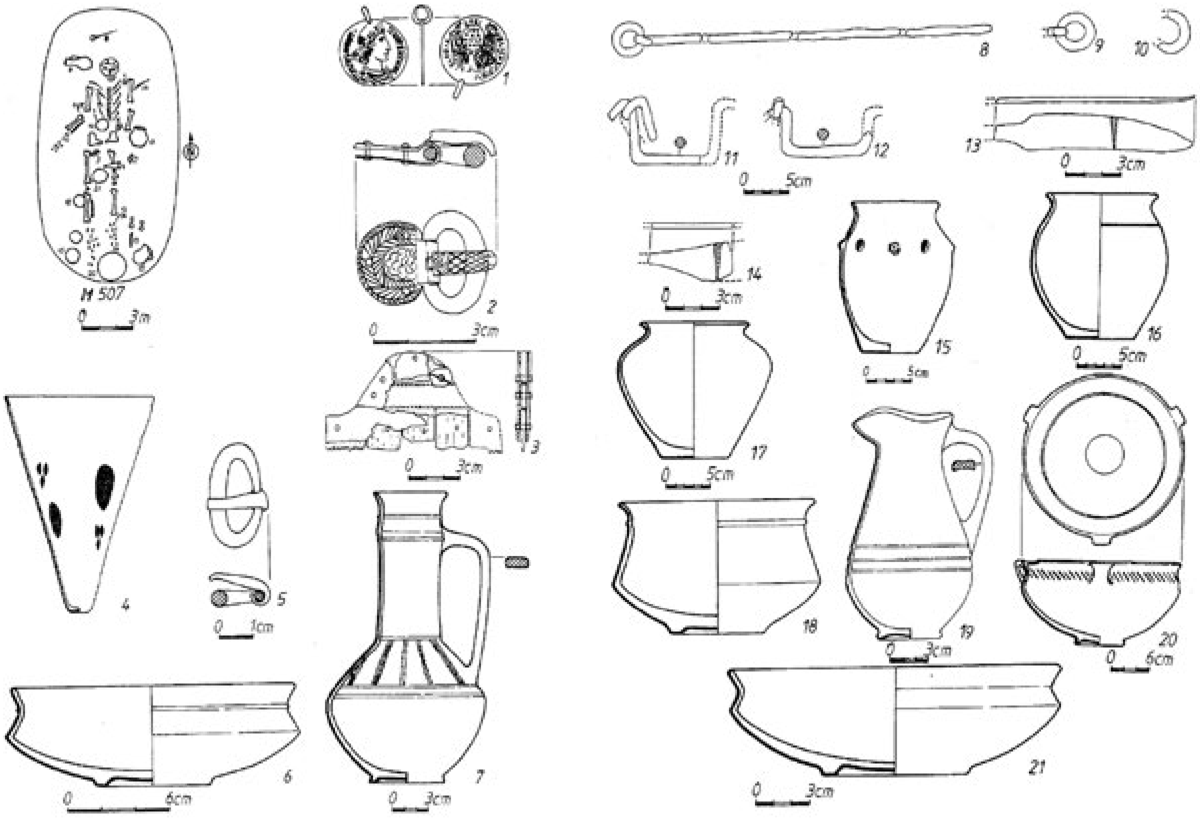

Fig. 3. Grave 507: items 6, 7 and 15-21 are part of the dataset (after Palade 2004).

excavations, Palade uncovered the remains of a large antler comb workshop, quite a rare phenomenon for Early Migration period. In 1961 Palade started systematic investigating the site, being convinced of the great value of his discovery. The excavations of the necropolis were continued between 1967-1975 and the settlement between 1967-1975 and 1980-1986 (Palade 2004).

The results were impressive: an area of 2500 m^2 was excavated with 24 surface dwellings (of which 5 stag antler comb workshops), 21 sunken floor dwellings (of which 18 also contained traces of stag antler comb production) and 8 open working places for antler processing. Furthermore 10 other outbuildings, 2 pottery kilns and over 40 waste pits were discovered. The necropolis was completely excavated, containing of 547 tombs (295 cremation graves and 252 inhumation graves) (Figs. 2 and 3).

Unfortunately, Palade did not manage to finalize the monograph of the site and it was only in 2004, that a team of archaeologists from the Bârlad Museum joined forces to finalize the work that was started by their now deceased colleague. The monograph, although it only contains the raw, un-interpreted documentation, field drawings and an inventory of the finds, discloses hitherto unknown information with high impact for the study of the Late Roman and Early Migration period.

2 The Sântana de Mureș - Černjachov culture

The great importance of the Bârlad-Valea Seacă site lies in the fact that it is one of the largest (and entirely excavated) sites that covers the complete chronology of the Sântana de Mureș - Černjachov (SMC) culture. Moreover, the site (that was never before studied in its entirety due to the huge quantity of material) is one of the richest cemeteries suffering little from post-disturbances. This makes Bârlad-Valea Seacă an ideal case for the study of chronological developments, and therefore may serve as a standard for comparing other important sites from this culture.

The concept of the 'Sântana de Mureș - Černjachov culture' appeared at the end of the 19th century after the discoveries of Černjachov, Ukraine and Sântana de Mureş, Romania (Wolfram 1990). This culture is attributed to a complex multicultural phenomenon of acculturation of several populations of which the Gothic component seems to be the most important. It was formed during the middle of the 3rd century AD north of the Black Sea and moved slowly southward towards the Danube during the 4th century AD (Ioniță 1966; Magomedov 2001). This cultural complex reached the territory of nowadays Romania probably at the beginning of the 4th century AD (Mitrea and Preda 1966), the population becoming *foederati*[1] after concluding a peace treaty with the Roman Empire in 332 AD (IstRom 1961; IstRom 2001). So the antiquities found at Bârlad-Valea Seacă belong to a wide cultural heritage, covering the area between the basin of the northern Donet (to the East - Ukraine) and Transylvania (to the West - Romania)

[1] *Foederati* in the 4th century AD were a group of 'barbarians' that were allowed inside the territory of the Roman Empire as part of a *foedus*, namely a peace treaty between a certain 'barbarian group' and the Roman Empire (Pohl 1997; Wolfram 1990).

and between the Lower Danube (to the South) and Volynia (to the North - Ukraine) (Bierbrauer 1995; Heather 1998).

Starting with the settling of the Goths in the northern region, we can discern a radical change at the ethnic and demographic level. The large number of sites from this period suggests a demographic boom (Petrescu 2002, see Fig. 1) together with a mixture of different populations and/or cultural traditions of local origin or newly arrived (Diaconu 1963; Diaconu 1964; Diaconu 1965; Diaconu 1965a; Diaconu 1975; Diaconu 1980; Niculescu 2003). One of the most relevant examples of this phenomenon is the cemetery at Târgșorul Vechi, Prahova County (Diaconu, 1965 and Niculescu 1993) although similarities are present in other necropolises such as e.g. Mihălășeni, Botoșani County (Șovan 2005) and Bârlad-Valea Seacă (Palade 2004). And even though the chronology of the SMC culture on the nowadays territory of Romania is generally attributed to the 4th century AD, some features argue both for an earlier dating towards the second part of the 3rd century AD as well as for the beginning of the 5th century AD for the late phase (Kazanski and Legoux 1988; Tejral 2000; Kazanski 2012; Schukin and Charov 1999), as is the case for the necropolis at Bârlad-Valea Seacă. See Lăzărescu (2014 and 2015) for the entire discussion and literature regarding the late phase of the SMC culture on the territory of nowadays Romania.

3 Sântana de Mureș - Černjachov pottery

Sântana de Mureș - Černjachov pottery is only briefly mentioned in the Romanian archaeological literature, limited to local classifications for specific sites and without a general approach or conclusions (Mitrea and Preda 1966; Ioniță 1966 and 1982; Nemeti 2007). The only attempt for a global approach of wheel thrown pottery so far was done by Diaconu (1970a). Worth mentioning are the studies of the cemeteries at Târgșorul Vechi (Diaconu 1965; Niculescu 1993), Mogoșani (Diaconu 1970), Independența (Ioniță 1971) and, more recently, the latest monographs about the necropolises at Mihălășeni (Șovan 2005) and Budești (Vornic 2006). The last two publications also present relative chronologies of certain types of pottery based on the different combinations in which they were found as part of closed contexts together with well-dated artefacts. This information improves the comparisons and dating of different sites considerably.

The way pottery was studied changed over time. In the 1960s-1970s there was a tendency to present an increasing number of new pottery types, due to the increasing number of newly discovered sites. During the 1980s-1990s, certain topics of special types of pottery were studied in more detail. And currently the approach focuses on the development of regional typologies whilst the corresponding pottery database is enlarged. This increased amount of data enables better site comparisons and might finally result in a general pottery typology and (relative) chronology of the individual pottery types from the SMC culture (see also Lăzărescu 2011).

4 The Secanto computer program

It is important that when dealing with a large collection of vessels (in our case 634) to group similar items in meaningful categories in order to recognise patterns in the dataset as well as providing a framework to link other information to (Orton, Tyres, Vince 1993). In our case, the first step was to establish shape categories and afterwards to attach to this classification structure other types of attributes relevant to pottery such as fabric, firing etc.

To do this the Secanto computer program was used. Secanto is a sophisticated version of the 'sliced method' as developed by Shennan and Wilcock (1975) in order to classify bell beakers from Central Germany. In figure 4 the main principle is shown: two vessel profiles are scaled to the same height and are divided into 150 equidistant slices along the vertical axes. The 'distances' between the vessels are calculated as the sum of squares of the distances between the points on the outer surfaces of the vessels. The profiles are shifted until the minimal value is obtained (Fig. 5). To incorporate not only the shape of the outer vessel wall, but also the overall vessel width, the distances between the central axes are added as well.

The Secanto computer program has several advantages when compared to the traditional intuitive classification. The main one being that it calculates exactly the distance between the overall shapes of vessels. Such a procedure is more precise, objective and repeatable (and therefore easier to check) than intuitive classifications such as 'beaker A looks very similar to B, however specimen C has an entirely different shape'. Such statements do not include a precise quantification of the degree of similarity.

However, it should be emphasised that the Secanto computer program focuses on the overall vessel shape and, therefore, ignores any details. Accordingly, nominal traits, such as inverted rims, protruding feet and carinated profiles, are not seen as being important, in contrast to traditional typologies. See Mom (2007 and 2008) for more information.

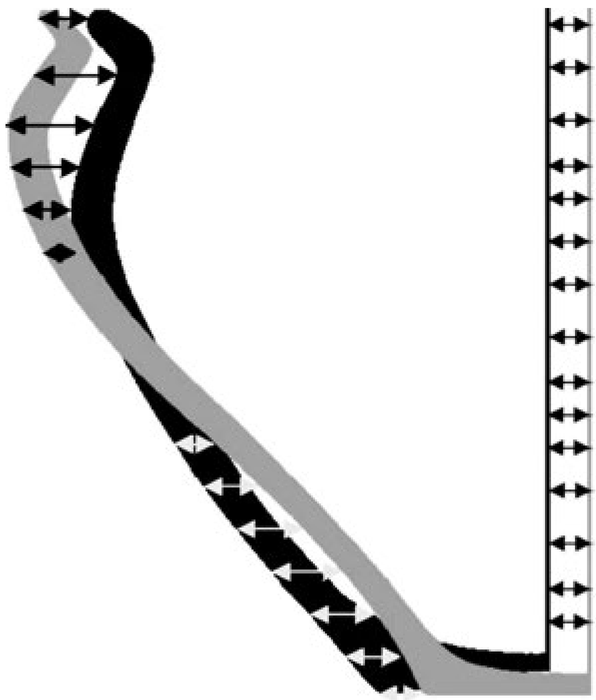

Fig. 4. Calculation of the distance between two vessel shapes.

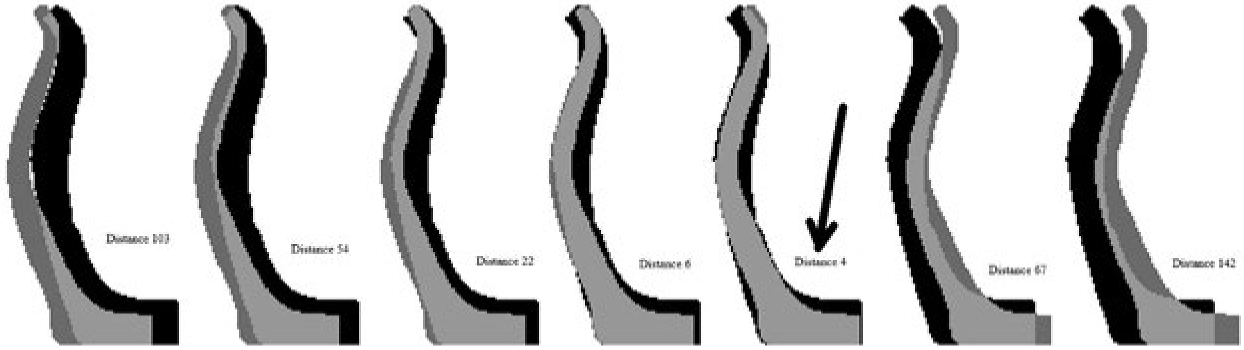

Fig. 5. Obtaining the lowest distance value.

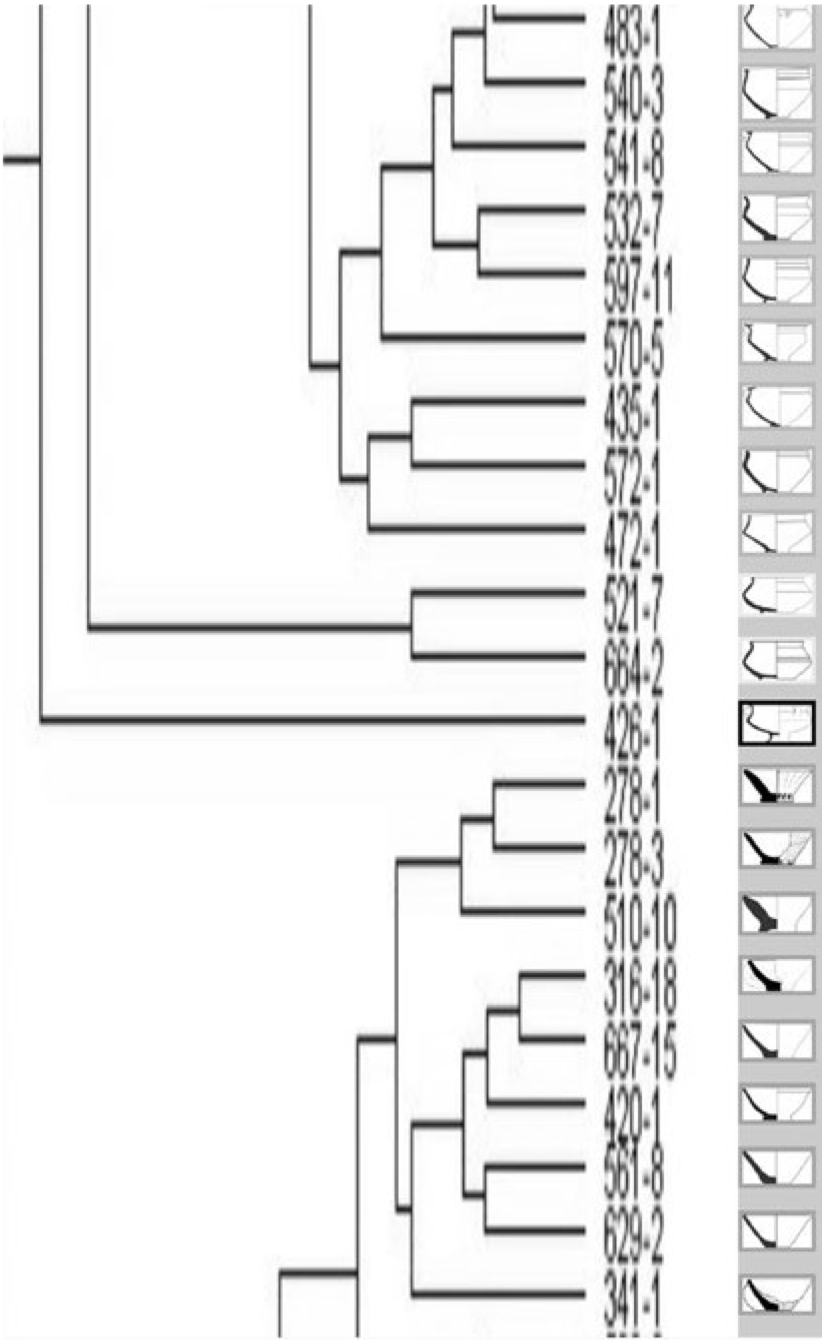

Fig. 6. Clustering using Ward's method.

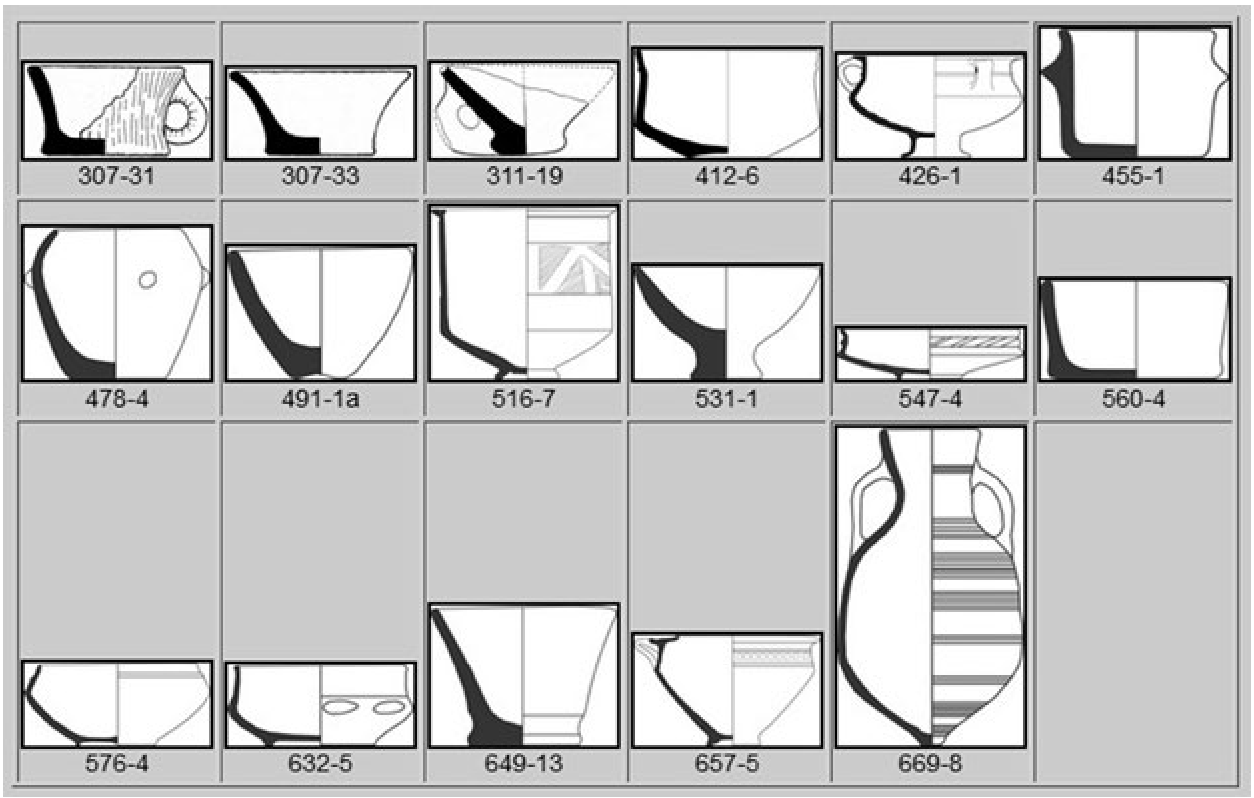

Fig. 7. Special shapes.

In this phase of the research of the SMC pottery we used the data from Bârlad-Valea Seacă to create the foundations for a local typology, which would also serve as a reference database for comparing other similar sites. Using Secanto the 634 vessels were grouped according to shape, to get an overview of the data set and also to detect any 'special' shapes. The distance matrix contains 634*(634-1)/2 = 200661 individual distances but this amount did not pose a problem to the PAST statistical program (Hammer 2001) that was used to do the subsequent cluster analysis of the distance matrix.

For this cluster analysis, Ward's method (Ward 1963) was used. The resulting hierarchical clustering, small part of which is shown in figure 6, gives a good overview and especially 'special' vessels (that is: unique ones without lookalikes) stand out clearly. Figure 7 shows the 17 special shapes that were detected.

The other 617 vessels were distributed over 56 clusters. Half of the vessels were distributed over 12 clusters only. In figure 8 the number of vessels per cluster is shown, with the image of the vessel that is considered to be the best representative of the shape cluster. The largest cluster contains 80 vessels.

A second method of clustering the vessels is by assigning them initially at random to a preset number of clusters, and then improving these assignments based on so-called silhouette criteria (Rousseeuw 1987). The silhouette value measures how well a vessel lies within its cluster. The values range from -1 (bad) to +1 (perfect). If the silhouette value of a vessel is below zero then this implies that there exists a better cluster for this vessel, and the vessel is moved to this better cluster. This iterative process ends when there are no more vessels that should be moved to another cluster.

The number of clusters at the end of the process is always less or equal to starting number, as clusters can 'evaporate' during the reassignment process. This makes it possible to manipulate the process such that the resulting number of clusters is (more or less) the same as the number of clusters resulting from Ward's method. This gives two different views on the dataset.

Using the silhouette method starting with 110 clusters results in an average of 75 clusters, of which on an average 5 are 'special shapes'. Because of the random starting position the end results vary and there is also a spread in the quality of the end results, measured as the average silhouette value of the complete dataset. See figure 9 for the 'special shapes'. In figure 10 the number of vessels per cluster is shown for the silhouette method. Ward's clustering technique provides, in our opinion, a better insight in the composition of the vessel dataset, especially as it isolates the 'special shapes' better.

Principal Coordinate analysis diagram of the 56 clusters is shown in figure 11. The horizontal coordinate relates strongly to the height/width ratio of the vessels, while the vertical coordinate reflects the 'openness' of the vessel: flask like vessels with a belly are found in upper/left part of the diagram while open bowl shapes are in the opposite corner.

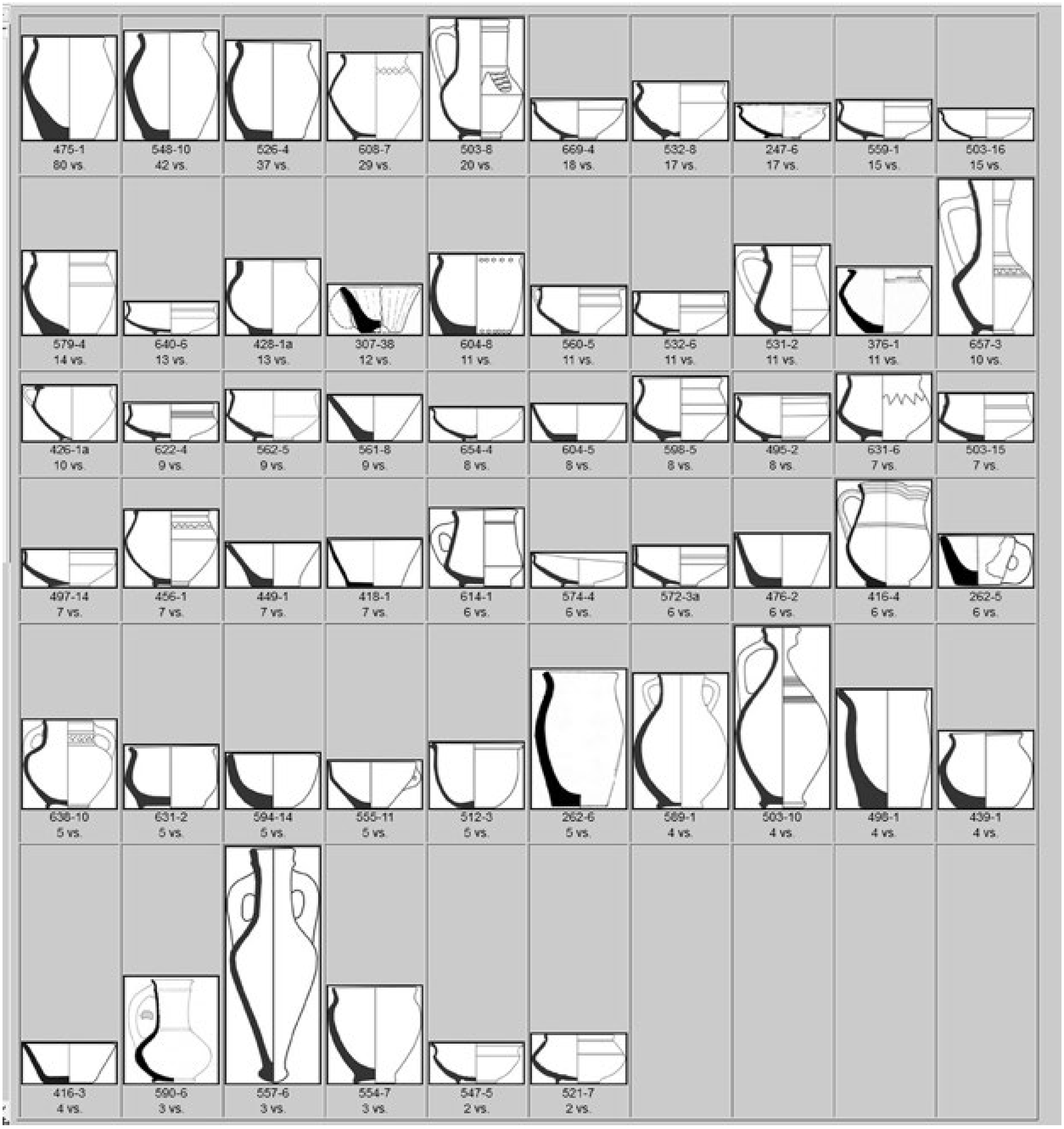

Fig. 8. 56 shapes and the number of vessels per shape cluster.

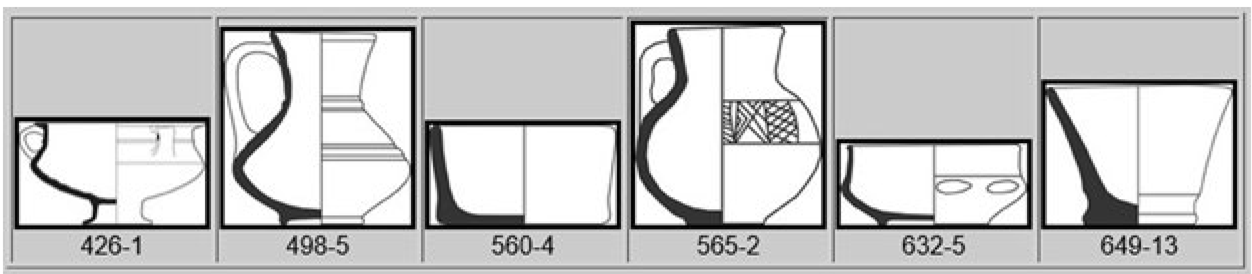

Fig. 9. Special shapes according to the silhouette method.

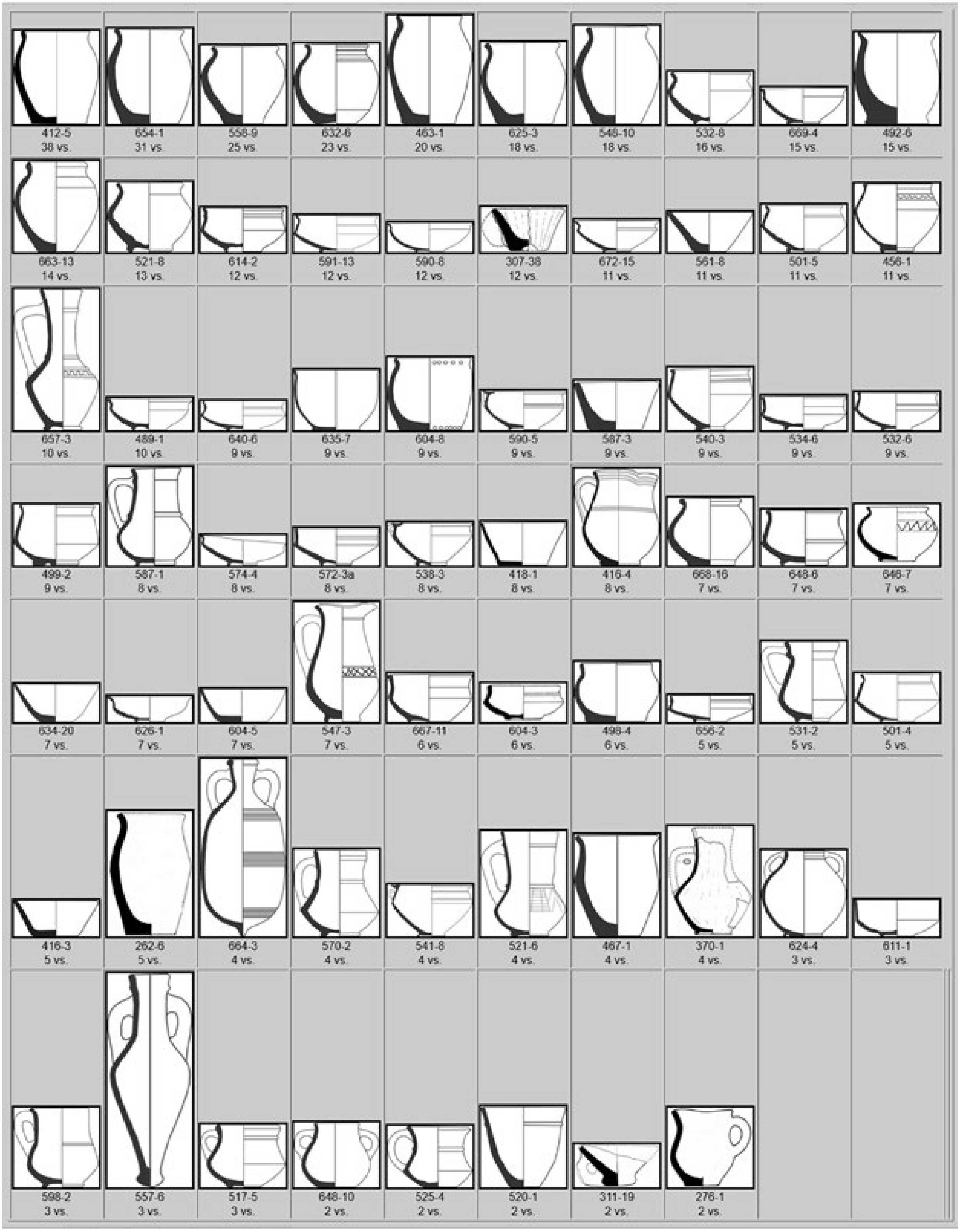

FIG. 10. 68 SHAPES USING THE SILHOUETTE METHOD AND THE NUMBER OF VESSELS PER SHAPE CLUSTER.

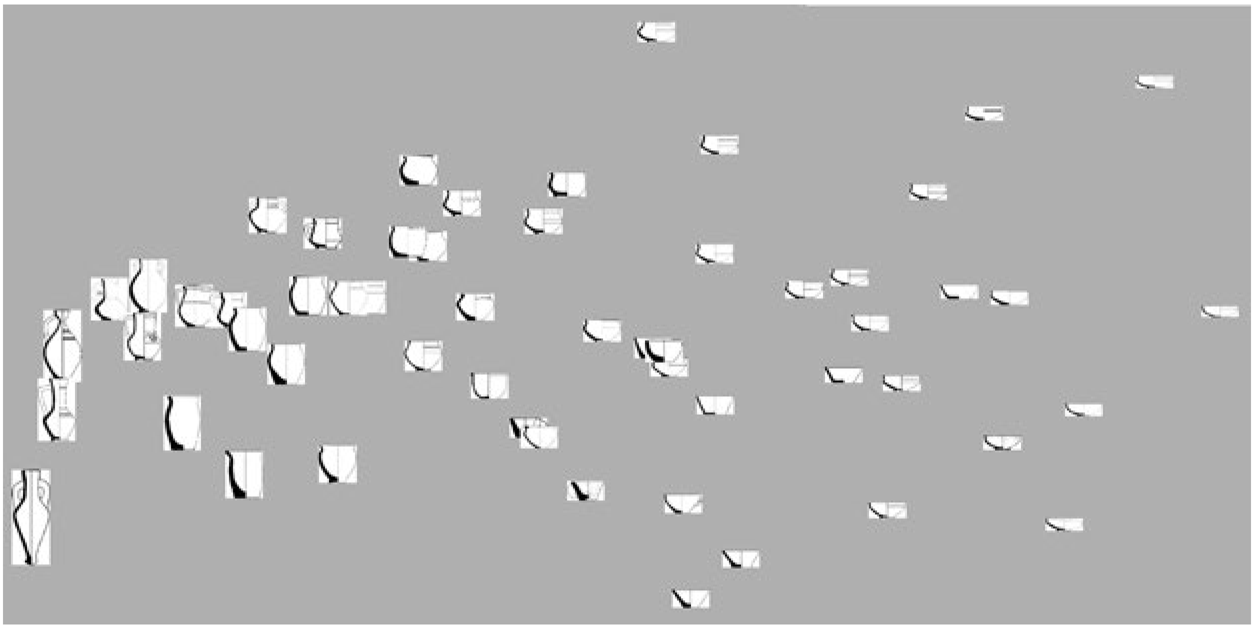

Fig. 11. Principal coordinate analysis of 56 shapes.

5 Preliminary results

Using combined artefacts from the closed contexts (in our case: graves) we established a preliminary relative chronology of the necropolis and implicitly of the pottery groups from the Secanto analysis.

To improve the accuracy two additional methods were used. In the first place the seriation of all the closed contexts suitable for such an analysis, incorporating also the superpositions of several graves using the PAST statistical program (Hammer 2001) and the spatial distribution of the pottery groups (Fig. 12). Secondly, the spatial distribution of the graves containing well-dated finds was analysed using the open source platform QGIS 2.8.2. Both methods confirm the chronological horizontal development of the site (Fig. 13).

Another topic of interest is the spatial evolution of the necropolis through time. Based on the dated finds we can distinguish the following phases:

The initial assumption was a simple linear evolution from the south-east towards the north-west. However, it appeared that the necropolis had a two-way evolution, both on the south-east to north-west axis and, at the same time, the development of a poly-nucleate structure. This may indicate that the group structure of the community is reflected in the structure of the necropolis with dedicated funerary spaces for different groups of people.

We also observed during each phase several changes in the frequency of used pottery types. Initially, only a handful of shapes, mainly handmade pots, is used. Later the typological diversity increases as well as the diversity of the pottery fabrics. During the late phase there is a decrease in the typological variability while at the same time new shapes and decorations emerge. Also the use of coarse handmade pottery diminishes. It is during the late phases that the necropolis spreads towards the north-west, probably due to capacity problems in the central, initial nucleus of the cemetery which is now out of use (Fig. 14).

Although these observations are preliminary working hypotheses that will be more thoroughly approached as part of future studies of this cemetery, our main goal at this stage was to establish a suitable classification technique to determine the general evolution of the site based on the combination and seriation of artefacts found in the graves.

6 Conclusions

In the past, the process of constructing typologies sometimes became an aim in itself as many a publication about Roman pottery bears witness to. The underlying questions were lost out of sight and interpretations and conclusions, if any were present, did not always get the proper attention that they deserved. But nevertheless, classification is a powerful tool in the hands of the archaeologist as long as one keeps in mind that the process must fit the research question at hand. Or, in other words, classifications as such have no absolute value (Adams and Adams 1991), but always are part of the interpretative reasoning that archaeologists produce to explain observed phenomena.

A classification is the result of the comparison of attributes of a set of objects (Klejn 1982). Both the attributes, chosen by the researcher, and the objects under study must obey certain rules, such as that each object in the set must possess enough attributes to allow comparison with the other objects. Also, each attribute is present in several objects although, in general, it is not necessary that all objects display all attributes (Clarke 1968). And, maybe the most important rule, all attributes must be relevant for the intrinsic nature of the objects. For example,

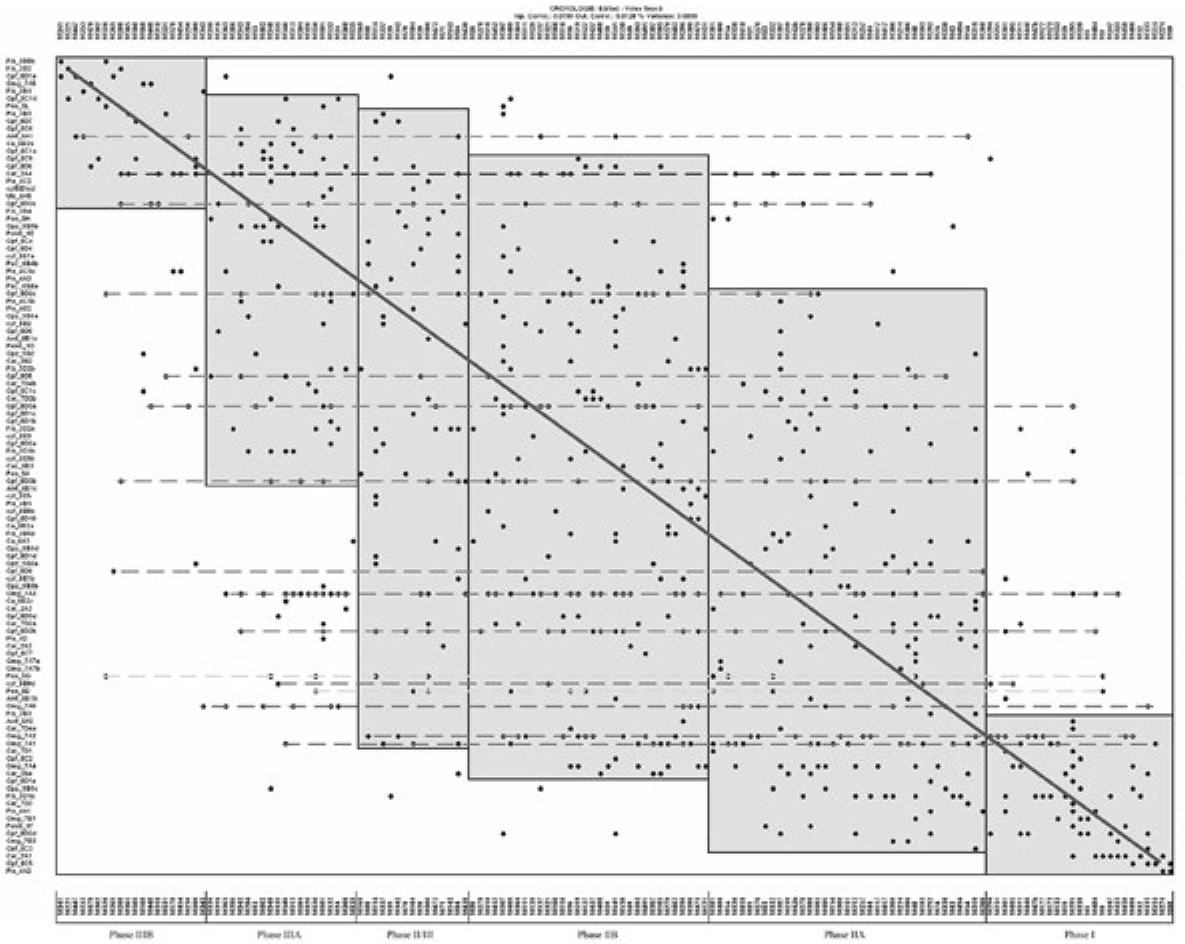

Fig. 12. Seriation of the main finds categories found in the cemetery at Bârlad-Valea Seacă.

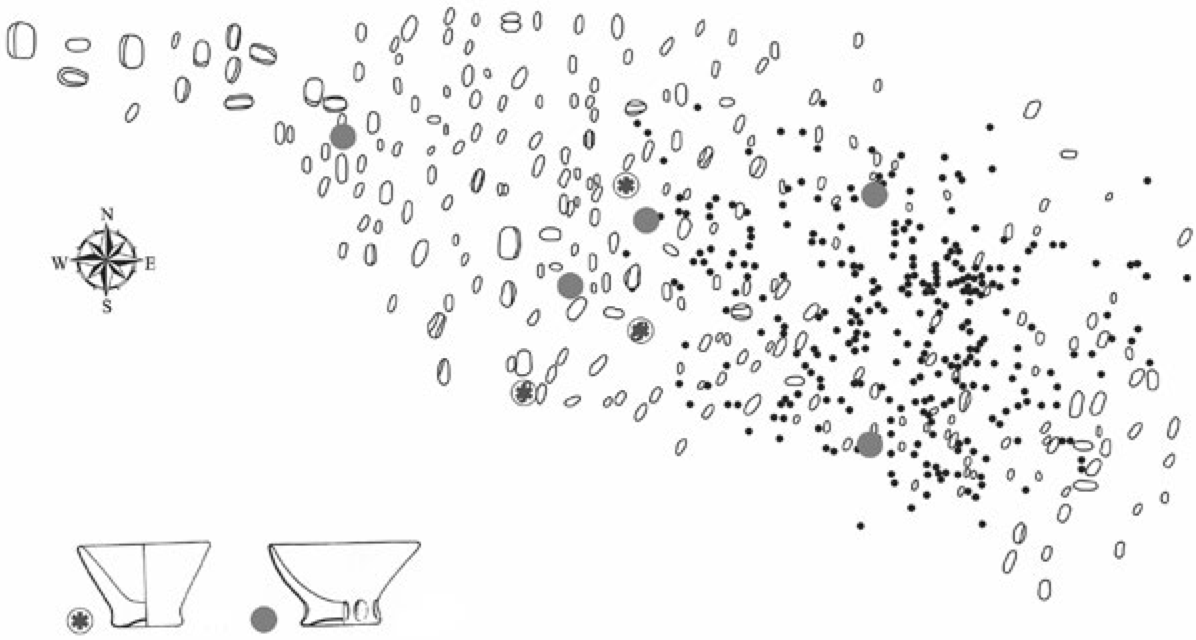

Fig. 13. Spatial distribution of cups in the necropolis at Bârlad-Valea Seacă.

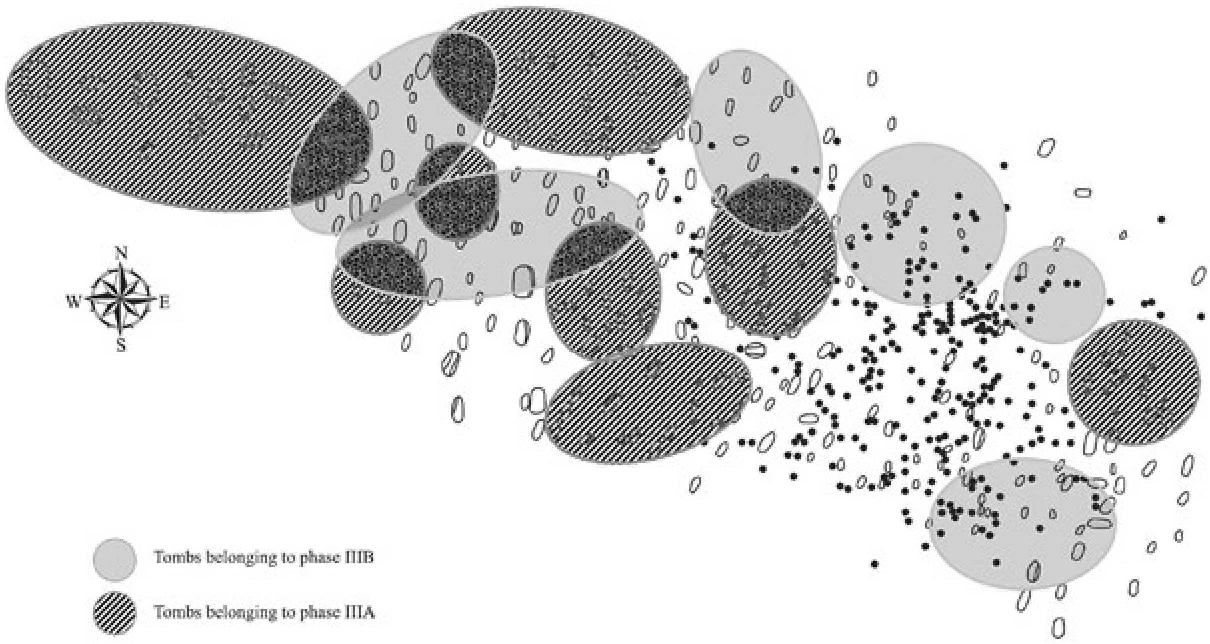

Fig. 14. Spatial distribution of the graves of Phase IIIA and Phase IIIB at Bârlad-Valea Seacă.

Tab. 1: Phases of the SMC culture necropolis at Bârlad-Valea Seacă.

Phase	Period
I	approx. 270-300 AD
II A-B	approx. 310-350 AD
II/III-IIIA	approx. 350-400 AD
IIIB	approx. 400-430 AD

the attribute 'colour' usually is not very relevant for pottery, but for dyes and paints it is the most important one.

For our current approach, where we have chosen the single attribute 'shape', the above rules become very simple. Shape is a good attribute for pottery, as it is closely related with 'volume' and therefore with the primary container functionality of pottery. Also, using one attribute removes the difficult, subjective task to weight the relative importance of different attributes. And it also simplifies the question about the contents of the dataset: either the attribute is present (the object has a complete profile) or not (shard).

The Secanto computer program proved to be quite effective and efficient in handling big datasets and generating large distance matrices that were the basis for the subsequent statistical analysis and creation of distribution maps. As the results obtained for the single site of Bârlad-Valea Seacă are quite satisfying, we intend to take our analysis a step further by creating similar datasets for other sites from the SMC culture such as Mihălăşeni (Şovan 2005), Târgşorul Vechi (Diaconu 1965) or even sites from neighbouring territories such as Velikaja Bugaevka (Petrauskas 2011), and study the differences and similarities that the comparisons will produce. It is only in this way that regional patterns may be discovered to shed a light on the complex historic events that occurred during the dynamic Late Roman and Early Migration period.

Bibliography

Adams, W. Y. and Adams, E. W. 1991. *Archaeological typology and practical reality. A dialectal approach to artefact classification and sorting*. Cambridge, Cambridge University Press.

Anghelinu, M. 2003. *Evoluția gândirii teoretice în România. Concepte și modele aplicate în preistorie*. Târgoviște, Ed. Cetatea de Scaun.

Bierbrauer, V. 1995. Archäologie und Geschichte der Goten vom 1.-7. Jahrhundert. *Frühmitteralterliche Studien* 29: 51-171.

Clarke, D. 1968. *Analytical Archaeology*. London-Colchester, Methuen & Company.

Diaconu, G. 1963. Despre sarmaţi la Dunărea de Jos în lumina descoperirilor de la Târgşor. *Studii și Cercetări de Istorie Veche* 14, 2: 323-45.

Diaconu, G. 1964. Einheimische u. Wandervölker im 4. Jahrhundert u.Z. auf dem Gebiete Rumäniens (Târgşor–Gherăseni Variante). *Dacia N.S.* 8: 195-211.

Diaconu, G. 1965. *Târgşor. Necropola din sec. III-IV e.n.*. Bucureşti, Ed. Academiei Române.

Diaconu, G. 1965a. Nordnordöstlische Elemente in der Tschernjachow-Sântana de Mures-Kultur. *Dacia N.S.* 9: 299-306.

Diaconu, G. 1970. *Mogoşani. Necropola din sec. III-IV e.n.*. Târgovişte, Ed. Muzeul Județean Dâmbovița.

Diaconu, G. (1970a) Über die scheibengedrehte Keramik in der Sântana de Mureş- Tschernjachowkultur. *Dacia N.S.* 14: 243-50.

Diaconu, G. 1975. On the Socio-Economic Relations between Natives and the Goths in Dacia. In M. Constantinescu, Ş. Pascu, P. Diaconu (eds.), *Relations between the Autochtonous Population and the Migratory Populations on the Territory of Romania*: 67-75. Bucureşti, Ed. Academiei Române.

Dragoman, A. 2009. Ideology and politics in researching the (e)neolithic in Romania. *Dacia N. S.* 53: 191-214.

Dragoman, A. and Oanţă-Mărghitu, S. 2006. Archaeology in Communist and Post-Communist Romania. *Dacia N. S.* 50: 57-76.

Dragoman, A. and Oanţă-Mărghitu, S. 2013. *Arheologie si Politică în România*, Baia Mare, Ed. Eurotip.

Dragomir, I. T. 2001. *Necropola birituală Sântana de Mureş-Cerneahov, (sec. III-IV e.n.), de la Lunca, regiunea de sud a Moldovei* [Danubius XIX]. Galaţi, Muzeul de Istorie Galaţi.

Drenth, E. and Mom, V. 2009. Continuity and change: on a computer-aided classification of Late Neolithic and Early Bronze Age pottery from the Netherlands. In B. Frischer and L. Fischer (eds.), *Making History Interactive. Computer Applications to Archaeology. Proceedings of the 37th Computer Applications and Quantitative Methods in Archaeology Conference, CAA 2009. Williamsburg, Virginia, USA. 22-26 March 2009*: 245-55. Oxford, Archaeopress.

Hammer, Ø., Harper D. A. T., Ryan, P. D. 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica* 4, 1: 37-66.

Harhoiu, R. 1998. *Die frühe Völkerwanderungszeit in Rumänien*. Bucureşti, Ed. Enciclopedică.

Heather, P. 1998. *The Goths*. Cornwall, Blackwell Publishers.

Horedt, K. 1982. *Siebenbürgen in spätrömischer Zeit*. Bucureşti, Kriterion Verlag.

Horedt, K. 1986. *Siebenbürgen in Frühmittelalter*. Bonn, Dr. Rudolph von Habelt Verlag.

Ioniţă, I. 1966. Contribuţii cu privire la cultura Sântana de Mureş – Černjachov pe teritoriul Republicii Socialiste România. *Arheologia Moldovei* 4: 189-259.

Ioniţă, I. 1971. *Das Gräberfeld von Independenţa*. Bonn, Dr. Rudolph von Habelt Verlag.

Ioniţă, I. 1982. *Din istoria şi civilizaţia dacilor liberi. Dacii din spaţiul est-carpatic în secolele II-IV e.n.* Iaşi, Ed. Junimea.

IstRom 1961. *Istoria Romîniei*, vol. I. Bucureşti, Ed. Academiei Române.

IstRom 2001. *Istoria Românilor*, vol. II, Daco-romani, romanici, alogeni. Bucureşti, Ed. Academiei Române.

Kazanski, M. 2012. Radagaise et la fin de la civilisation de Černjachov. In V. Ivanišević and M. Kazanski (eds.), *The Pontic-Danubian Realm in the Period of the Great Migration*: 381-403. Paris-Beograd, Association des amis du centre d'histoire et civilisation de Byzance.

Kazanski, M. and Legoux, R. 1988. Contribution à l'étude des témoinages archéologiques des Goths en Europe orientale à l'époque des Grandes Migrations: La chronologie de la culture de Černjahov récente. *Archéologie Médiévale* 18: 7-53.

Klejn, L. S. 1982. *Archaeological Typology*. British Archaeological Reports International Series 158. Oxford.

Lăzărescu, V. A. 2011. The Wheel-made Pottery from Sântana de Mureş-Černjachov Wallachian Necropolises – Present Stage of Research and New Approaches. In J. Bemmann, M. Hegewisch, M. Meyer, M. Schmauder (eds.), *Drehscheiben Töpferei im Barbaricum – Technologietransfer und Professionalisierung eines Handwerks am Rande des Römischen Imperiums. Bonner Beiträge zur Vor- und Frühgeschichtlichen Archäologie 13, Bonn 11-14 June 2009*: 463-83. Bonn, Univ. Bonn.

Lăzărescu, V. A. 2014. Is there a meaning behind the distribution patterns of the Late Roman coins found in Barbaricum? A comparative approach between the inner- and extra-Carpathian areas. In S. Cociş (ed.), *Archäologische Beiträge - Gedenkschrift zun hundertsten Geburtstag von Kurt Hored*: 207-42. Cluj-Napoca, Ed. Mega.

Lăzărescu, V. A., Ciupercă, B., Anton, A. 2015. The post-Černjachovian horizon in Wallachia revisited. A case study for the newly discovered site at Ciorani, Prahova county. In S. Cociş, V. A. Lăzărescu, M. Gui, D. Deac (eds.), *Ad Finem Imperii Romani. Studies in Honour of Coriolan H. Opreanu*: 211-37. Cluj-Napoca, Ed. Mega.

Magomedov, B. 2001. *Černjachovskaja Kultura. Problema etnosa*. Lublin, Wydawn. Uniw. Marii Curie-Sklodowskiej.

Magomedov, B. 2011. Zum forschungsstand der Drechscheibenkeramik in der Černjachov-Kultur. In J. Bemmann, M. Hegewisch, M. Meyer, M. Schmauder (eds.), *Drehscheiben Töpferei im Barbaricum – Technologietransfer und Professionalisierung eines Handwerks am Rande des Römischen Imperiums. Bonner Beiträge zur Vor- und Frühgeschichtlichen Archäologie 13, Bonn 11-14 June 2009*: 373-82. Bonn: Univ. Bonn.

Măgureanu, A. 2007. Dezbateri privind etnogeneza românilor în anii '50. De la manualul lui Roller la Tratatul de Istorie. *Studii şi Comunicări de Istorie Veche şi Arheologie* 58, 3-4: 289-319.

Mitrea, B. and Preda, C. 1966. *Necropole din secolul al IV-lea e.n. în Muntenia*. Bucureşti, Ed. Academiei Române.

Mom, V. 2007. SECANTO, the SECtion ANalysis TOol. In A. Figueiredo and G. Velho (eds.), *The World is in your eyes. Proceedings of the XXXIII Computer Applications and Quantitative Methods in Archaeology Conference, CAA 2005, Tomar, Portugal*: 95-101.

Mom, V. 2007. Where Did I See You Before... A Holistic Method to Compare and Find Archaeological Artifacts. In R. Decker and H. J. Lenz (eds.), *Advances in Data Analysis. Studies in Classification, Data Analysis and Knowledge Organization*: 671-80. Berlin, Springer Verlag.

Mom, V., Paijmans, H. 2008. SECANTO, a Retrieval system and Classification tool for Simple Artifacts. In A. Posluschny, K. Lambers, I. Herzog (eds.), *Layers of Perception, Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA) Berlin, Germany, 2-6 April 2007*: 171. Bonn, Dr. Rudolf Habelt Gmbh.

Nemeti, S. 2007. Burial Pottery in 4th Century AD Cemeteries and Isolated Graves from Transylvania. In C. Cosma (ed.), *Funerary Offerings and Votive Depositions in Europe's 1st Millenium AD. Cultural Artefacts and Local Identities*: 99-111. Cluj-Napoca, Ed. Mega.

Niculescu, G. A. 1993. The Cremation Graves from the Cemetery of Târgşor (Third-Fourth Centuries A.D.). *Dacia N.S.* 37: 197-220.

Niculescu, G. A. 2002. Nationalism and the Representation of Society in Romanian Archaeology. In: *Nation and National Ideology. Past, Present and Prospects: proceedings of the international symposium held at the New Europe College,* *Bucharest, April 6-7,* 2001: 209-34. Bucureşti, New Europe College.

Niculescu, G. A. 2003. Die sarmatische Kultur im Zusammenhang der kaiserzeitlichen archäologischen Funde aus Muntenien - unter besonderer Berücksichtigung der Funde von Tîrgşor. Mit einem Beitrag von Nicolae Miriţoiu: „Sarmatische Gräber mit künstlich deformierten Schädeln in Muntenien”. In C. von Carnap-Bornheim (ed.), *Kontakt - Kooperation - Konflikt. Germanen und Sarmaten zwischen dem 1. und dem 4. Jahrhundert nach Christus*: 177-205. Neumünster, Wachholtz Verlag.

Niculescu, G. A. 2004-2005. Archaeology, nationalism and the ‘History of the Romanians’. *Dacia N. S.* 48-49: 99-124.

Orton, C., Tyres, P., Vince, A. 1993. *Pottery in archaeology*. Cambridge, Cambridge University Press.

Palade, V. 2004. *Aşezarea şi necropola de la Bârlad – Valea Seacă (sfârşitul sec. al III-lea – a doua jumătate a sec. al V-lea)*. Bucureşti, Ed. Arc 2000.

Palincaş, N. (2006) On power, organization and paradigm in Romanian archaeology before and after 1989. *Dacia N. S.* 50: 7-56.

Petrauskas, O. V. (2011) Scheibengedrehte keramik als chronologischer anzeiger nach den materialen des gräberfeldes der Černjachov-kultur bei Velikaja Bugaevka, Kievskaja obl., Ukraine. In J. Bemmann, M. Hegewisch, M. Meyer, M. Schmauder (eds.), *Drehscheibentöpferei im Barbaricum – Technologietransfer und Professionalisierung eines Handwerks am Rande des Römischen Imperiums. Akten der Internationalen Tagung in Bonn vom 11. bis 14. Juni 2009*: 399-416. Bonn, Univ. Bonn.

Petrescu, F. 2002. *Repertoriul monumentelor arheologice de tip Sântana de Mureş – Cerneahov de pe teritoriul României*, Bucureşti, Ed. Ars Docendi.

Pohl, W. 1997. Introduction: The Empire and the Integration of Barbarians. In W. Pohl (ed.), *Kingdoms of the Empire. The Integration of Barbarians in Late Antiquity*: 1-12. Leiden – New-York – Köln, Brill Ann Arbor.

Pohl, W. 1998. Introduction: Strategies of distinction. In W. Pohl and H. Reimitz (eds.), *Strategies of Distinction. The Construction of Ethnic Communities, 300-800*: 1-15. Leiden – Boston – Köln, Brill Ann Arbor.

Rousseeuw, P. 1987. Silhouettes: a Graphical Aid to the Interpretation and Validation of Cluster Analysis. *Computational and Applied Mathematics* 20: 53-65.

Schmidt, I. and Mom, V. 2012. Computer-aided classification of archaeological objects –methodological issues in comparing shapes of Solutrean points. In J. Cascalheira and C. Gonçalves (eds.), *Actas das IV Jornadas de Jovens em Investigação Arqueológica, Faro, 11-14 may 2011, JIA 2011 Vol. I*: 39-46. Faro, Núcleo de Arqueologia e Paleoecologia (Universidade do Algarve).

Schukin, M. and Charov, O. 1999. A propos de la date de la fin de la civilisation de Tcherniachov. In J. Tejral, C. Pilet, M. Kazanski (eds.), *L’Occident romain et l’Europe centrale au début de l’époque des Grandes Migrations*: 327-40. Brno, Archeologický ústav Akademie věd České republiky.

Shennan, S. J. and Wilcock, J. D. 1975. Shape and style variation in Central German Bell Beakers, a computer-assisted study. *Science and Archaeology* 15: 17-31.

Şovan, O. L. 2005. *Necropola de tip Sântana de Mureş-Černjachov de la Mihălăşeni (jud. Botoşani)*. Târgovişte, Ed. Cetatea de Scaun.

Stanciu, I. 2010. Epoca romană imperială (barbaricum), epoca migrațiilor și etapa de început a epocii medievale timpurii - cursul cercetării arheologice românești din ultimele două decenii. In H. Pop, I. Bejinariu, S. Băcueț-Crișan, D. Băcueț-Crișan (eds.), *Identități culturalelocale și regionale în context european. Studii de arheologie și antropologie istorică*: 603-12. Cluj-Napoca, Ed. Mega.

Tejral, J. 2000. The Problem of the Primary Acculturation at the Beginning of the Migration Period. In M. Mączyńska and T. Grabarczyk (ed.), *Die spätrömische Kaiserzeit und die frühe Völkerwanderungszeit in Mittel- und Osteuropa*: 5-31. Łódz, Wydawn. Uniw. Lódzkiego.

Ursachi, V. 2007. *Monografia arheologică – Săbăoani* I, Iași, Ed. Demiurg.

Ursachi, V. (2010) *Monografia arheologică – Săbăoani* II. Iași, Ed. Demiurg.

Vornic, V. 2006. *Aşezarea şi necropola de tip Sântana de Mureş - Černjachov de la Budești*. Chișinău, Ed. Pontos.

Ward, J. H. 1963. Hierarchical Grouping to Optimize an Objective Function. *Journal of the American Statistical Association* 58: 236-44.

Wolfram, H. 1990. *History of the Goths*. Berkley – Los Angeles – London, University of California Press.

A Bridge to Digital Humanities: Geometric Methods and Machine Learning for Analysing Ancient Script in 3D

Hubert Mara
hubert.mara@iwr.uni-heidelberg.de

Bartosz Bogacz
bartosz.bogacz@iwr.uni-heidelberg.de

IWR – Interdisziplinäres Zentrum für Wissenschaftliches Rechnen
FCGL - Forensic Computational Geometry Laboratory
Universität Heidelberg, Deutschland

Abstract: In the Digital Humanities, text sources are digitized using various methods resulting in different data representations of related documents. This challenge is exacerbated for clay tablets with cuneiform script, which is one of the oldest handwritten scripts used for more than three millennia. A cuneiform tablet acquired using a 3D-Scanner and a manually created line tracing are two completely different representations of the same type of text source. Additionally, a line tracing can be born-digital as a vector graphic or it can be a raster image of a drawing with ink on paper. Each representation is typically processed with its own tool-set and the textual analysis is therefore limited to a certain type of digital representation. We present a work-flow for unification of the three most common representations of cuneiform tablets: raster images, polylines and 3D meshes. The result is one representation exportable as Scalable Vector Graphics (SVGs)

Keywords:. Cuneiform, Character Retrieval, Source Unification, Feature Extraction, Conflict Resolution, Born-digital Tracings, Retro-digitized Tracings.

Introduction

Cuneiform tablets are one of oldest textual artefacts comparable in extent to texts written in Latin or ancient Greek. Since those tablets were used in all of the ancient Near East for over three thousand years (VonSoden 1994), many interesting research questions can be answered regarding the development of religion, politics, science, trade and climate change (Kaniewski 2013). These tablets were formed from clay and written on by impressing a rectangular stylus (Borger 2010), require novel methods in the field of computer science for documentation and analysis than methods used for flat objects i.e. ink on paper. Additionally, there are scarcely any methods in the field of Optical Character Recognition (OCR) that are applicable to language written in cuneiform (Sperl 1981).

The Assyrian language also has complicated grammar and numerous derivations where postfixes, prefixes and even infixes are added to verbs. There is no whitespace between cuneiform characters. It is therefore very hard to infer word boundaries since any sequence of words may look very similar to any other sequence of differently stemmed words. Common methods of word segmentation are thus not applicable.

The digitization of cuneiform tablets and the development of respective databases, started in the same spirit as the Open Data Initiative, has already been initiated by the Cuneiform Database Library Initiative (CDLI) (http://cdli.ucla.edu/) of the Max Planck Institute for the History of Science in Berlin, Germany and the University of California at Los Angeles, USA (Groneberg 2005). At that point, usually, photos and images taken by flatbed scanners are used which are cheap and fast to create. This technique creates blurred and/or shadowed areas if the tablet is damaged or crooked, which is the case for most tablets. Therefore modern 3D measuring instruments are employed in Jena, Würzburg (Cammarosano 2014) and in Heidelberg, Germany (Mara 2010) to create highly exact digital replicas used to create appropriate visualizations. The long-term goal is to develop methods and tools for OCR.

We work with three different representations of cuneiform tablets. Traditional manually created tracings that have been retro-digitized shown in Figure 1(a), born-digital vectorized tracings created with vector graphics editors shown in Figure 1(b) and 3D-Mesh data acquired by scanning the original cuneiform tablets shown in Figure 1(c). Each of these different representations of cuneiform tablets requires their own tool-set for processing and computational analysis. This diversity of sources and methods required to analyse the tablets, inhibits the development of general purpose algorithms and inhibits the use of general purpose machine learning approaches.

In this paper, we present a workflow for unifying the various data sources of cuneiform script using methods from computational geometry and pattern matching to arrive at a standard and simple representation of cuneiform characters. We employ a pipeline of transformation stages. The result is the same mathematical representation of cuneiform characters. This paper structure reflects the structure of the pipeline. The stages of our pipeline are explained consecutively.

1 Data acquisition and data representation

We acquire cuneiform tablets from three different sources and employ different methods to digitize these tablets. This section

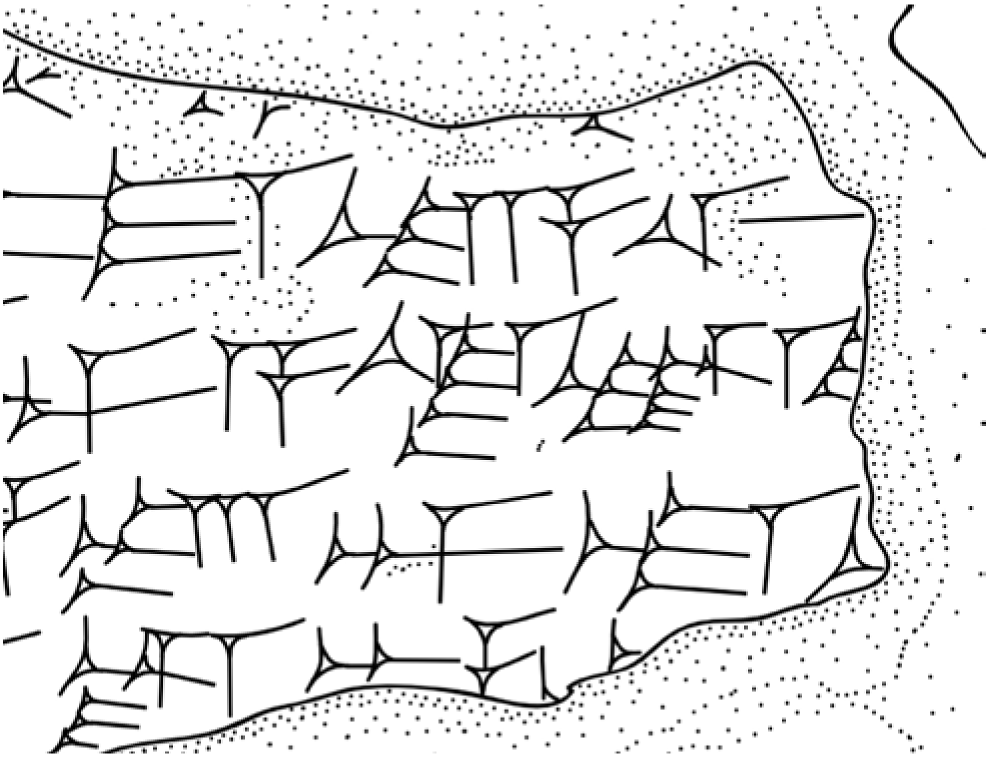

Fig. 1. The three data sources used in our workflow. (a) Born-digital tracings created directly on graphics tablets, (b) Retro-digitized tracings created by scanning manually created documents and (c) 3D-Mesh data acquired by scanning an original cuneiform tablet with a structured light scanner.

describes the format of the sources used and the methods necessary to extract information from the cuneiform tablets.

1.1. Acquiring retro-digitized tracings

Most current tracings of cuneiform tablets are done manually with paper and ink. An Assyriologist traces the wedge-shaped impressions, the shape and the damage of an original cuneiform tablet or the photograph of a cuneiform tablet. Flat-bed scans of such tracings and the photographs of the original cuneiform tablets are available freely to download from the CDLI.

Since these tracings are created by different drafts people that use different conventions to describe the same concepts. For example, most cuneiform tablets are moderately damaged or broken into parts. Damage and break lines are then often drawn using either crosshatching lines or indicated with dots of differing densities.

Wedge-shaped impressions are most commonly drawn as triangles with arms. We call the triangle the wedge-head, the three edges extending from the triangle the wedge-arms. The wedge-head can be either a filled triangle or three slightly curved pairwise intersecting strokes. Wedge-arms are strokes used to indicate the type of a wedge.

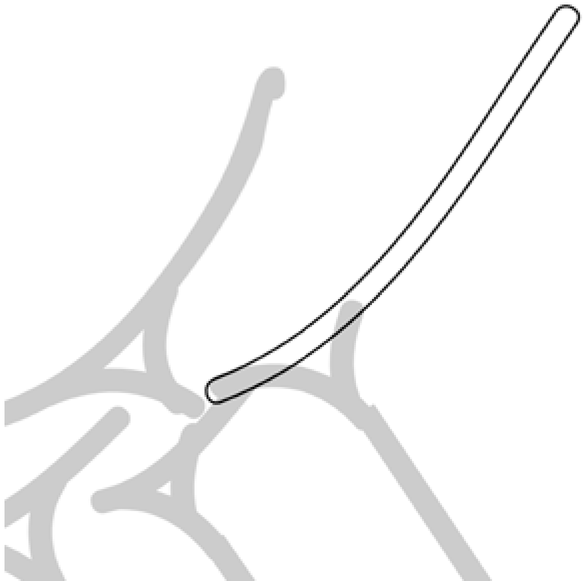

Fig. 2. An excerpt from a born-digital tracing of a tablet. The outline, shown in red, of a stroke of one of the wedges.

1.2 Acquiring 3D mesh data

If a cuneiform tablet is available in original, we scan the tablet using a stereo and structured light 3D-scanner (Sablatnig 1992). An alternating pattern of structured light is projected on the cuneiform tablet and is deformed by its surface shape. These deformations are measured by the two cameras of the scanner. Then, the software associated with the 3D-scanner calculates a mesh from the set of captured images. The result is a mesh of triangulated measuring points, the vertices of the mesh, capable

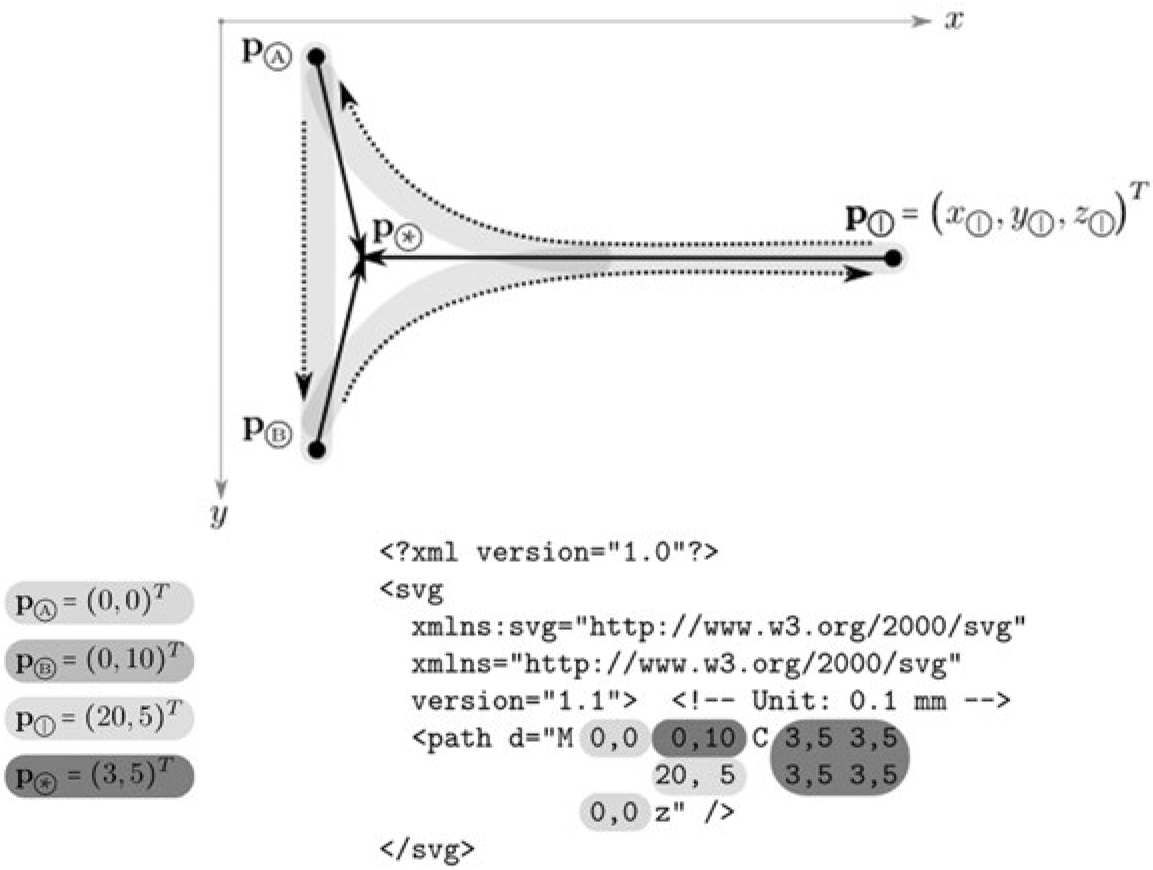

FIG. 3. THE KEY-POINTS OF A WEDGE. THE CENTRE OF THE WEDGE-HEAD AND THE THREE POSITIONS OF THE ENDPOINTS OF THE WEDGE-ARMS.

of resolving features up to 2mm. The distance between vertices is one hundredth of a millimetre.

1.3 Acquiring born-digital tracings

A more modern process used by Assyriologists are born-digital tracings of cuneiform tablets. Figure 1(a) shows an excerpt of such a tracing. Just like tracings drawn on paper, born-digital tracings are created manually using a vector graphics editor like Inkscape (http://www.inkscape.org). An Assyriologist draws the tracing of an original cuneiform tablet using a graphics tablet.

Wedges in a born-digital tracing are typically drawn using three distinct strokes without filling the inside of a wedge-head. This decomposition is shown in figure 2. The shape of cuneiform tablet is indicated by consecutive contour lines tracing the break lines of a damaged tablet. Dots of varying density are used to show unreadable or damaged areas.

A born-digital tracing has two very important advantages over retro-digitized tracings for computational analysis. First, each stroke performed by the Assyriologist, no matter how small and short, is encoded in the born-digital tracing. This encoding allows for much easier pattern matching of wedge-like shapes than the analysis of raster data. Second, the strokes used for the wedges, the tablet contour lines and the dots indicating tablet damage are typically in completely separate layers. Computational analysis can work directly on the wedge layer without the need for a background detection or tablet damage detection.

2 Digitalization and extracting shape features

The meaning of a cuneiform character does not change with different stroke widths or different stroke shapes. We abstract over these differences by extracting the skeleton of a cuneiform character. Figure 3 shows the key-points of a wedge. These are the centre and shape of the wedge-head and the three endpoints of the wedge-arms. The skeleton of a cuneiform character connects the key-points of cuneiform character, the position of the wedge-head and the endpoints and intersections of the wedge-arms.

2.1 Filtering and segmentation of mesh data

We extract the curvature of the 3D wedge-shaped impressions on an original cuneiform tablet by filtering the 3D mesh data using the Multi-Scale Integral Invariant (MSII) (Mara, 2013) filter. It is sensitive to local geometrical features created by the wedge-shaped impressions. The result of the filtering is a feature space on the mesh data. Figure 4 shows the distinct stages of the extraction.

By thresholding the feature space created through filtering we can easily segment wedge configurations and extract the

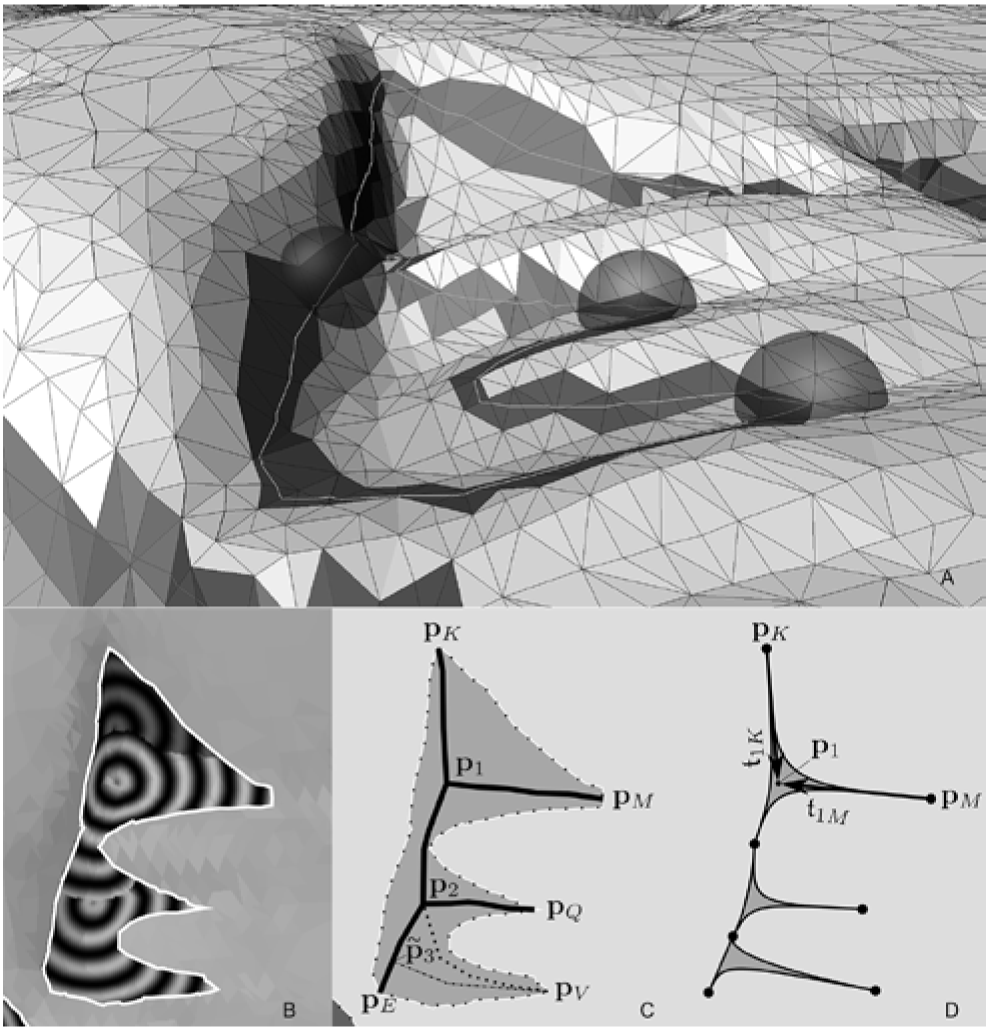

Fig. 4. (a) The triangular mesh of a scanned cuneiform tablet.
(b) The visualized filter response and Voronoi-based skeletonization.
(c) Using the filter to find key-points.
(d) Final vectorized representation using splines.

outlines. The extracted outlines are not guaranteed to be singular wedges but can be any configuration of intersecting wedges. The connectivity and position of key-points of the wedges is extracted by Voronoi-based skeletonization. Instead of naively skeletonizing the extracted outline, we use the feature space induced by MSII filtering to guide the skeletonization.

2.2 Vectorization and pattern matching of retro-digitized tracings

Cuneiform tablets in raster image format are vectorized using the Potrace (http://potrace.sourceforge.net) algorithm. Potrace creates closed vectorized spline paths in regions of high contrast changes between black and white. Groups of intersecting wedges create therefore complex outlines where no singular wedge has its own outline. Enclosed areas, i.e. holes inside wedge groups, are also outlined with a spline path by the algorithm.

Then, the set of outlined wedge groups is skeletonized to extract a simplified description of the wedges. The outline of a wedge group as well as the outlines of holes are discretized by equidistantly sampling points along its poly-lines. Then, a Voronoi (Aurenhammer, 1991) diagram is calculated on these discretized points. The resulting graph is the skeleton (Fabbri, 2002) of the wedge group. Figure 5 shows the stages of this conversion process.

Perturbations in the raster images of the wedges induce large numbers of small edges in the resulting skeleton. We simplify the skeleton by merging edges not intersecting with the outline of a wedge group. The result of this process is shown in Figure 6(b).

2.3 Extracting graphs from born-digital tracings

Born-digital tracings of cuneiform tablets are in a format that makes every stroke drawn during tracing of the original tablet available. We extract the key-points of a stroke to construct a graph: The key-points of a stroke are its endpoints, the two most distant points on its path, and the centres of any intersections with other strokes. If two key-points of two strokes are less

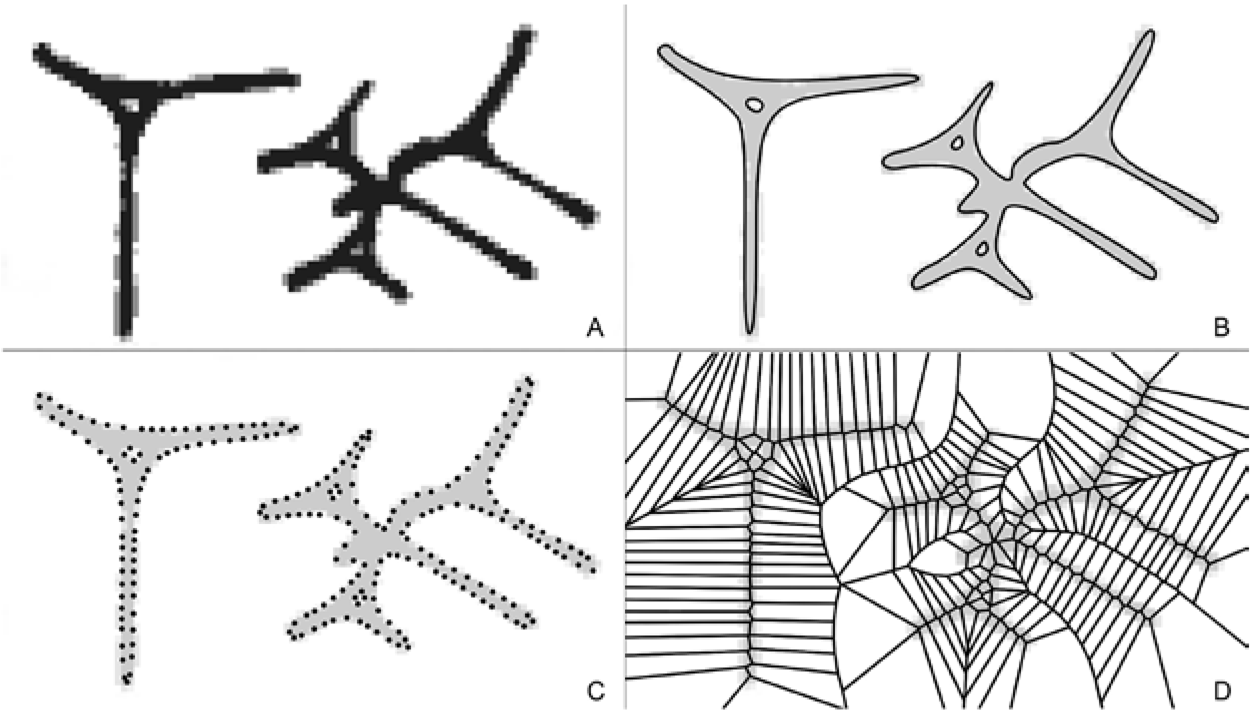

Fig. 5.

than some Epsilon apart, the key-points are merged into one single key-point. We connect the key-points belonging to a stroke using a sweep-line algorithm. We denote the resulting graph as the skeleton graph.

2.4 Unified representation as skeleton graphs

By unifying the three very distinct representations of cuneiform tablets we can now represent cuneiform characters with skeleton graphs. These graphs use only edges and vertices to describe a cuneiform character. This reduced representation of cuneiform characters does not encode irrelevant properties like stroke thickness, curvature and random perturbation.

A description of cuneiform characters with graphs representing the topology also enables us to compare cuneiform character using standard graph comparison.

Since a mathematical graph and the graph comparison methods only work with graph connectivity and not the actual positions of the vertices, we triangulate the graphs with the Delaunay algorithm (Aurenhammer 1991) to enforce rigidity and an ordering of vertices. Any significant change in vertex positions will influence the triangulation of the graph and thus compare differently. In Bogacz (2015b) we provide a detailed analysis of cuneiform character comparison using graph based methods, i.e., the Weisfeiler-Lehman graph kernel (Shervashidze 2011), the spectral decomposition (Chung 1997) and random-walk graph kernels (Vishwanathan 2010).

3 Wedge recognition and description

Even a simplified and skeletonized graph-based representation still encodes unnecessary details of a cuneiform character. The exact intersections, exact wedge-head size and wedge-arms lengths are not necessary to identify a cuneiform character. A topological graph does not encode the exact positions of the wedges, a highly discriminating feature of cuneiform characters.

We extend our approach to cuneiform character recognition by directly representing the wedge with a short feature vector, i.e. a feature vector with typically 12 components. These are 6 two-dimensional position vectors, 3 position vectors for the shape of the wedge-head triangle and 3 position vectors for the endpoints of the wedge-arms.

3.1 Pattern matching wedges in retro-digitized tracings

In retro-digitized tracings of cuneiform tablets wedges are detected in two steps. Two types of wedge heads are detected. Type I is an unfilled wedge-head with a hole, that has been skeletonized into a triangle. We search for all triangles with three incident edges, the wedge-arms. Type II is filled and has been skeletonized into a single vertex with three incident edges. We search for all vertices of degree three. These wedge types are shown in Figure 6(b).

In the second step, wedge-arms are traced from the centre of the detected wedge-head. We follow the path of each of the three wedge-arms ensuring that the curvature stays below a threshold. If the curvature of a wedge-arm exceeds this threshold, following a wedge-arm is aborted and the endpoint of a wedge-arm is set. The extracted wedges are shown in Figure 6(d).

3.2. Extracting wedges from 3D meshes

The MSII feature space induces points for the skeleton graph that are wedge key-points, that is, the positions of wedge-heads

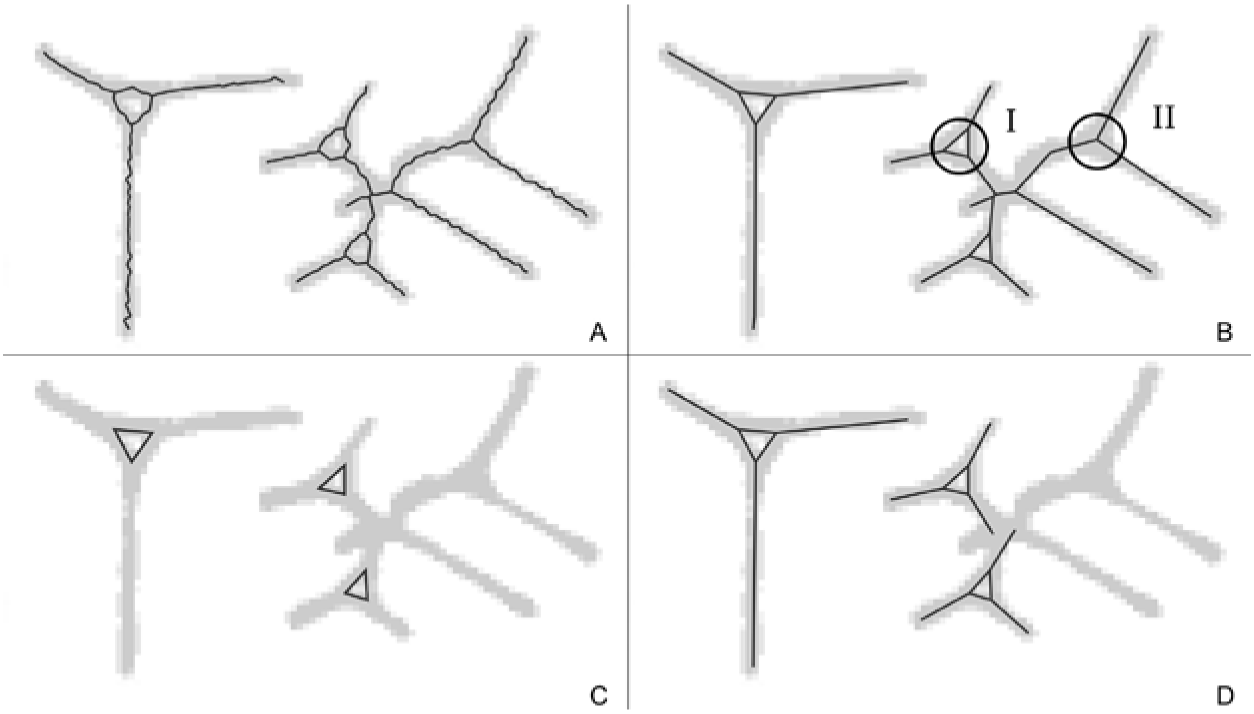

Fig. 6. (a) The inner edges of the Voronoi diagram are used to build a skeleton.
(b) The simplified Voronoi diagram after merging edges.
(c) The detected wedge-heads are highlighted.
(d) The extracted wedges after following wedge-arms until points of high curvature are encountered.

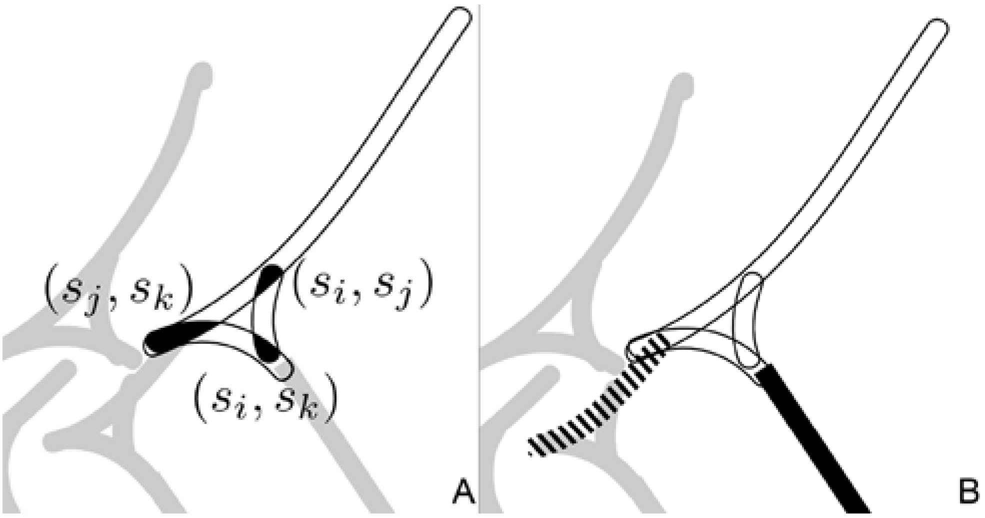

Fig. 7. (a) The outlines of three pairwise intersecting strokes. Their intersection areas are shown in black.
(b) Two adjacent strokes intersecting the wedge-head. Only the black stroke is chosen as a viable wedge-arm.

and the positions of the wedge-arms. A rule-based approach is able to discern the key-points of the individual wedges in the segmented wedge-groups. Then, the wedge is represented and extracted by a predefined spline template that spans all key-points of the wedge. Figure 4(d) shows the extracted wedges and splines reconstructed from the detected key-points.

3.3. Pattern matching wedges in born-digital tracings

In born-digital tracings, wedge-heads are typically drawn using three strokes. Since all strokes made during the tracing of cuneiform tablet are accessible in a vectorized file, the wedge-head extraction is not performed on the skeleton graph of the born-digital tracing but on the original set of strokes. Figure 7 shows this detection process. A wedge-head is identified by

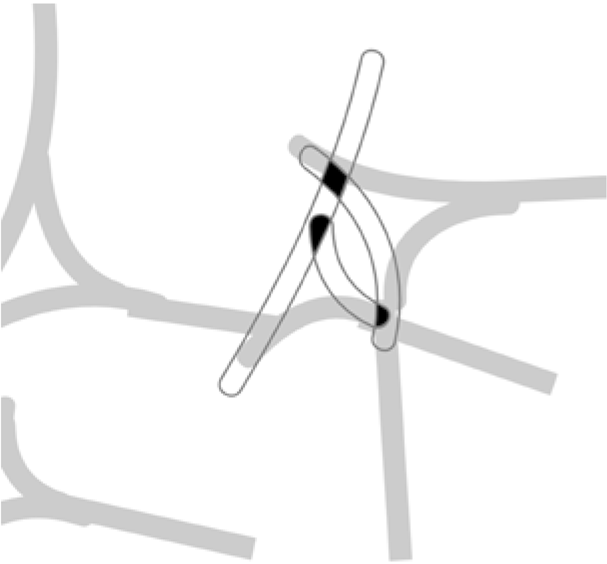

Fig. 8. A false positive wedge-head created by writing wedges densely. The red outlines show the strokes in the wrongly detected wedges.

finding three pairwise intersecting strokes. The wedge-arms are any strokes intersecting the wedge-head. From this set of wedge-arms we choose the three most likely to be correct. The suitability of a wedge-arm is calculated from the angle to the centre of the wedge-head. Proper wedge-arms are most likely in line with the centre and the vertices of a wedge-head.

3.4 Conflict resolution

Interpreting any three pairwise intersecting strokes as wedge-heads leads to conflicts. Some wedges intersect in complex patterns that introduce wrongly detected, false positive, wedge-heads. Such a false positive wedge-head is shown in Figure 8. False positive wedge-heads are always created by the intersection of true positive wedge-heads and never stand-alone.

Instead of adding rules to our wedge-head detection method, we over-segment wedges and resolve conflicts in a later stage. This allows us to keeps the wedge detection logic simple and ensures that no complex edge-cases are created. To resolve conflicts between wedges, we only need to specify a set of declarative rules deciding on the quality of wedge segmentation. If two wedges, one a true positive wedge, the other a false positive, are in conflict, the wedge-head with lower quality is discarded.

3.5 Unifying minimal feature vector representation

After extracting wedge-heads and wedge-arms we describe wedges with a short feature vector that encodes the shape of the wedge-head and the endpoints of the wedge-arms, c.f. Section 4. This short representation is sufficient to describe all wedge types and can be extracted from all three sources of cuneiform tracings. Wedges can be reconstructed as a graph from this feature vector as shown in Figure 9.

Given short feature vectors for each wedge in a cuneiform character, we can now compare characters easily. When two cuneiform characters are being compared, wedges cannot be simply assigned from left to right. Handwritten script necessarily has some variation in shape and form. We assign most similar wedges to each other and compute therefore an optimal assignment between the wedges of the two characters. This is an optimization problem, comparable to the Traveling Salesman Problem (TSP) but of lower complexity, that can be solved using Munkre's algorithm (Munkres, 1957).

In Bogacz (2015b) we perform a detailed analysis of our cuneiform character matching approach using short wedge feature vectors. Our approach outperforms our previous graph based matching and state-of-the-art optical character recognition methods, i.e., Dynamic Time Warping (Rath 2007), Word Warping (Kennard 2011) and Hidden Markov Models (Wshah 2014).

4 Summary

There are currently only few methods for computational analysis of cuneiform (Mara, 2013) (Bogacz, 2015.08) (Bogacz, 2015.02) script and various sources of cuneiform script. We introduced a work-flow for unifying retro-digitized tracings and born-digital tracings as well as 3D scanned meshes of cuneiform tablets. The result is a common and simplified representation of wedges and cuneiform characters as shown in Figure 10.

Retro-digitized tracings are scanned and then vectorized and skeletonized. Wedges are extracted by detecting two types of wedge tracings, and then following the wedge-arms to points of high curvature.

Born-digital tracings do not require any skeletonization and wedges are extracted directly. A conflict resolution step allows for significant over-segmentation of wedges, simplifying the extraction algorithm, and reduces the count of false positive wedges.

Mesh data acquired by scanning cuneiform tablets with a structured light 3D- scanner is filtered using the MSII algorithm with the GigaMesh Software Framework. In the resulting feature space wedge configurations are extracted through thresholding and segmentation in 3D. The MSII filter is additionally used to skeletonize and extract wedges from the wedge-groups.

5 Outlook

The unified representation of cuneiform characters is an essential prerequisite for any computational analysis of cuneiform script. Since the size of the corpus of cuneiform script is small, we avoid apply any extensive feature reduction methods. The small feature vector length allows us to directly use clustering and classification methods from the field of machine learning.

We are currently working on automatically classifying the wedges without prior domain knowledge. Then, we apply pattern mining algorithms on the configuration of cuneiform character types to extract frequent configuration of wedges, cuneiform characters, usable as anchors for a subsequent cuneiform character search engine. The long-term goal of our work is the unification of source of cuneiform tablets and

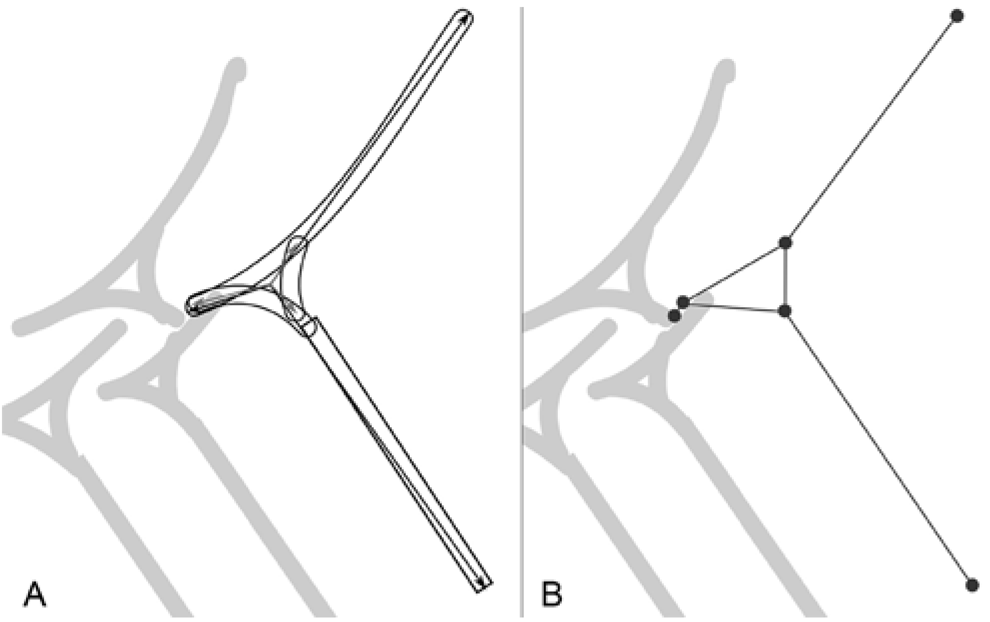

Fig. 9: (a) The feature vector of a pattern-matched wedge. The feature vector is composed from the three vertices (gray arrows) of the wedge-head and the three vertices of the wedge-arms (black arrows).
(b) The reconstruction of a wedge solely from its feature vector.

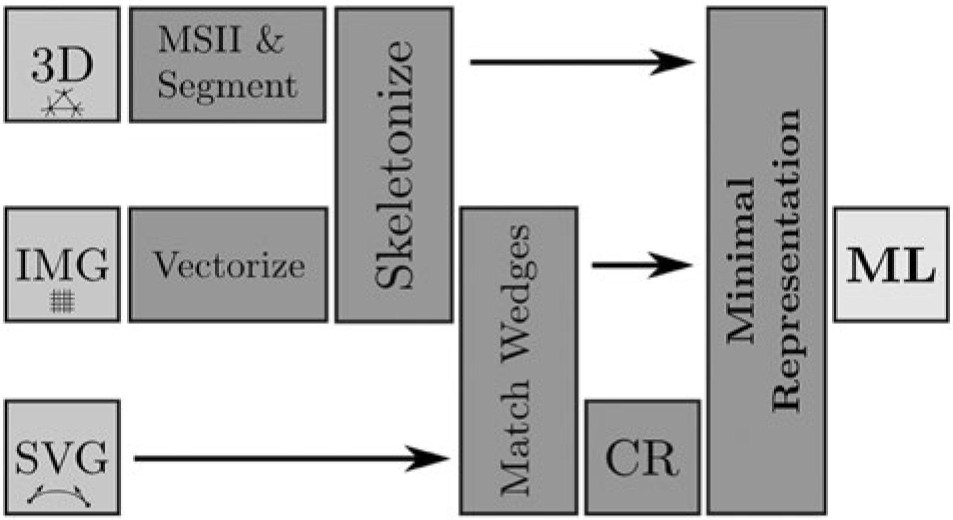

Fig. 10: We employ a multistage work-flow to unify the representation of cuneiform tablets from various sources: (3D) 3D-mesh data from structured light scanning of originals, (IMG) raster images from scanned tracings created manually and (SVG) digitally created tracings with vector graphics editor. The abbreviated stages are (CR) conflict resolution and a prospective (ML) machine learning stage.

the creation of a database that can be queried with cuneiform character keywords.

Bibliography

Aurenhammer, F. 1991. Voronoi Diagrams: a Survey of a Fundamental Geometric Data Structure. *ACM Computing Surveys* 23: 345–405.

Bogacz, B., Gertz, M., Mara, H. 2015. Character retrieval of vectorized cuneiform script. In *Proceedings of the 13th International Conference on Document Analysis and Recognition* (ICDAR 2015). Available at: https://www.researchgate.net/publication/281781820_Character_Retrieval_of_Vectorized_Cuneiform_Script

Bogacz, B., Gertz, M., Mara, H. 2015. Cuneiform character similarity in graph representations. In P. Wohlhart, V. Lepetit (eds.), *Proceedings of the 20th Computer Vision Winter Workshop* (CVWW*), Seggau, Austria, 9-11 february 2015*. Available at: http://cvww2015.icg.tugraz.at/papers_web/cvww2015_paper_id27.pdf

Borger, R. 2015. *Mesopotamisches Zeichenlexikon*. Ugarit Verlag.

Chung, F. R. K. 1997. *Spectral Graph Theory*. American Mathematical Society.

Cammarosano, M., Müller, G., Fisseler, D., Weichert, F. 2014. Schriftmetrologie des Keils: Dreidimensionale Analyse von Keileindrücken und Handschriften. *Die Welt des Orients* 44,1.

Fabbri, R., Estrozi, L. F., Costa, L. F. 2002. On Voronoi diagrams and medial axes. *Journal of Mathematical Imaging and Vision* 17: 27–40.

Groneberg, B., Weiershäuser, F., Linnemann, T., Ullrich, D. 2005. Digitale Keilschriftbibliothek Lexikalischer Listen aus Assur. *Jahrbuch der Max-Planck-Gesellschaft*. Göttingen, Gesellschaft für wissenschaftliche Datenverarbeitung mbH.

Kennard, D. J., Barrett, W. A., Sederberg, T. W. 2011. Word warping for offline handwriting recognition. In *Proceedings of the International Conference on Document Analysis and Recognition*: 1349–53.

Kaniewski, D., Van Campo, E., Guiot, J., Le Burel, S., Otto, T., Baeteman, C. 2013. Environmental roots of the late bronze age crisis. *PLoS ONE* 8.

Mara, H., Krömker, S. 2013. Vectorization of 3D-Characters by Integral Invariant Filtering of High-Resolution Triangular Meshes. In *Proceedings of the 12th International Conference on Document Analysis and Recognition*: 62–6.

Munkres, J. 1957. Algorithms for the assignment and transportation problems. *Journal of the Society for Industrial and Applied Mathematics* 5: 32–8.

Rath, T. M., Manmatha, R. 2007. Word spotting for historical documents. *International Journal of Document Analysis and Recognition* 9, 2: 139–52.

Sablatnig, R., Menard, C. 1992. Stereo and Structured Light as Acquisition Methods in the Field of Archaeology. *Mustererkennung DAGM-Symposium* 14: 398-404.

Sperl, G. 1981. *Erkennen von Keilschriftzeichen mit Hilfe Elektronischer Rechenanlagen*. Unpublished PhD thesis Leopold-Franzens-Universität, Innsbruck, Austria

Shervashidze, N., Schweitzer ,P., van Leeuwen, E. J., Mehlhorn, K., Borgwardt, K. M. 2011. Weisfeiler-lehman graph kernels. *Journal of Machine Learning Research* 12: 2539–61.

Von Soden, W. 1994. *The Ancient Orient: An Introduction to the Study of the Ancient Near East.* Wm. B. Eerdmans Publishing Company.

Vishwanathan, S. V. N., Schraudolph, N. N., Kondor, R., Borgwardt, K. M. 2010. Graph kernels. *Journal of Machine Learning Research*: 1201–42.

Wshah, S., Kumar, G., Govindaraju, V. 2014. Statistical script independent word spotting in offline handwritten documents. *Pattern Recognition* 47: 1039–50.

CHAPTER 11
Remote Sensing: Computational Imaging Advances and Sensor Data Integration

The Possibilities of the Aerial Lidar for the Detection of Galician Megalithic Mounds (NW of the Iberian Peninsula). The Case of Monte De Santa Mariña, Lugo

Miguel Carrero-Pazos
miguel.carrero@usc.es
University of Santiago de Compostela

Benito Vilas-Estévez
vieito4@hotmail.com
University of Wales Trinity Saint David

Abstract: Over the last decade, the aerial Lidar has become one of the most interesting tools for archaeological survey because it allows, among other things, to analyse the field in detail, especially by obviating vegetation. Thus, we propose an example of the possibilities that Lidar technology could offer in the case of megalithic culture. We have chosen the megalithic necropolis of Monte de Santa Mariña (Lugo, Galicia), which had some 34 monuments officially catalogued. Consequently, before starting the archaeological survey we planned a methodology based on Lidar data. Thanks to the study of different types of visual analysis proposed by some authors, we were able to identify correctly all the monuments, and even find a new one.

Keywords: Megalithic culture, Santa Mariña, GIS, Lidar, Galicia.

Introduction

Galicia is one of the areas in the Iberian Peninsula with a huge concentration of megalithic archaeological sites. It is a territory characterized by strong physiographic contrasts.

The necropolis of Monte de Santa Mariña is located on a plateau at an altitude of almost 800 m among the watersheds Oribio and Mao. This necropolis is situated in the municipalities of Sarria, Samos, and Incio (Province of Lugo, Galicia, NW Spain). This area conforms to the typical landscape of the west-central part of Galicia, characterized by lowlands, mountains, and landscape depressions (Yebra 1990). The vegetation cover combines low brush with forested areas. In addition, the whole area is covered with thorny bushes, which makes archaeological prospection difficult.

The megalithic complex of Monte de Santa Mariña is first referenced by F. Acuña Castroviejo 1968 in *Carta Arqueológica del Ayuntamiento de O Incio*. In 1987 the 'Xunta de Galicia' officially catalogued a total of 29 tumuli in this area. In 1991 T. Rodríguez Fernández catalogued 40 tumuli. Three years later, the number of tumuli decreased to 34 structures, pointing to the possibility that between 1991 and 1994 six of them were destroyed (Filgueiras Rey and Rodríguez Fernández 1994: 221).

This area was also explored by Professor A.A. Rodríguez Casal at the beginning of the 1990s. According to the author, a total of 30 monuments were catalogued and at the same time, a dozen monuments were discarded (Rodríguez Casal 1998; Rodríguez Casal *et al*. 1998). Finally, most recently, we have completed work there based on the use of Light Detection and Ranging (Lidar) technology; our work confirms the existence of 34 megalithic monuments (Carrero-Pazos *et al*. 2014).

All of Santa Mariña's megalithic sites show the typical characteristics of Galician monuments. The majority of them are burial mounds, 15–20 m in diameter, each 1–1.5 m high. Some of them have a burial chamber made of granite. In addition, it is a common factor that the whole monument is covered by a mound with abundant vegetation.

1 The aerial Lidar and its application to archaeology

Lidar is an active system that generates a laser pulse of light and allows one to take measurements and make calculations based on a sensor that emits a light beam over the ground. This technology is included within the technologies of remote sensing classified according to their analytical typology in Terrestrial Laser Scanning (TLS), Airborne Laser Scanning (ALS), and Airborne Laser Swath Mapping (ALSM). Together with photogrammetry, it is the most common form of geometric documentation of the territory.

Lidar data is managed in Galicia by the Instituto de Estudos do Territorio (IET). By 2009 a new Digital Terrain Model had been updated, based on Lidar data, and collected during two periods — the eastern part of Galicia was recorded in 2009 (which corresponded to Lugo, Ourense, and the south of Pontevedra province). By 2011, the western part had been studied (north of Pontevedra province and the whole of A Coruña). From a general perspective, Lidar data have a density of 0.5 points/m. The altimetry precision obtained is better than 20 cm RMSE Z. The pulse had a scan frequency of 45 kHz (minimum), assuming a FOV of 50º and a full extent of 3000 m.

Against this background, it is now possible to create a digital elevation model (DEM) of excellent quality. Currently, thanks to PNOA (Plan Nacional de Ortofotografía Aérea) it is possible to count in Galicia with data with a resolution of 0.5 points per square metre and with a resolution pixel between 25 and 50 cm.

The following are suggested as the four most important advantages that Lidar technology offers in the study of megalithic archaeological sites:

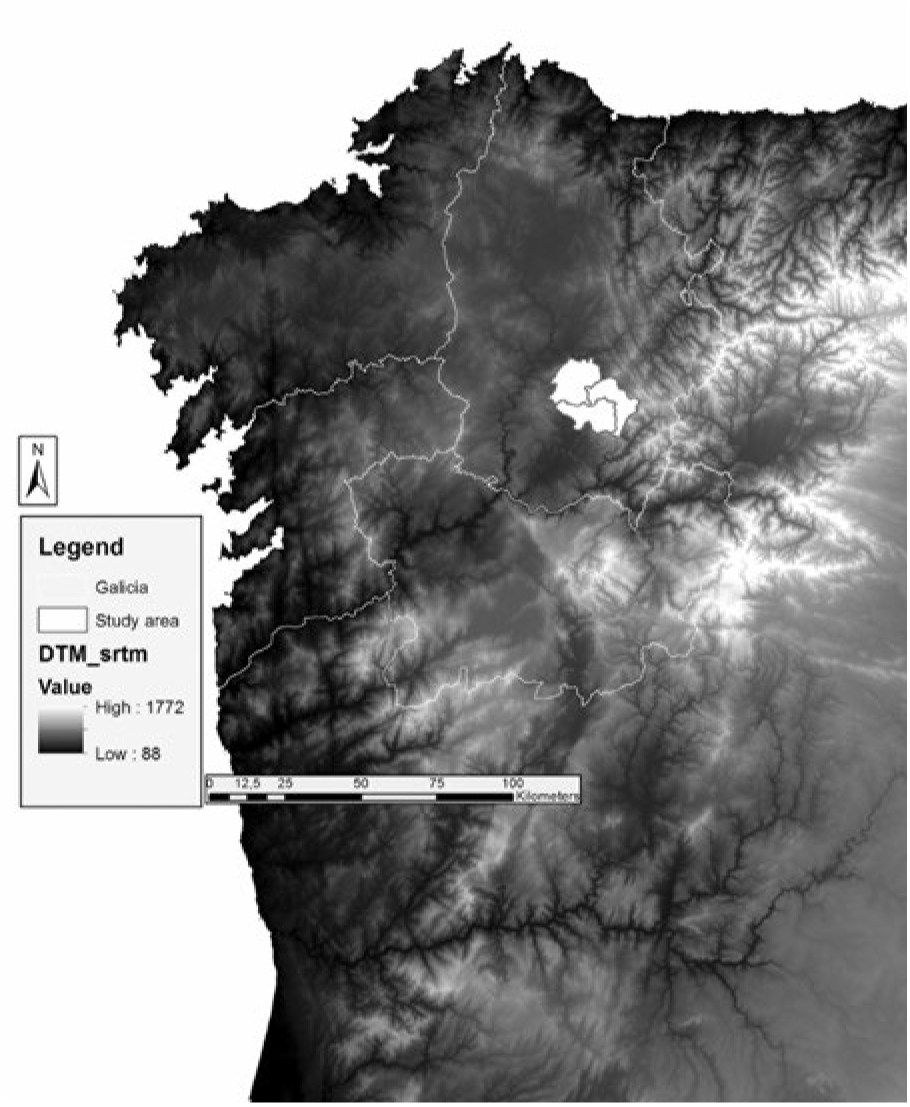

Fig. 1. Galicia (NW of Iberian Peninsula).

1. Lidar enables a pre-prospection of the field because it allows us to see through photo-interpretation different anomalies that might be checked in the field (from a small tumulus to hill forts, rocky outcrops, or constructions of different typologies). It does not matter whether it is undergrowth, pasture, forested areas, or areas with dense vegetation (which are very common in Galicia). This is one of the greatest advantages of Lidar, especially in Galicia where intensive prospection is very difficult, due to the dense vegetation.

2. Lidar allows one to review the database of monuments of previous years; this goes further than a simple photo-interpretative analysis, which is ineffective in forested areas.

3. Thanks to Lidar data, which are geometric, it is possible to measure the field and therefore the height and contour of visible Galician megaliths. We are conscious that some mistakes occur due to the precision of the data, but they are not important for the scale of the elements that we present here.

Despite being one of the fundamental pillars of basic research, this technology is also a basic tool of applied research, in this case in an analytical way. We are thus able to generate information before going in the field, although it is important to note that this 'informatics prospection' must always be justified by the fieldwork, where it will be possible to corroborate the accuracy of archaeological points of interest we have marked, thanks to photo-interpretation; they are subjective, however, as we are interpreting, not confirming, them.

2 Methodology: microtopographic visualization techniques

The identification studies of archaeological locations with Lidar technology are nowadays found in gradual development. If we compare the development of the studies in Galicia based on this technology, it is easy to observe that multiple works exist, but they are mainly focused on the Iron Age (Fonte and Gonçalves 2010a, 2010b; Fonte *et al.* 2014; Blanco Rotea *et al.* 2014).

Although some works exist in Galicia that have been integrating this methodology as a part of more general studies (Mañana

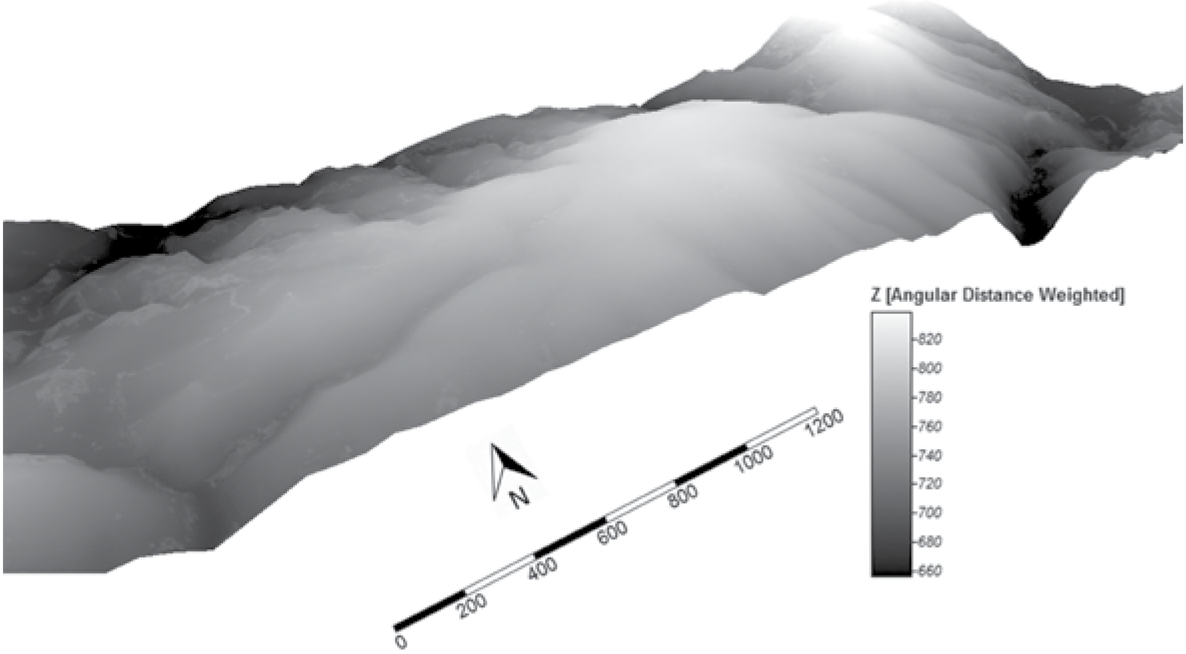

Fig. 2. 3D reconstruction of the study area: Monte de Santa Mariña (Lugo). (Based on LiDAR data).

Borrazás *et al*. 2010; Fonte, Gonçalves 2012; López Romero, Mañana Borrazás 2013), only in one case do we have a work based on an integral study of Galician megalithism with Lidar technology (Carrero-Pazos *et al.* 2014). Other researchers have developed some visualization techniques that allow for a better interpretation of the possible archaeological structures from a general perspective (Caninas *et al.* 2011; Pires *et al.* 2013; Pires *et al.* 2014; Carrero Pazos *et al.* 2015).

For the development of this work, we have used the software ArcGIS 10.2 and the toolbox lastools for the management of the data. Furthermore, for the visualization of the Lidar data, we have employed different filters using the software Saga GIS (Open source). This allowed us to provide a better photo-interpretation of the data for detecting Galician tumuli.

Although many different techniques exist, we have used the following three (perhaps the most common):

2.1 Analytical hill shading.

This is the most common visualization technique. This method consists of an illumination that works with directional light, simulating a certain angle of the sun that can be modified manually (Horn 1982; Jenny 2001; Tzelepis *et al.* 2008; Zakšek *et al.* 2012). This provokes the effect that some areas exist that are directly illuminated by the sun and therefore visible, while others are not. The user can modify the visualization using several options to change variables, however, such as the azimuth or the vertical exaggeration. By modifying the optics, we can have different perspectives of the topographic surface.

2.2 Laplace filter

Also known as Laplacian filter, Laplacian of Gaussian, LoG, or Marr filter (Marr 1982), it is a visualization technique that highlights the regions with changes of intensity quickly, permitting the study of the different shapes of the ground throughout the DEM, highlighting the convexities and concavities.

2.3 Local relief model

This method produces a representation of the topographic values based on a local elevation data (Hesse 2010, 2013). This method is attractive because it creates a colour map in which it is possible to observe positive and negative shapes. Thanks to a 'resampling filter', this creates very interesting results.

3 Results and further research: reconstructing the past of Santa Mariña

The study of the Monte de Santa Mariña with Lidar data allowed us to adjust the geographic coordinates of the megalithic sites (UTM). Traditionally, geographic coordinates are noted during the fieldwork with a conventional GPS but this can lead to errors in the accuracy of the site's positions (5–10 m).

Starting from the first map of the zone (Rodríguez Casal 1998: 124), where 30 monuments were registered, we concluded that all the monuments continue to exist today.

On the other hand the official catalogue, produced by Xunta de Galicia, registered 40 monuments in this area, some of them ignored for the present study.

The most up to date map, which is presented here, shows 34 megalithic sites, with a new monument not known previously.

It would be interesting to try to reconstruct the traditional landscape of Monte de Santa Mariña, through the study of the historic photographs from the 1956 American flight (Series B)

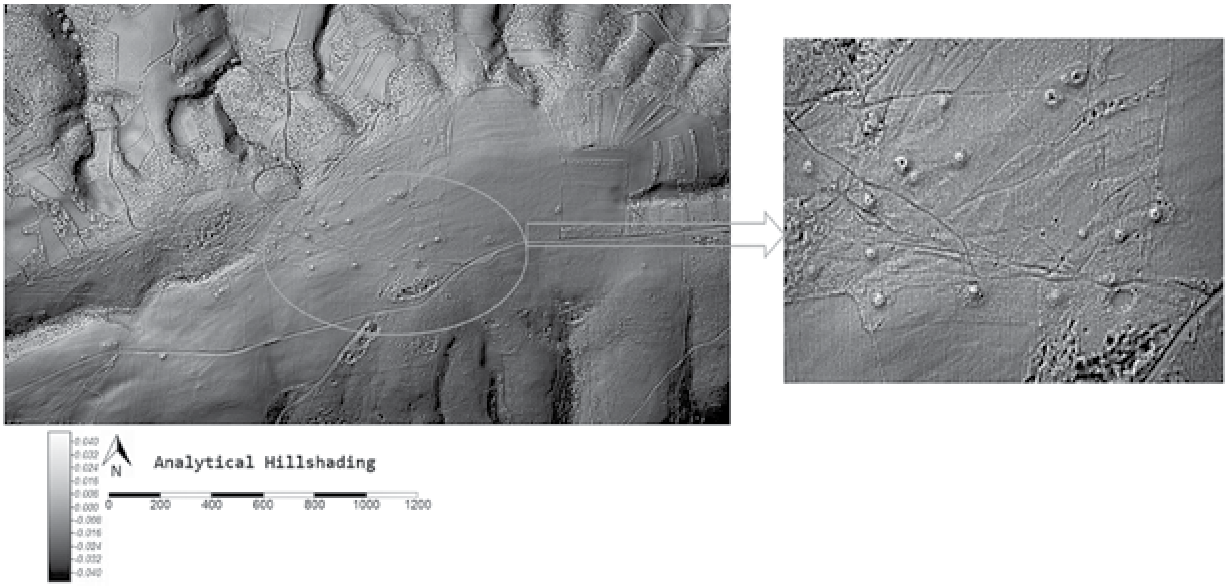

Fig. 3. Analytical hill shading.

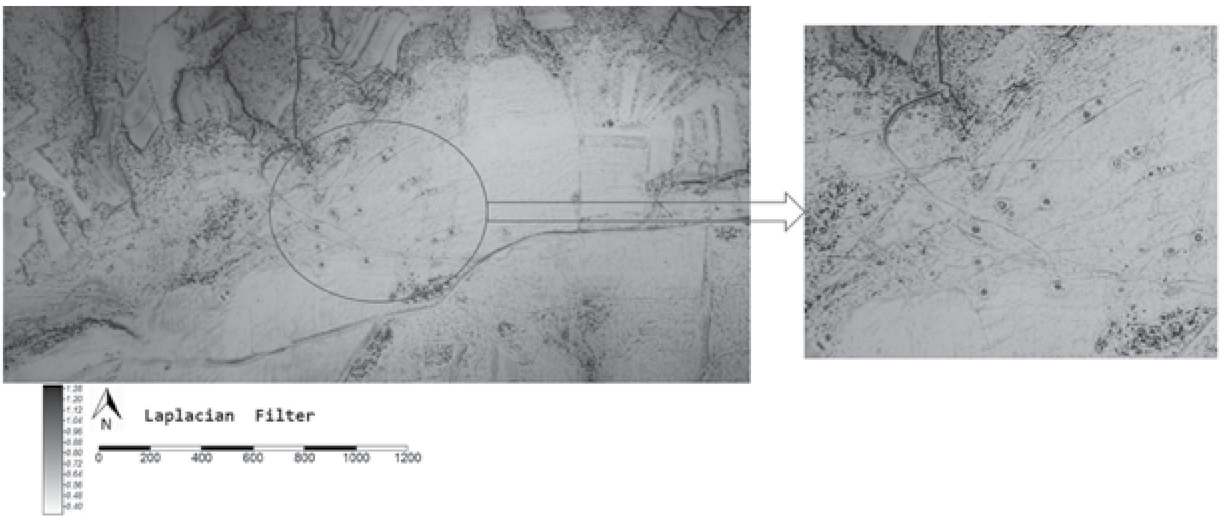

Fig. 4. Laplace filter.

in order to locate those tumuli that are currently lost (Filgueiras Rey and Rodríguez Fernández 1994; Rodríguez Casal 1998). These tumuli can therefore be taken into account for other studies on spatial character or tumular density. In order to do this, the creation and use of stereoscopic images are of great value, as it has been proved in other areas (Vilas Estévez *et al*. 2015). Unfortunately, once again, what we are doing is photo-interpreting. Furthermore, we cannot verify the presence of these mounds in the field, as they are lost, although we can, up to a point, consider and situate them; the other problem is that it is at present not possible to measure the height of the tumuli. In addition, this technique is limited due to the need to use anaglyphic glasses to observe the stereoscopic images. It is the best solution, however, as the model created by SFM photogrammetry does not offer such a good resolution to observe the tumuli.

Even considering the methodological limitations, however, we have tried to undertake preliminary research, reconstructing the traditional landscape of Monte de Santa Mariña in 1956. To do that, we created a 3D model using as the base the actual DEM and moulding it with historical pictures. In so doing, we might get an initial sense of where these megalithic archaeological sites are situated, via an ortho-image of the year 1956, and therefore recreate the traditional landscape.

4 Conclusions

We have applied three different types of filters to the Lidar data with the aim of seeing the Galician tumuli more clearly. The results have been very interesting because, despite the fact that we could not eliminate the vegetation that covers the

Fig. 5. Local relief model based on resampling filter.

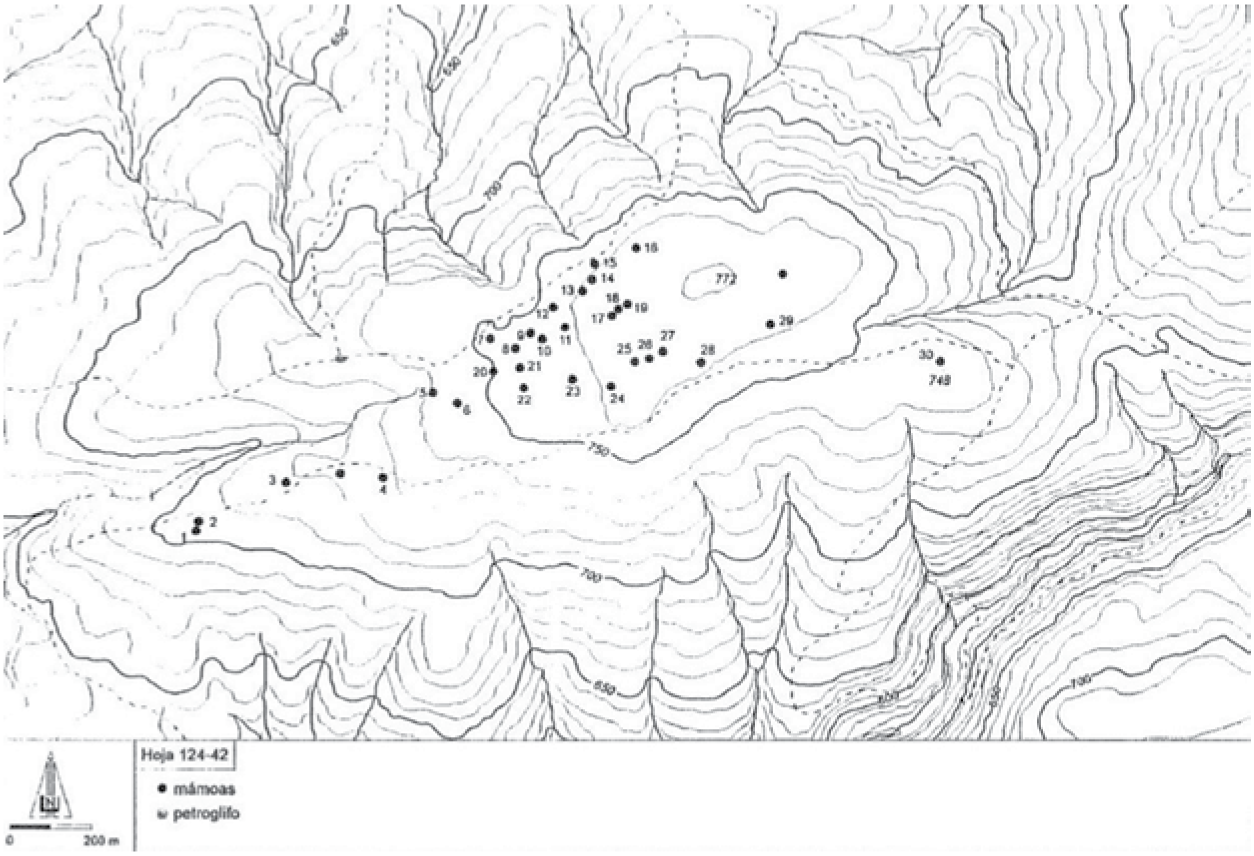

Fig. 6. First approaches to 3D reconstruction of the past landscape of Monte de Santa Mariña.

archaeological sites, we have obtained a better visualization through the use of different analyses, all of them open-source.

The necropolis of Monte Santa Mariña has been historically studied too many times, but thanks to Lidar data, we have discovered and catalogued a new monument (Carrero-Pazos *et al.* 2014).

Henceforth, we think that this kind of approach should be a first step in any archaeological prospection if Lidar data are available. In particular, we consider that this is necessary in regions such as Galicia with dense vegetation, where it is difficult to undertake intense prospections, although flat areas should not be ignored.

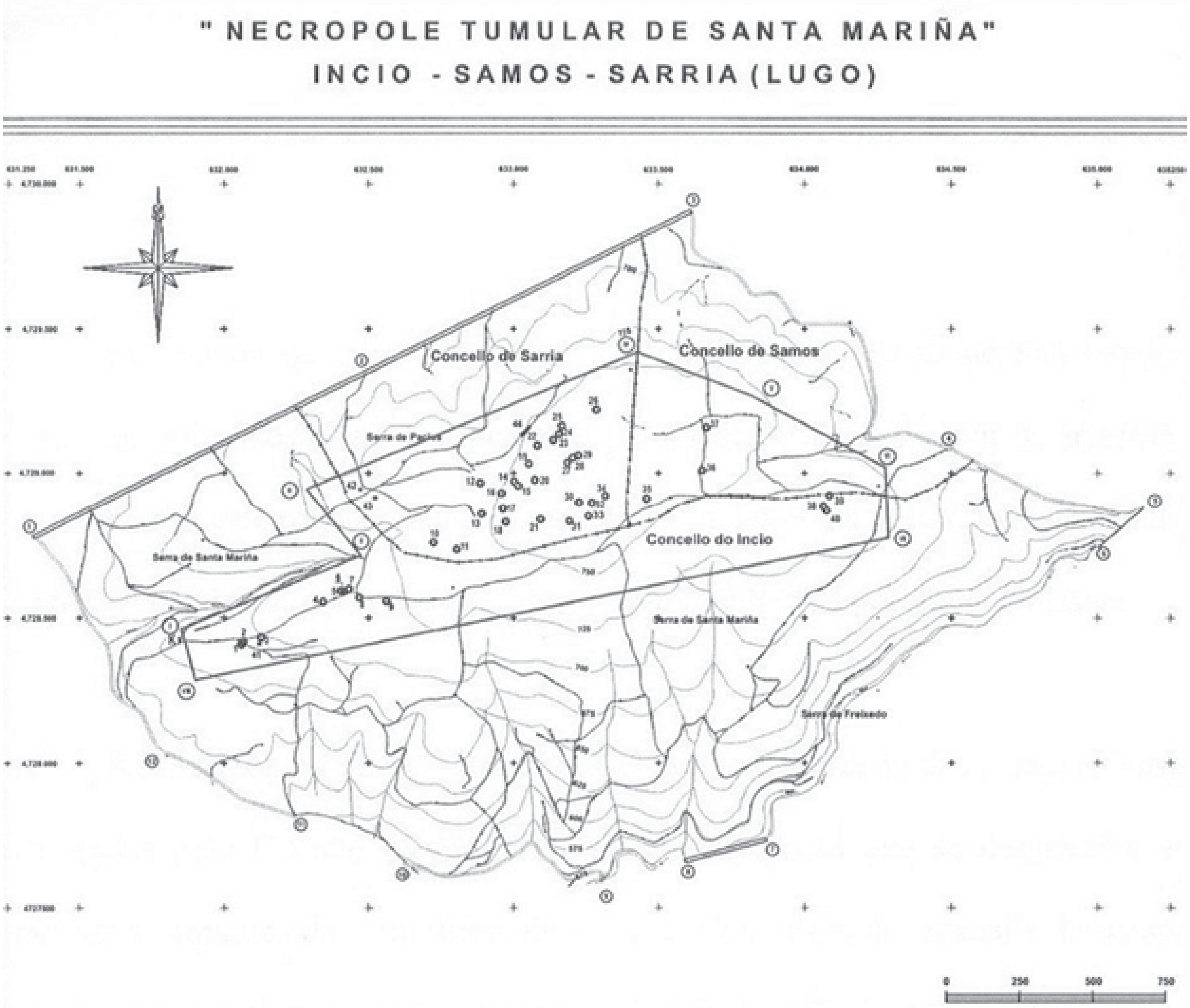

Fig. 7. Official catalogue of megalithic sites in Monte de Santa Mariña.

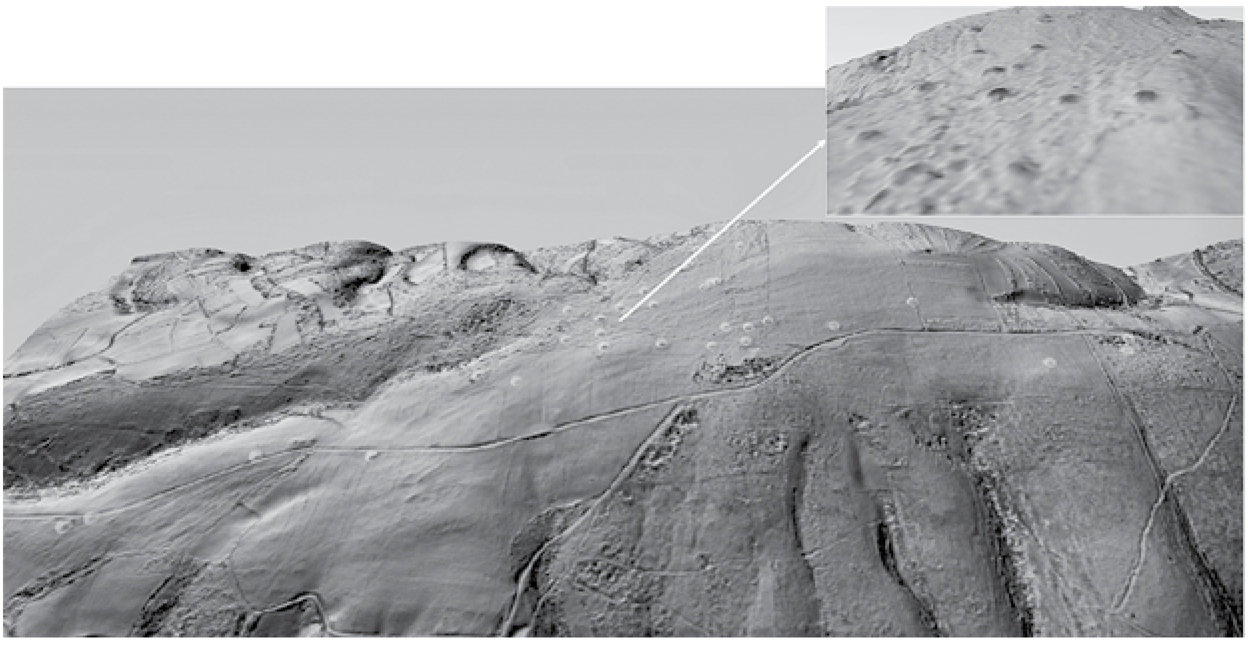

Fig. 8. 3D reconstruction of the current Monte de Santa Mariña.

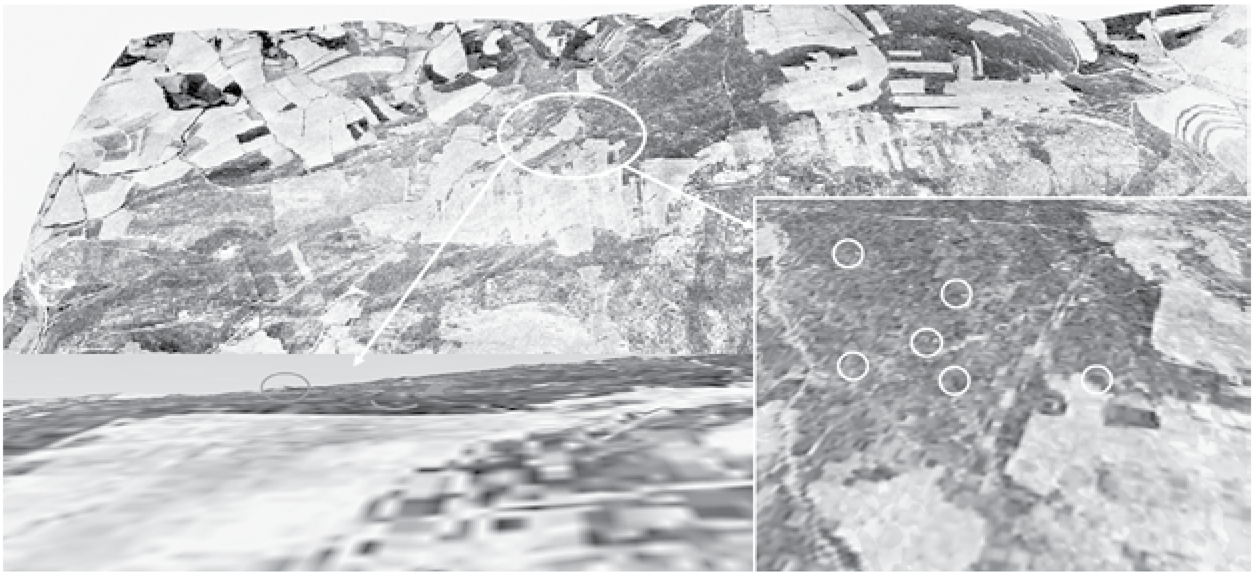

Fig. 9. First approaches to 3D reconstruction of the past landscape of Monte de Santa Mariña.

By studying these data, the total land cover becomes more accessible, and we believe that this process should be established as a prerequisite to the archaeological field survey that should never be overlooked.

Finally, another aspect to consider is the possibility of digital techniques recreating scenes from the past that no longer exist. Thanks to photogrammetric techniques, or reconstructions as we have done here, we can produce images with great media coverage, which may be of general interest or, at least, from a museological point of view.

Bibliography

Aparicio Resco, P., Carmona Barreiro, J. D., Fernandez Diaz, M. and Martin Serrano, P. M. 2014. ' Fotogrametría Involuntaria ': Rescatando información geométrica en 3D de fotografías de archivo. *VAR*, 5 (10): 11-20.

Blanco Rotea, R., Fonte, J., Guimil Fariña, A. and Mañana Borrazás, P. 2014. Using airborne laser scanning and historical aerial photos to identify Modern Age fortifications in the Minho valley, Northwest Iberia. *XVII World UISPP Congress*, Burgos, Spain. Poster presentation.

Caninas, J. C., Henriques, F., Batista, Á. and Pires, H. 2011. Pedra das Cruzinhas: notícia de um monólito gravado na fronteira entre os concelhos do Sabugal e da Guarda. *Sabucale* 3: 35-56.

Carrero Pazos, M., Vilas Estévez, B., Romaní Fariña, E. and Rodríguez Casal, A. A. 2014. La necrópolis megalítica del Monte de Santa Mariña revisitada: aportaciones del Lidar aéreo para la cartografía megalítica de Galicia. *Gallaecia* 33: 39-57.

Carrero Pazos, M., Vilas Estévez, B. and Vázquez Martínez, A. 2015. New possibilities to enhance ancient carvings: the AsTrend. *TRACCE Online Rock Art Bulletin* 36: 1-3.

Cerrillo De Cuenca, E. 2011. Recorriendo un territorio desaparecido: Restitución fotogramétrica y análisis del paisaje de la necrópolis prehistórica del Vado de Alconétar. *Actas del V Simposio Internacional de Arqueología de Mérida. Tecnologías de Información Geográfica y Análisis del Territorio*: 145-59. Mérida**,** Archivo Español de Arqueología.

Filgueiras Rey, A. I. and Rodríguez Fernández, T. 1994. Túmulos y petroglifos. La construcción de un paisaje funerario. Aproximación a sus implicaciones simbólicas. *Espacio, Tiempo y Forma* 7: 211-53.

Fonte, J. and Gonçalves Seco, L. 2010a. An integration of Airborne LiDAR and vertical aerial imagery to analyse two Iron Age hillforts in Northern Galicia (Spain). *International Aerial Archaeology Conference (AARG, 2010)*, Bucarest, Rumania. Poster presentation.

Fonte, J. and Gonçalves-Seco, L. 2010b. Integração de LiDAR Aéreo e de Fotografia Aérea Vertical na documentação e investigação de Património Cultural. *I Congresso Internacional Povoamento e Exploração de Recursos Mineiros na Europa Atlântica Ocidental, Braga, Universidade do Minho*. Poster presentation.

Fonte, J. and Gonçalves-Seco, L. 2012. LiDAR data evaluation for archaeological purposes in Northwest Iberia. *Computer Application & Quantitative Methods in Archaeology (CAA 2012)*, Southampton, University of Southampton. Poster presentation.

Fonte, J.; Pires, H.; Gonçalves-Seco L.; Matías Rodríguez, R.; L. and Lima, A. 2014. Archaeological research of ancient mining landscapes in Galicia (Spain) using Airborne Laser Scanning data. *Simpósio Internacional Paisagens Mineiras Antigas na Europa Ocidental. Investigação e Valorização Cultural*, Boticas. Poster presentation.

Hesse, R. 2010. LiDAR - Derived Local Relief Models - a New Tool for Archaeological Prospection. *Archaeological Prospection*, 17: 67-72.

Hesse, R. 2013. *Lidar Visualization Toolbox*. Visual Basic .NET (version 1.0.0.20), from http://sourceforge.net/projects/livt/?source=navbar.

Horn, B. K. P. 1982. Hill-shading and the reflectance map, *Geo-Processing* 2: 65-146.

Imhof, E. 1982. In Steward H.J. (ed.), *Cartographic Relief Presentation*. Walter de Gruyter, Berlin.

Jenny, B. 2001. An interactive approach to analytical relief shading. *Cartographica* 38 (1-2): 67-75.

Kokalj, Ž., Zakšek, K. and Oštir, K. 2013. Visualizations of Lidar Derived Relief Models. In Opitz, R., Cowley, D. (eds.), *Interpreting Archaeological Topography: Lasers, 3D Data, Observation, Visualization and Applications*: 100-4 Oxford, Oxbow Books.

López Romero, E., Mañana Borrazás, P. 2013. *El círculo lítico de Monte Lobeira (Vilanova de Arousa, Pontevedra). Trabajos de 2008 y 2010*. Santiago de Compostela, Incipit, CSIC.

Mañana Borrazás, P., Gianotti García, C., González Insua, F., Caramés Moreira, V. 2010. Aplicación de tecnologías geoespaciales para la documentación del círculo lítico de Monte Lobeira, Vilanova de Arousa (Pontevedra). *Cuadernos de estudios Gallegos* LVII (123): 25-52.

Mark, R. 1992. *Multidirectional, oblique-weighted, shaded-relief image of the Island of Hawaii*, U.S. Geological Survey. http://pubs.usgs.gov/of/1992/of92-422

Marr, D. 1982. *Vision*. Freeman.

Pires, H., Gonçalves-Seco, L., Fonte, J., Parcero-Oubiña, C. and Fábrega- Álvarez, P. 2013. Lidar-derived morphological relief models for the detection of archaeological features using mesh decimation. *AARG Conference 2013*, Amersfoort, The Netherlands. Poster presentation.

Pires, H., Gonçalves-Seco, L., Fonte, J., Parcero-Oubiña, C. and Fábrega-Álvarez, P. 2014. Morphological Residuals Model - a mesh decimation filtering tool for detection and contrast of archaeological evidences in point- cloud derived models. Jo*urnal of Cultural Heritage* (forthcoming).

Rodríguez Casal, A. A. 1998. La necrópolis megal**ítica** del Monte de Santa Mariña. *Gallaecia* 17: 121-35.

Rodríguez Casal, A. A., Gómez Nistal, C., Romaní Fariña, E. 1998. El fenómeno tumular y megalítico en las tierras de Sarria- O Incio (Lugo). *Gallaecia* 17: 60-105.

Rodriguez Navarro, P. 2010. La Fotogrametría digital automatizada frente a los sistemas basaos en sensores 3D activos. *Revista de Expresión Gráfica Arquitéctónica* 20: 100-11.

Tzelepis, N., Loisios, D. and Nakos B. 2008. A new method of analytical hillshading by using different lighting directions. *Proceedings of the 10th National Cartographic Conference, Hellenic Cartographic Society*, Ioannina.

Vilas Estévez, B., Carrero-Pazos, M., Eguileta Franco, J. Mª and Hast, A. 2015. Recreando con técnicas de fotogrametría histórica unha paisaxe megalítica asolagada: o caso do encoro do salas. *III Congreso Internacional de Arqueoloxía de Vilalba (Vilalba, Lugo, 20-23/07/2015)*. *Férvedes, Revista de Investigación* 8: 9-16.

Yebra Biurrun, M. J. 1990. *Geografía rural del municipio de Sarria*. Lugo, Diputación Provincial.

Zakšek, K., Oštir, K., Pehani, P., Kokalj, Ž., Polert, E. 2012. Hill Shading Based on Anisotropic Diffuse Illumination. *Symposium GIS Ostrava 2012*: 1-10. Ostrava, Technical University of Ostrava.

Reflectance Transformation Imaging Beyond the Visible: Ultraviolet Reflected and Ultraviolet Induced Visible Fluorescence

E. Kotoula
ek12v07@soton.ac.uk, e.t.kotoula@hotmail.com
University of Southampton, UK

Abstract: This paper presents the recent developments of Reflectance Transformation Imaging (RTI) beyond the visible spectral area, with an emphasis on Ultraviolet (UV) RTI and in particular Reflected UV (UVR) RTI and UV induced visible fluorescence (UVF) RTI. A painted and incised ceramic vessel from the Archaeological Collection of the University of Southampton as well as fragments of Faenza maiolica ceramics from the Southampton City Council Archaeological Collection were used as case studies. Results indicate that a complete multispectral RTI visualization, including additional captures in the infrared and ultraviolet spectral region, can be a valuable addition to the examination protocol. In particular, the UV-RTI techniques, as advanced digital analogues of UV imaging, enhance examination of subtle variations of the outer layer that are not clear in the visible, reveal manufacture evidence and decay relevant to glazes and varnishes as well as episodes of the 'museum' life of the artefacts.

Keywords: Multispectral RTI, Reflected UV-RTI, UV induced visible fluorescence-RTI, IR-RTI

Introduction

It is well known that areas of the electromagnetic spectrum, which are not visible to the human eye, have been used for the examination of artworks and antiquities. Infrared imaging is particularly useful for authentication and art history studies of painted surfaces, revealing original features covered by restorations, enabling characterization and mapping of pigments, inks, and binding media. It has also been used in order to improve the reading of ancient inscriptions and differentiate texts written in different historical periods. Ultraviolet imaging successfully identifies retouching over painting and can be of great assistance in studies of varnishes (Warda *et al.* 2011). Furthermore, spectral imaging can provide a valuable tool in the assessment of conservation treatments. Alterations introduced during conservation operations or damage can be determined and visualized, providing a better understanding of the material ageing phenomena, as well as for the processes used in order to pace their rate, as demonstrated by applications on marble, paper, parchment, and wall paintings (Liang 2011). The application of multispectral imaging techniques prior to physicochemical analyses (Baldia and Jakes 2007) assures better results, providing an enhanced sampling strategy.

RTI (Mudge *et al.* 2005) and the most common fitting algorithm, Polynomial Texture Mapping (PTM), developed in 2001 at Hewlett Packard Laboratories (Malzbender *et al.* 2001), are non-destructive, affordable, and easy imaging techniques, providing a more holistic approach for visualization than other two-dimensional techniques. Previous work in the field of RTI technologies and applications proved that the technique revolutionizes artefacts recording and examination, assisting analysis and conservation (Earl *et al.* 2010). The technique has found applications in a broad range of material and artefacts types, from large objects (Miles *et al.* 2014) to microscopic features (Kotoula 2013; Messier 2014). Worth mentioning is the contribution of Cultural Heritage Imaging (CHI) in the development and dissemination of RTI technologies, in addition to cultural heritage organizations, research centres, and universities.

1 Previous work

The synergy of RTI and multispectral imaging technologies is one of the most promising techniques for the development of artefacts' examination methodology. They have already managed to provide valuable techniques for artefacts visualization, analysis, and conservation. One of the earlier applications was the study of ancient Dead Sea scrolls, using a combined RTI and infrared methodology (Caine and Magen 2011). Further work on the Derveni papyrus (Kotoula and Earl 2015a) as well as experimentations on replicas (Valergas 2014) proved the effectiveness of synergistic RTI approaches. Similar results were reached from experimentations on a variety of painted artefacts (Kotoula and Earl 2015b). Testing various methodological approaches signals a significant step for the development of multispectral RTI (Hanneken 2014). Nevertheless, there are still undiscovered areas and future developments that can enhance methodological approaches, such as the synergy of RTI and UV imaging techniques, which is the main focus of the present study.

2 Methodology

The Highlight RTI multispectral datasets were captured with a UV-VIS-IR modified DSLR (Digital Single-Lens Reflex) camera (Nikon D700), a range of filters, and IR or UV radiation sources in the Archaeological Imaging laboratory of the University of Southampton. Modified DSLR cameras have sensitivity from 350nm up to 1000nm. For infrared, imaging filters that absorb visible and transmit infrared are used (720nm, 760nm, 850nm, 950nm). For ultraviolet imaging UV transmitter filters are necessary. The reflected ultraviolet RTI datasets were captured with a UV transmitter filter (HOYA 330) and an IR barrier (SCHOTT BG 38). The ultraviolet induced visible fluorescence RTI datasets were captured with an IR and an UV barrier (B+W 021) filter. For the purposes of this study, the subjects were irradiated by IR light emitting diodes (LED) and a UV flash from different angles. The images were pre-processed using common digital image software and recommendations for multispectral imaging (Warda *et al.* 2011). The resolution of each digital image was 300ppi. PTM and RTI files were built

Fig. 1. Gnathian skyphos. Height 8.5cm. (University of Southampton Archaeological Collection).

using the mainstream highlight RTI methodology and viewed using the RTI viewer (Cultural Heritage Imaging 2012) and the InscriptiFact Standalone Viewer (2015) developed at the University of Southern California. The files produced varied from 60MB to 110MB, depending on the quantity and the quality of the photos and the RTIBuilder settings. Digital image processing of RTI visualizations can lead to useful illustrations that highlight specific features of the visualized objects. This experimentation was inspired by previous work on image processing (Brognara *et al.* 2013; Raskar 2004), mental ray contours (Earl *et al.* 2011), maximum entropy calculation (Malzbender and Ordentlich 2005), the CARE tool (Cultural Heritage Imaging 2013), and normals-based illustration (Toler-Franklin *et al.* 2007).

3 Selection of study material

A Corinthian-type Gnathian skyphos from the Archaeological Collection of the University of Southampton (Fig. 1) as well as fragments of Faenza maiolica ceramics from the Southampton City Council Archaeological Collection (Fig. 2) were used as case studies. The skyphos is a deep-bodied drinking cup with a plain rim, low foot, and two horizontal handles below the rim. On one side there is a band of white egg-pattern on the rim, and below this is a band of wavy lines also in white, a row of white dots, and a red stem followed by a highly stylized grapevine pattern. The back side features a single white wreath with an incised stem. In addition, fragments of two late medieval (*c.*1490–1510) north Italian Sgraffito jugs, probably from Faenza, with medallions on the front depicting piscine zoomorphic designs painted with blue and orange mineral pigments on a tin-glazed opaque background (Brown 2002) were captured. The fragments are in different preservation states. Some of them have been cleaned while others are covered with deposits from the excavation environment and salt efflorescence.

These objects were selected based on our extensive experience in the application of RTI on a variety of artefacts and materials types. There are obvious similarities between Gnathian ceramics and red-figure ceramics wares, where previous research has shown the advanced options for visualization and analysis provided by RTI (Kotoula and Earl 2015). Similarly, RTI visualization of lustrous glazed ceramic wares proved to be an effective way for capturing colour and surface properties, even in cases of minor surface relief (Bridgman and Earl 2012). In addition the fact that the selected objects have painted decoration was another parameter that suggested the experimentation because of the long list of published research dealing with the multispectral imaging of painted surfaces. Also notable is the fact that the Gnathian skyphos is restored and offers the possibility of exploring evidence of materials used during previous repairs. Moreover, the visualization of the ceramic shreds in different preservation states (cleaned and not cleaned material) can assist in defining the potential of the proposed methodologies, following the example of previous RTI studies in numismatics (Kotoula and Kyranoudi 2013).

4 Results and discussion

4.1 Gnathian skyphos

RTI visualization of the Gnathian skyphos enabled detailed examination of the surface properties. In the area of the handle

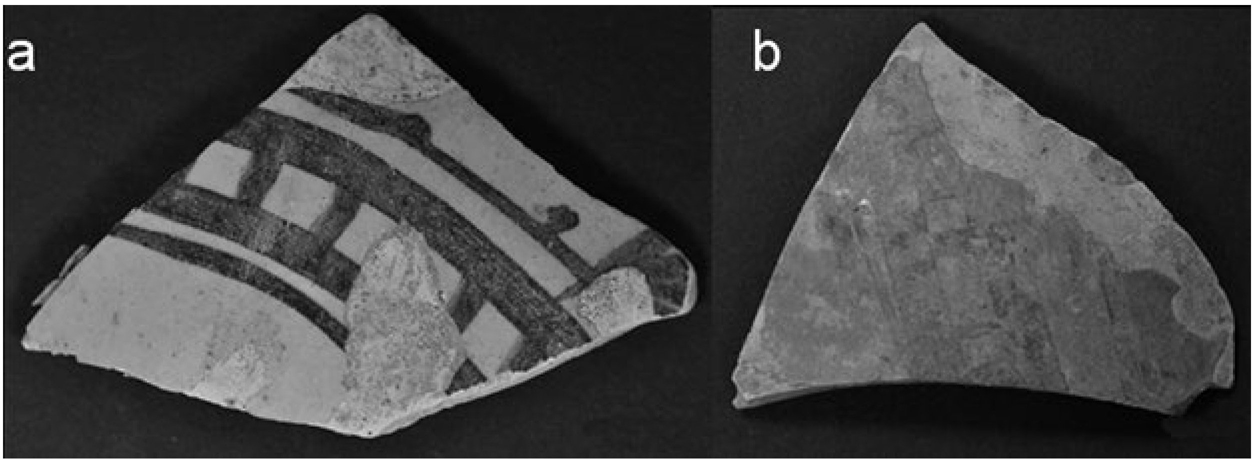

Fig. 2. Faenza maiolica fragments: a) cleaned; b) with encrustation and earth deposits. (Southampton City Council Archaeological Collection).

the tiny lines reveal the pressure applied by the person who crafted the skyphos when they attached the handle, and in the area of the body marks of the ceramic wheel are observable (Fig. 3). The infrared image of the skyphos demonstrates a differentiation in the response of the black glaze in the infrared radiation as a result of its poor state of preservation. In addition, the deposits on the surface appear eliminated (Fig. 4).

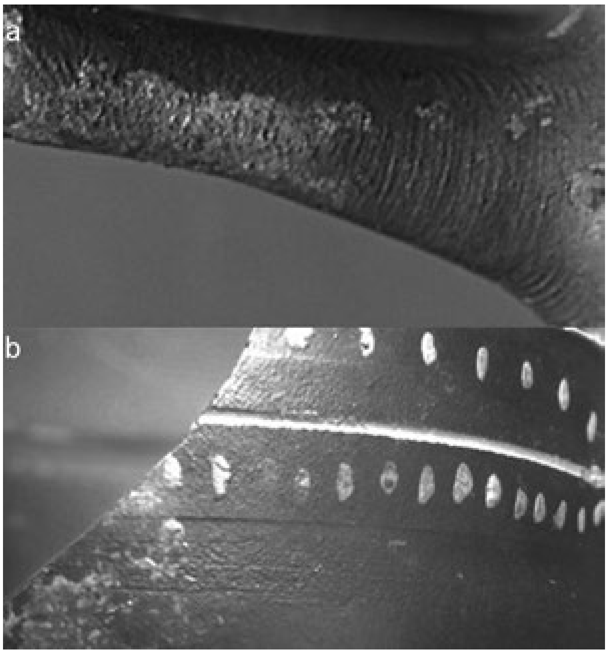

Fig. 3. RTI visualization of the Gnathian skyphos in the visible spectral area: a) rendering in image unsharp [OK?] masking reveals fingerprints in the areas of the handle and b) rendering in specular enhancement mode underlines wheel marks covered by encrustations.

The ultraviolet induced visible fluorescence image reveals the remains of conservation materials on the surface of the ceramic skyphos and the previous repairs, because of the visible fluorescence emission of common adhesives used. It is known that in static UV induced visible fluorescence imaging, the axial positioning of the radiation source, as well as moving the handheld radiation units around, are actions usually undertaken to facilitate improved documentation of objects and a better perception of the features revealed. The UV induced visible fluorescence RTI enables the user to move virtually the radiation source around the object leading to numerous different visualizations (Fig. 5). In this way the conservator can reach a better understanding about the morphology of the previous repairs. In addition, digital image processing of the RTI renderings can be used for the demonstration of results. A characteristic example is the UV induced visible fluorescence RTI visualization of the skyphos, shown in Figure 6. The application of find edges filter results in outlines of the remnants of the conservation materials. These examples demonstrate that the subtractive illustration approach may be useful for the interpretation and explanation of the results of multispectral RTI.

Reflected UV-RTI offers the opportunity for enhanced examination of subtle surface variations. In the case of the skyphos, these variations are the remains of the conservation materials, the differentiations of the glaze due to its poor preservation, and the salts' efflorescence. The UV-RTI provided in a single file a combination of axial and UV imaging (Fig. 7). It is notable that the axial positioning of radiation sources in reflected UV imaging is 'advantageous' and is proposed for the recording of scratches and smudges (Warda *et al.* 2011: 161). By applying the specular enhancement-rendering

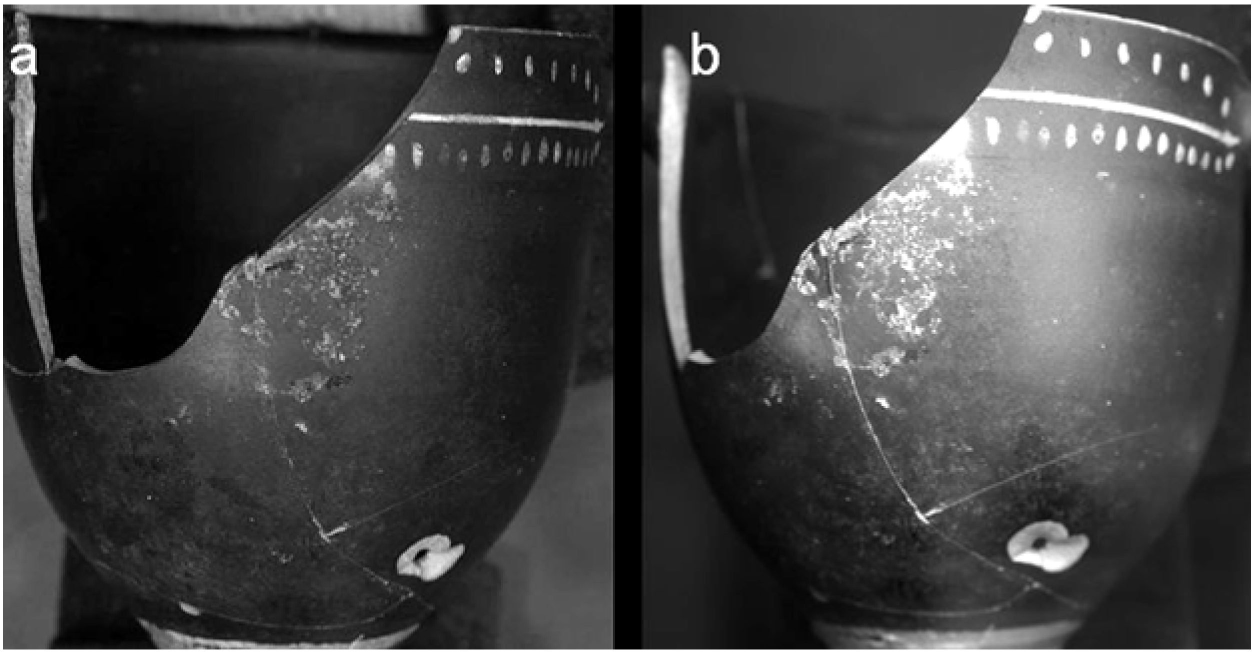

Fig. 4. Comparison of RTI visualization of the Gnathian skyphos: a) rendering in the visible and b) rendering in the infrared spectral area.

Fig. 5. Gnathian skyphos. UVF-RTI visualizations a) in default and b) and c) specular enhancement rendering modes

Fig. 6. Gnathian skyphos, detail. Application of the find edges filter in ImageJ: a) digital image; b) UV-RTI visualization.

mode and additional setting of the parameters the findings appear emphasized. The normal maps produced are complete representations of the surface topography of the surface in the ultraviolet region.

As shown in Figure 8, the comparison of the renderings in different spectral area visualizes different features. In the visible RTI the engravings and the depositions as well as the colour variation are visualized in great detail. In the IR-RTI, the colour application and the painted design appear emphasized, as the depositions are not visible, because of the penetration of infrared radiation. In the UVF-RTI traces of the conservation materials appear emphasized, providing evidence for previous repairs. On the other side of the vessel similar features are observed in the comparison of the renderings in different spectral areas. The most interesting feature is the variation of the varnish, which is emphasized in the UV-RTI.

4.2 Faenza maiolica sherds

In the Faenza maiolica ceramic sherd the most interesting feature revealed from the RTI visualization was the surface anomaly-curvature, which may be associated to the lack of attachment of the glaze to the body as well as the three-dimensionality of the low relief detail of the painted designs. Moreover, the network of cracks of the glaze, and the tiny blisters, were not visible in the digital images but appeared emphasized in the RTI renderings (Fig. 9). RTI visualization of the sherds covered with

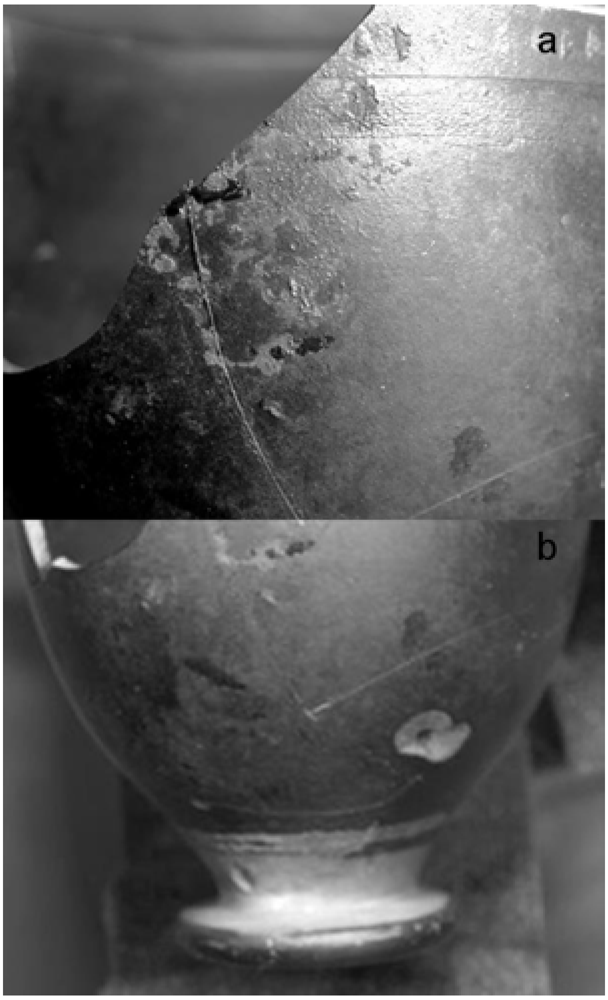

Fig. 7. Gnathian skyphos. UVR-RTI visualizations in a) specular enhancement and b) default rendering mode.

soil and deposits emphasized the painted pattern, which was barely visible in the digital images. In detail images the surface anomalies, scratches, surface topography of the deposits, and rough and porous ceramic texture in the areas where the glaze was missing can be observed. Find edges and trace contour filters proved to be useful tools for the clearer identification of differences between digital images and RTI visualization. Comparison of visualizations produced by applying the find edges filter in digital image and RTI visualization emphasizes the network of cracks (Fig. 10).

Infrared imaging of the ceramic sherd covered with superficial dirt and deposits reveals the painted design. In the case of the clean sherd, the preparatory drawing and the application of colour can be examined. In the presence of different colours, their varying response can assist in materials' differentiation and characterization. Infrared RTI visualizations reveal the three-dimensional characteristics of the paint layer, while the layer of depositions appears significantly eliminated due to the penetration ability of infrared irradiation, as demonstrated by the comparison of RTI renderings between the visible and IR spectral area from the same light parameters. Infrared radiation penetrates the paint layer and the cracking is revealed (Fig. 11).

The reflected UV-RTI did not provide as much evidence compared to the Gnathian skyphos, due to the preservation state of the fragment, but assisted in identifying the benefits of UVR-RTI. The UVR-RTI depicts not only the areas where the encrustations have different properties, as it happens in static UV imaging, but also the texture of the fragment. A complete RTI visualization includes captures in the visible, infrared, and ultraviolet spectral region, as shown in the example of the Faenza maiolica fragment covered by encrustations in Figure 12.

Although the RTIViewer provides the option to apply different rendering modes, enhancing the visualization, the InscriptiFact Viewer enables the simultaneous viewing of two files. This feature proved particularly helpful in the comparative analysis of the visualizations in the different spectral areas (Fig. 13), even if the use of high-resolution files is problematic.

5 Conclusions

As far as the multispectral RTI methodologies are concerned, even if their feasibility has been proved since 2007 (Redman and Mudge), the applications in this study, using different spectral imaging techniques, provided the necessary case studies to demonstrate their utility to the cultural heritage community. Synergistic RTI approaches are expected to strengthen the role of digital techniques in terms of investigation, prevention, intervention, and communication.

Visible RTI should be used for the recording of surface and texture of objects for condition reporting, general documentation, presentation, and dissemination. The nature of the artefact is irrelevant, although the curvature of the object will have an impact on the size, orientation, and position of the area to be captured each time. IR-RTI should be used for the recording of subsurface texture for examination, analysis, condition reporting, and presentation. The applicability of IR-RTI according the nature of the object follows the general knowledge from 2D multispectral imaging. For example, substrates of painted surfaces, preparatory drawings, obscured decoration elements, and faded writings are among the features that can be visualized effectively using IR-RTI.

UV-RTI should be used for the recording of subtle surface variations and documentation of previous repairs for examination, analysis, condition reporting, and presentation of findings. The technique is applicable to objects that can benefit from the application of UV imaging techniques. The synergy of RTI and UV imaging results in an enhanced methodology for non-destructive examination of artefacts and virtual visual analysis. UV-RTI techniques reveal episodes of the museum life of the artefact. In particular, traces of adhesive/tape, reassembled [text missing? or reassembling?], additions, restorations, repainting, and in-painting can be detected by UVF-RTI. For the subtle variations in the outer layer, not clear in the visible spectral area, as well as manufacture evidence relevant to varnish layer or glazes, UVR-RTI is recommended.

6 Future work

The issue of distortion introduced by filters, which has been discussed in the literature (Brauers and Aach 2011), has not been discussed in this paper, since such an impact has not been noticed in the visual analysis of the files. The development of

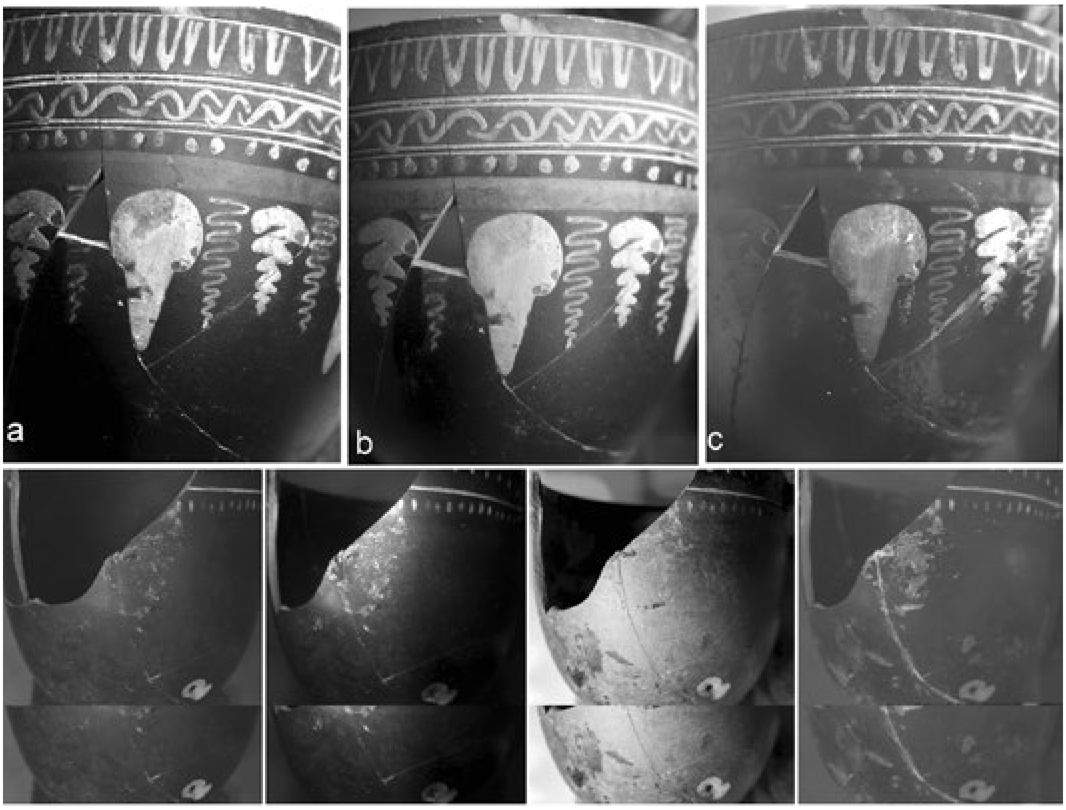

Fig. 8. Complete RTI visualization of Gnathian skyphos: a) visible RTI; b) IR-RTI; c) UVF-RTI; d) visible RTI; e) IR-RTI; f) UVR-RTI; g) UVF-RTI renderings and h) visible RTI; i) IR-RTI; j) UVR-RTI; k) UVF-RTI normal maps.

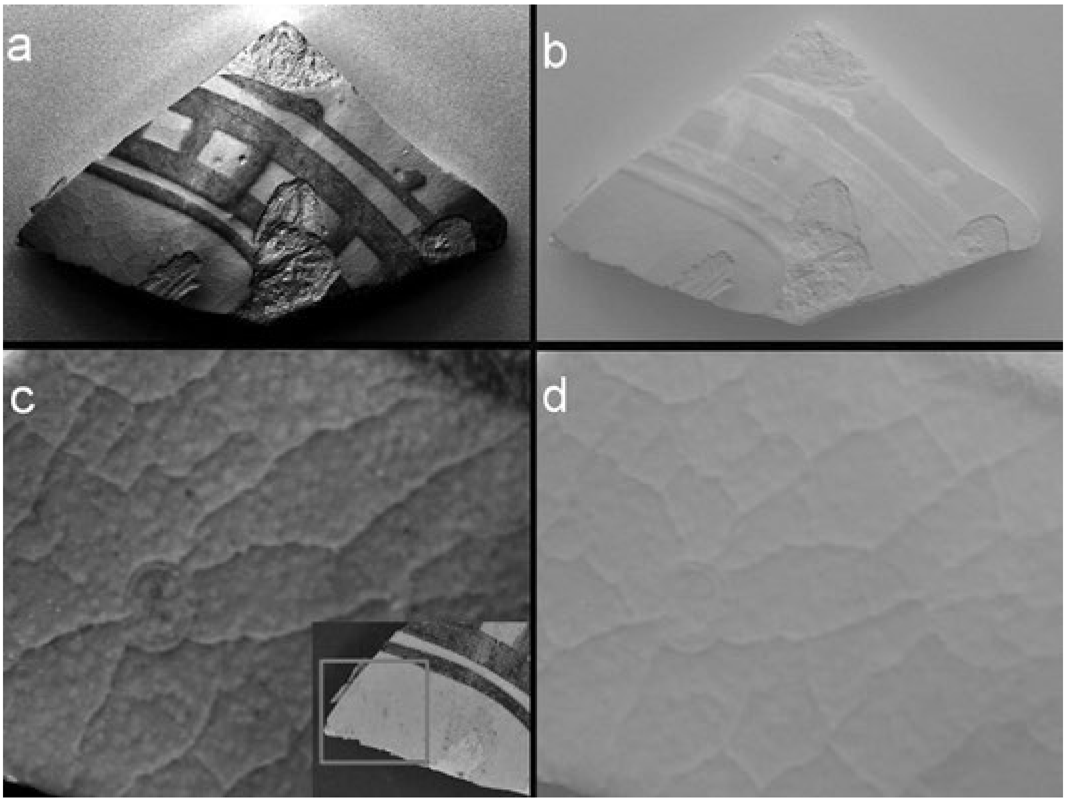

Fig. 9. RTI visualizations of Faenza maiolica sherd: a) rendering in specular enhancement mode; b) normal map; c) detail rendering in specular enhancement mode; d) normal map.

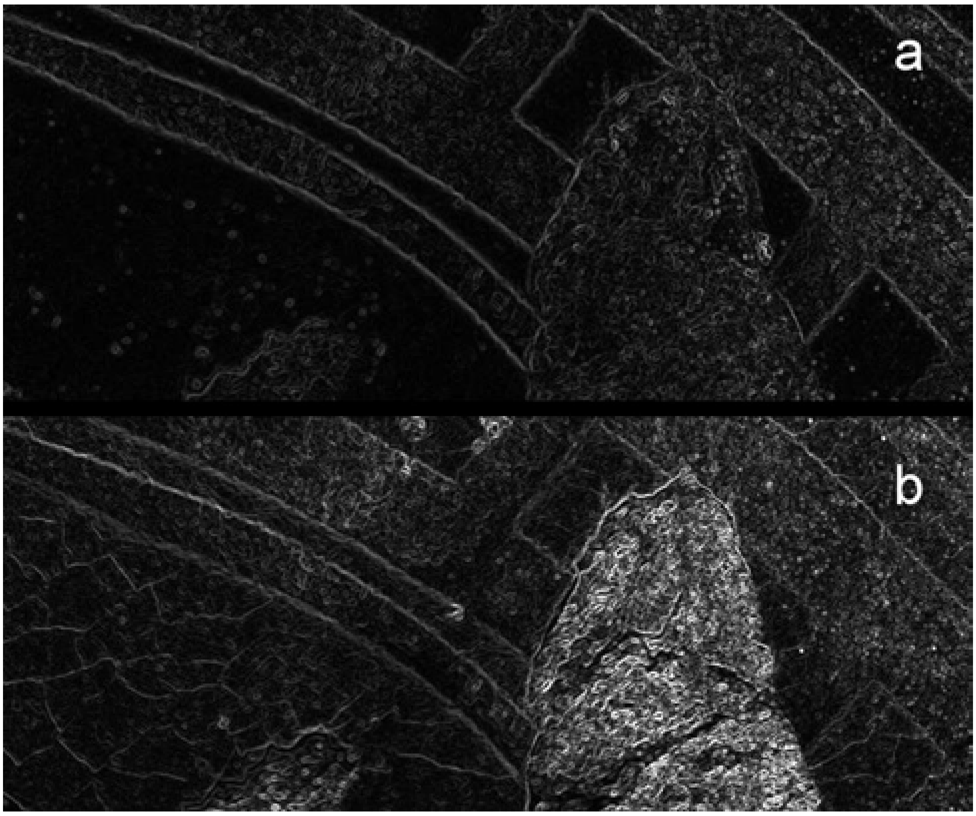

Fig. 10. Faenza maiolica shred. Application of the find edges filter in ImageJ: a) digital image; b) RTI visualization.

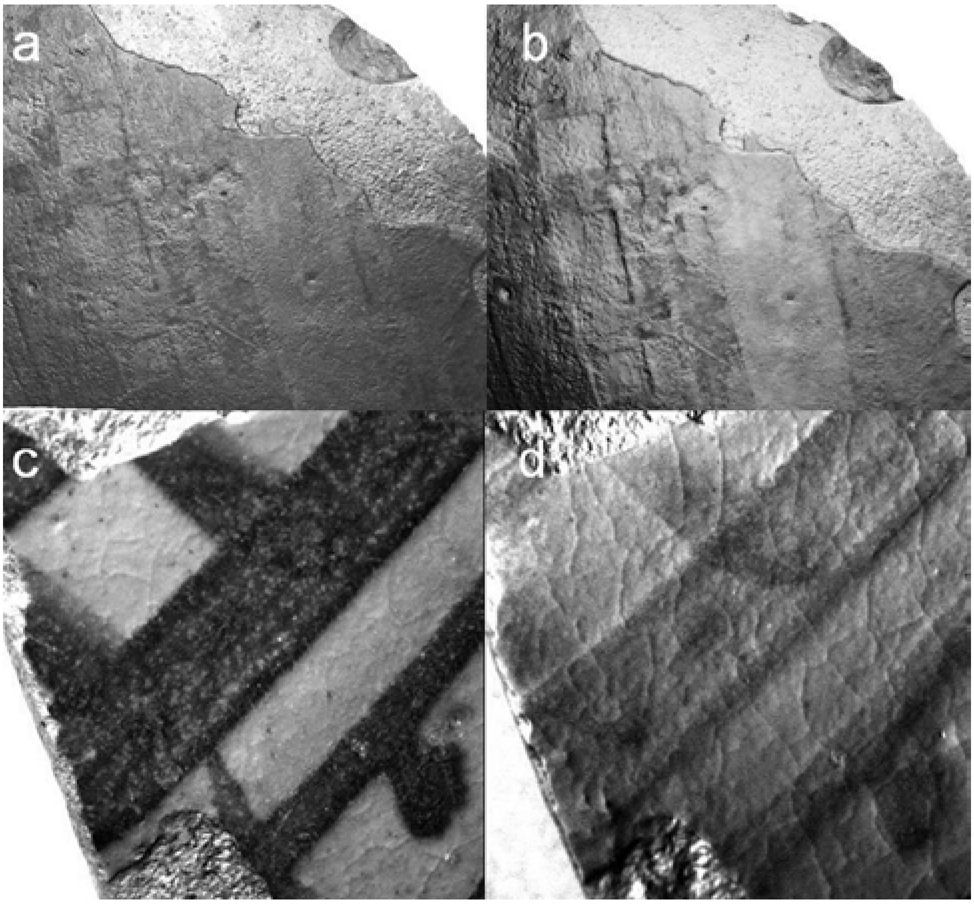

Fig. 11. Comparison of visible and IR-RTI visualization of Faenza maiolica sherds in different conservation states: a) rendering in the visible and b) infrared spectral area of sherd covered by encrustations and c) rendering in the visible and d) infrared spectral area of cleaned sherd.

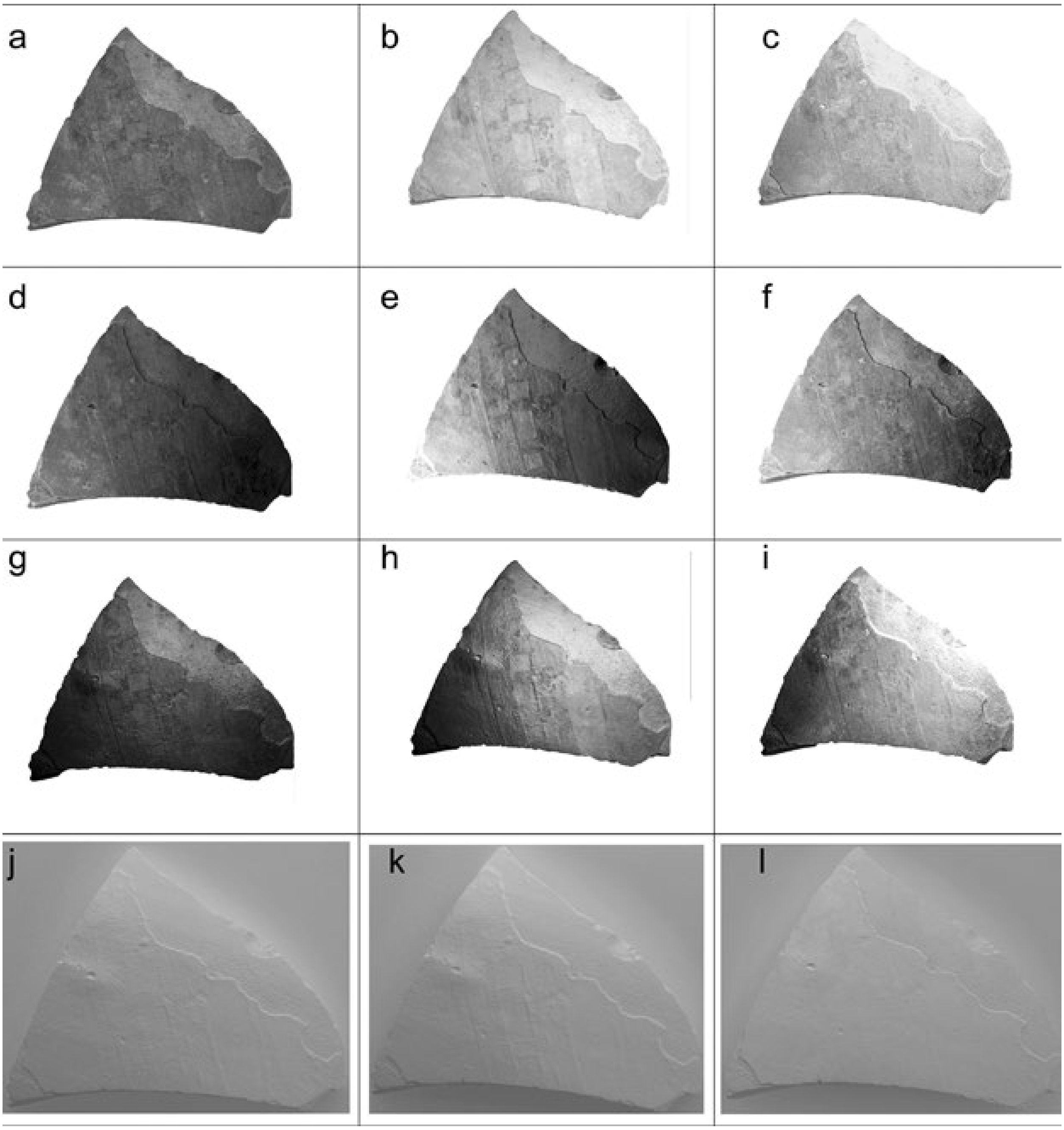

Fig. 12. Complete RTI visualization of Faenza maiolica sherd: a) digital image; b) infrared image (950nm); c) ultraviolet reflected image; d) visible RTI visualization in default rendering mode; e) IR-RTI visualization in default rendering mode; f) UVR-RTI visualization in default rendering mode; g) visible RTI visualization in specular enhancement rendering mode; h) IR-RTI visualization in specular enhancement rendering mode; i) UVR-RTI visualization in specular enhancement rendering mode; j) visible normal map; k) IR normal map; l) UVR normal map.

multispectral RTI methodologies should take into consideration photo-degradation research findings (Macchia *et al.* 2013). Appropriate lighting is a necessity for the safe recording and examination of artefacts and LEDs are considered to be the most convenient and safe choice (Ishii *et al.* 2008), which have found application in museums beyond simple illumination of artefacts (Viénot *et al.* 2011). Nevertheless, experimental results from multispectral RTI data capture are missing and this is an area for future research and of particular interest both for conservation scientists and archaeological computer experts.

The integration of RTI visualization produced as part of this research into the web-based RTI viewer developed by CNR-ISTI (Palma *et al.* 2013) will enhance the dissemination of the results and encourage further analysis as well as scientific cooperation, following the successful online RTI visualization of data from other projects, such as coins (Palma and Callieri 2013) and rock art (Riris and Corteletti 2015). The presented examples lead to the conclusion that filtering RTI visualizations may be useful for documentation, analysis, and demonstration purposes. There is a clear need for meticulous documentation

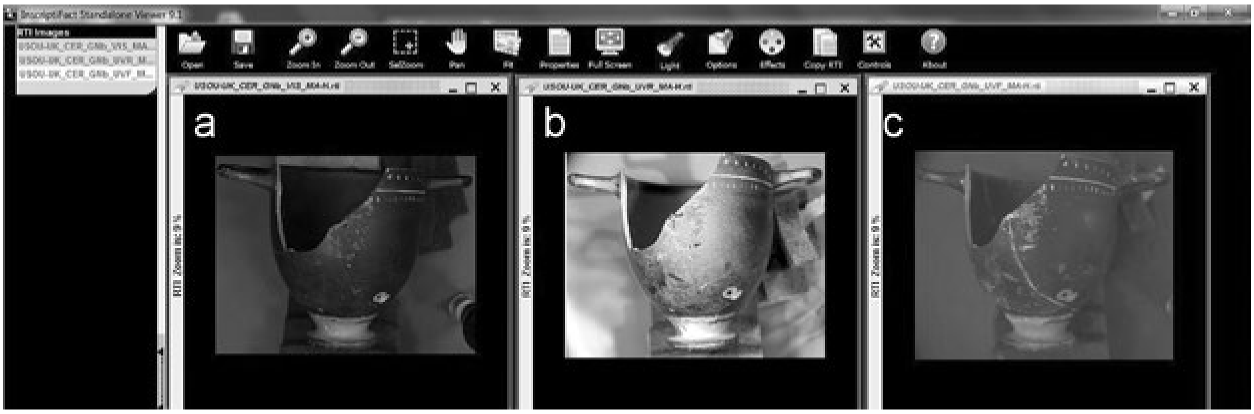

Fig. 13. InscriptiFact Viewer (USC) screenshot. Simultaneous visual analysis of RTI visualizations in the visible and ultraviolet spectral area: a) visible RTI; b) UVR-RTI; c) UVF-RTI.

of the processing filters applied to each illustration produced. The development of an improved version of Viewer, which will incorporate standard image-processing filters, will provide assistance in the documentation of filtering and offer an easy way to produce not only RTI visualizations but also stylistic illustrations of artefacts. At the same time the incorporation of filtering options to viewers in addition to further experimentation will enable the development of guidelines in order to avoid confusing illustrations.

Bibliography

Baldia, C. M. and Jakes, K. A. 2007. Photographic methods to detect colourants in archaeological textiles. *Journal of Archaeological Science* 34 (4): 519–25.

Brauers, J., and Aach, T. 2011. Geometric calibration of lens and filter distortions for multispectral filter-wheel cameras. *IEEE Transactions on Image Processing* 20 (2): 496-505.

Bridgman, R. and Earl, G. 2012. Experiencing lustre: polynomial texture mapping of medieval pottery at the Fitzwilliam Museum. In R. Matthews and J. Curtis (eds.), *Proceedings of the 7th International Congress of the Archaeology of the Ancient Near East (7th ICAANE)*: 497–512. Harrasowitz.

Brognara, C., Corsini, M., Dellepiane, M., Giachetti, A. 2013. Edge Detection on Polynomial Texture Maps. In Petrosino, A. (ed.), *Image Analysis and Processing – ICIAP 2013 SE - 49. Lecture Notes in Computer Science*: 482–91. Berlin Heidelberg, Springer.

Brown, D. H. 2002. *Pottery in Medieval Southampton: c 1066-1510*. York, Council for British Archaeology.

Caine, M. and Magen, M. 2011. Pixels and Parchment: The Application of RTI and Infrared Imaging to the Dead Sea Scrolls. In S. Dunn, J. P. Bowen, K. Ng (eds.), *EVA London 2011: Electronic Visualisation and the Arts*, London, 6-8 July 2011. Swindon, British Computer Society. [Online] http://ewic.bcs.org/upload/pdf/ewic_ev11_s8paper2.pdf. [Accessed: 29 November 2013].

CULTURAL HERITAGE IMAGING 2012. *Reflectance Transformation Imaging (RTI)*. [Online] http://culturalheritageimaging.org/Technologies/RTI/. [Accessed: 18 January 2013].

CULTURAL HERITAGE IMAGING 2013. *Digital Lab Notebook*. [Online] http://culturalheritageimaging.org/Technologies/Digital_Lab_Notebook/index.html. [Accessed: 20 January 2014].

Earl, G., Basford, P., Bischoff, A., Bowman, A., Crowther, C., Dahl, J., Hodgson, M., Isaksen, L., Kotoula, E., Martinez, K., Pagi, H. and Piquette, K. E. 2011. Reflectance Transformation Imaging Systems for Ancient Documentary Artefacts. In S. Dunn, J. P. Bowen, K. Ng (eds.), *EVA London 2011:Electronic Visualisation and the Arts,* London, 6-8 July 2011. Swindon, British Computer Society. [Online] http://ewic.bcs.org/upload/pdf/ewic_ev11_s8paper3.pdf. [Accessed: 19 January 2014].

Earl, G., Martinez, K., Malzbender, T. 2010. Archaeological applications of polynomial texture mapping: analysis, conservation and representation. *Journal of Archaeological Science* 37, 8: 2040–50.

Hanneken, T. R. 2014. *Integrating Spectral and Reflectance Transformation Imaging Technologies for the Digitization of Manuscripts and Other Cultural Artifacts. Final Report on Experiments Conducted and Lessons Learned.* [Online] http://palimpsest.stmarytx.edu/integrating/WhitePaper-20140630.pdf . [Accessed: 20 May 2015].

INSCRIPTIFACT 2015. Instructions for inscriptifact standalone viewer. University of Southern California. [Online] http://ruth.usc.edu:7060/inscriptifact_standalone.html. [Accessed: 20 May 2015].

Ishii, M., Moriyama, T., Toda, M., Kohmoto, K., Saito, M. 2008. Color degradation of textiles with natural dyes and of blue scale standards exposed to white LED lamps: Evaluation of white LED lamps for effectiveness as museum lighting. *Journal of Light and Visual Environment* 32, 4: 370-8.

Kotoula, E. and Earl, G. 2015a. Digital research strategies for ancient papyri: a case study on mounted fragments of the Derveni papyrus. In F. Giligny, F. Djindjian, L. Costa, P. Moscati, S. Robert (eds.), *Computer Applications and Quantitative methods in Archaeology 2014, 22-25 March 2014*, *Paris*: 145-54.

Kotoula, E. and Earl, G. 2015b. Integrated RTI approaches for the study of painted surfaces. In F. Giligny, F. Djindjian, L. Costa, P. Moscati, S. Robert (eds.), *Computer Applications and Quantitative methods in Archaeology 2014, 22-25 March 2014*, *Paris*: 123-34.

Kotoula, E. and Kyranoudi, M. 2013. Study of Ancient Greek and Roman coins using Reflectance Transformation Imaging. *E-conservation magazine* 25: 74-88.

Kotoula, E. 2013. Microscopic RTI of gilded silver discs from the Derveni tombs, Macedonia, Greece. In S. Duffy (ed.), *Multi-light Imaging for Heritage Applications. English Heritage*: 21–23. [Online] http://www.english-heritage.org.uk/publications/multi-light-imaging-heritage-applications/ [Accessed: 20 May 2015].

Liang, H. 2011. Advances in multispectral and hyperspectral imaging for archaeology and art conservation. *Applied Physics A* 106, 2: 309–23.

Macchia, A., Cesaro, S. N., Campanella, L., Maras, A., Rocchia, M. and Roscioli, G. 2013. Which Light for Cultural Heritage: Comparison of Light Sources with Respect to Realgar Photodegradation. *Journal of Applied Spectroscopy* 80 5: 637-43.

Malzbender, T. and Ordentlich, E. 2005. *Maximum entropy lighting for physical objects*. Hewlett-Packard Technical Report HPL-2005-68. [Online] http://www.hpl.hp.com/techreports/2005/HPL-2005-68.html. [Accessed: 10 June 2013].

Malzbender, T., Gelb, D. and Wolters, H. 2001. Polynomial texture maps. In L. Pocock (ed.), *Proceedings of the 28th annual conference on Computer graphics and interactive techniques, Los Angeles, 12-17 August 2001*: 519–528. New York, ACM.

Messier, P. 2014. *Monkey Brain Project Page*. [Online] http://paulmessier.com/pm/mb.html. [Accessed: 14 November 2014].

Miles, J., Pitts, M., Pagi, H., Earl G. 2014. New applications of photogrammetry and reflectance transformation imaging to an Easter Island statue, *Antiquity* 88, 340: 596-605.

Mudge, M., Voutaz, J. P., Schroer, C., Lum, M. 2005. Reflection Transformation Imaging and Virtual Representations of Coins from the Hospice of the Grand St. Bernard. In M. Mudge, N. Ryan, R. Scopigno (eds.), *Proceedings of the 6th International conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, *Pisa, 8-11 November 2005*: 195–202. Aire-la-Ville, Eurographics Association.

Palma, G. and Callieri, M. 2013. *The coins of Palazzo Blu: The Simoneschi Collection.* [Online] http://vcg.isti.cnr.it/PalazzoBlu/ [Accessed: 10 October 2015].

Palma, G., Siotto, E., Proesmans, M., Baldassari, M., Baracchini, C., Batino, S., Scopigno, R. 2013. Telling the Story of Ancient Coins by Means of Interactive RTI Images Visualization. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, D. Wheatley (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*, *Southampton, 26-29 March 2012*: 177–84. Amsterdam, Amsterdam University Press.

Raskar, R., Tan, K. H., Feris, R., Yu, J., Turk, M. 2004. Non-photorealistic camera: depth edge detection and stylized rendering using multi-flashimaging. *ACM Transactions on Graphics*. 23, 3: 679-88.

Redman, J. and Mudge, M. 2007. The simultaneous capture of spectral and textural information. In S. A. Stovall (ed.), *Archiving 2007: final program and proceedings*, *Arlington, 21-24 May 2007*. Springfield, Society for Imaging Science and Technology.

Riris, P. and Corteletti, R. 2015. A New Record of Pre-Columbian Engravings in Urubici (SC), Brazil using Polynomial Texture Mapping. *Internet Archaeology*. (38). [Online] http://intarch.ac.uk/journal/issue38/riris_toc.html [Accessed: 10 October 2015].

Toler-Franklin, C., Finkelstein, A., Rusinkiewicz, S. 2007. Illustration of complex real-world objects using images with normals. In B. Gooch, M. Agrawala, O. Deussen (eds.), *Proceedings of the 5th international symposium on Non-photorealistic animation and rendering*, *San Diego, 4-5 August 2007*: 111-119. New York, ACM.

Valergas, V. 2014. *Use of Transmitted imaging and RTI for the study of ancient texts*. Upublished MSc Thesis, University of Southampton.

Vienot, F., Coron, G., Lavedrine, B. 2011. LEDs as a tool to enhance faded colours of museums artefacts. *Journal of Cultural Heritage* 12 4: 431-40.

Warda, J. 2011. *The AIC Guide to Digital Photography and Conservation Documentation*. Washington, American Institute for Conservation.

Endangered Archaeology in the Middle East and North Africa: Introducing the EAMENA Project

Robert Bewley
robert.bewley@arch.ox.ac.uk

Andrew Wilson
andrew.wilson@arch.ox.ac.uk

Michael Fradley
michael.fradley@arch.ox.ac.uk

David Kennedy
david.kennedy@arch.ox.ac.uk

Richard Jennings
richard.jennings@arch.ox.ac.uk

David Mattingly
djm7@leicester.ac.uk

Robyn Mason
robyn.mason@arch.ox.ac.uk

Rebecca Banks
rebecca.banks@arch.ox.ac.uk

Louise Rayne
ler14@leicester.ac.uk

Michael Bishop
michael.bishop@arch.ox.ac.uk

Martin Sterry
mjs66@leicester.ac.uk

Jennie Bradbury
jennie.bradbury@arch.ox.ac.uk

Nichole Sheldrick
nichole.sheldrick@arch.ox.ac.uk

Emma Cunliffe
emma.cunliffe@arch.ox.ac.uk

Andrea Zerbini
andrea.zerbini@arch.ox.ac.uk

School of Archaeology, 36 Beaumont Street, Oxford OX1 2PG

Abstract: This project uses satellite imagery and historic aerial photographs to discover and interpret archaeological sites. It has created an open access database of archaeological records that provides basic information so that the sites can be better understood and preserved in the future. The threats to sites in the Middle East and North Africa are increasing and creating a record of previously unrecorded sites using this methodology may be our the last chance before they are destroyed.

Keywords: Endangered archaeology, Satellite imagery, Middle East, North Africa

1 Background

Archaeological sites across the Middle East and North Africa are at risk from a range of threats: intensification of agriculture; population growth and the concomitant expansion of villages, towns, and cities; industrial developments, dam, and road building; looting and the illicit traffic of artefacts; warfare and deliberate and targeted destruction of heritage for religious or ideological reasons. Moreover, in many countries the pace of change is accelerating either because the economy is growing, or because there is conflict. These conflicts not only affect the individual countries where they are fought, but also neighbouring countries with the movement of refugees. This is happening in Iraq, Libya, Syria, Yemen and, to an extent, Egypt and Tunisia. The situation is fluid and is unlikely to improve in the short term, and may become worse unless the conflicts are resolved soon, which is unlikely.

Discussions about 'endangered archaeology' in the Middle East and North Africa have a long pedigree. In Jordan, Nelson Glueck lamented the growth of modern villages over ancient ruins in the 1930s (Glueck 1939). Discussions to develop this project on 'endangered archaeology' began in 2014 and built on previous archaeological surveys in Jordan, especially by Kennedy and Bewley (2004) and a pilot-study in Saudi Arabia by Kennedy and Bishop (2011: 1284–93). Previous work demonstrated that the very rich archaeological resource of the Middle East was under enormous pressure, from a variety of agents (Kennedy and Bewley 2010).

Similarly fieldwork conducted in North Africa by Mattingly and colleagues at the University of Leicester demonstrated that the project should also include that region (Mattingly 2013; Mattingly and Sterry 2013; Mattingly *et al.* 2013).

The Endangered Archaeology in the Middle East and North Africa (EAMENA) project began in January 2015, generously supported by the Arcadia Fund (www.arcadiafund.org). The project is based in the School of Archaeology at Oxford University (with 10 staff) and has one core team member and an affiliated researcher in the School of Archaeology and Ancient History at the University of Leicester under the supervision of

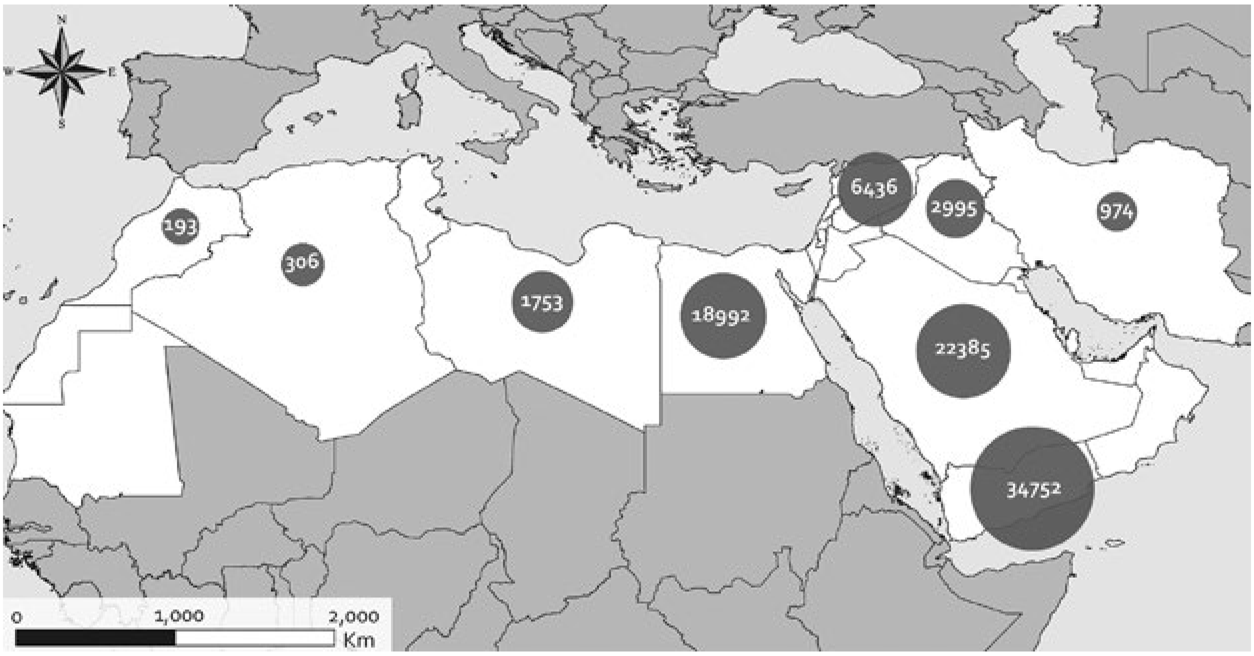

FIG. 1. THE REGION COVERED BY EAMENA AND THE NUMBER OF SITES RECORDED IN EACH COUNTRY (AS OF OCTOBER 2015).

Professor D. Mattingly. The project stretches from Mauretania to Iran (http://eamena.arch.ox.ac.uk) (Fig. 1).

The approach for the project is what might be termed 'rapid archaeological survey' involving the examination of satellite imagery, historical aerial photographs, and other sources to provide the location and brief description of each site and an assessment of threat. It is a first, but major, step in creating and then disseminating information about archaeology, which is at risk or 'endangered'. The intention is that this will help those with the responsibility, or desire, in their respective countries, to preserve and conserve those archaeological sites that need better protection, so that future generations can study, enjoy, and profit from them.

Although the world's media have recently focused on the shocking and headline-grabbing events in Iraq and Syria in 2015 (for example at Hatra and Nimrud in Iraq, and Palmyra in Syria), similar incidents of wanton destruction have also occurred much more widely across the MENA region. This includes the destruction of many Islamic monuments alongside the non-Islamic heritage; the latter has received more media attention in the West.

There are, however, other forces of destruction at work — as already listed — which are less dramatic but which, in aggregate pose an even greater threat to the cultural heritage of the MENA countries. Every day, through a range of destructive agencies archaeological sites are being lost. This loss is primarily through a lack of information and planning. Here we mean 'planning' as in the development sense of 'town planning' and the principle that any development, be it a road or a shopping centre, is only built after an archaeological investigation (or at least a proper evaluation of the archaeological implications of the development) has taken place. Even the rapid-approach employed by EAMENA can help to alleviate the worst damage, when it comes to understanding where archaeological sites are, as it aims to create an initial record before many sites disappear completely.

2 Methodology

Unlike much of western Europe where many archaeological sites have been ploughed, and some of the remains are buried, largely invisible beneath the soil, in the arid or semi-arid regions of the Middle East and North Africa many sites remain visible on the surface and are made of stone or earth, rendering them detectable by means of aerial photography and satellite imagery. The vast majority of the sites we examine have not been recorded and are largely unknown to the relevant authorities in the countries concerned. The use of satellite and aerial imagery is especially important for those countries where access on the ground is either impossible or severely restricted.

The methodology for discovering and obtaining information about endangered sites consists of three elements:

1. the systematic analysis and interpretation of satellite and air-photo images utilizing established techniques and in conjunction with regional maps and archival data;

2. the creation of individual site records (using internationally recognized data standards) and building on work and procedures developed by the APAAME project (www.apaame.org) and others;

3. monitoring the condition of sites using a combination of remotely-sensed data and ground verification to provide appropriate documentation of the status of the visible remains so that their management can be improved.

The satellite imagery used is mainly that available on Google Earth and Bing Maps, although we have purchased some satellite imagery for specific sites in Syria, Libya, and Iraq, which is currently being analysed. We also examine historic imagery where it is available and we have a programme of digitizing collections where we have permission, the most recent example being the Sir Aurel Stein collection, held at the British Academy which contains nearly 700 images: https://www.flickr.com/photos/apaame/albums/72157652009016911.

The approach is to look for sites in areas of high archaeological significance, where previous surveys may or may not have taken place, and assess these areas for the threats to the sites and landscapes. We have also worked in coordination and collaboration with authorities in certain countries, for example in Jordan to survey places in advance of infrastructure projects, such as the Madaba ring road (see Jordan below).

From the very beginning the project aimed to use the open source Arches software (www.archesproject.org) for a variety of reasons, not least because the MEGA-J archaeological database (for Jordan) was its prototype (funded by the Getty Conservation Institute and the World Monument Fund, http://megajordan.org). The Arches software has also been designed using agreed international data standards in a user-friendly way. The database now forms part of the EAMENA website and can be accessed via (http://eamena.arch.ox.ac.uk). At the time of writing the location of over 90,000 sites has been entered on the database and the full records are being created.

The information created, including both samples of the imagery and the database records, will be used to undertake or support fieldwork in those countries where this is possible. So far fieldwork has been possible in Jordan, Lebanon, and Morocco with plans in place for fieldwork on Iraq, and possibly Egypt, Iran, and Oman.

In association with the project we have developed a series of conferences and workshops, Protecting the Past (http://www.protectingthepast.com/wordpress/), which aims 'to highlight, and promote discussion of threats to cultural heritage sites as well as to develop strategies aimed at their preservation'. These workshops are aimed raising awareness of the EAMENA project information and for developing networks for on-the-ground monitoring of sites by local archaeologists.

The criteria for selecting areas to work in can be described as flexible and a judgement sample. Rather than allocate all the team to one country we needed to be able to respond to external needs as well as internal expertise. We also wanted to test the methodology in a variety of landscapes, so we began examining satellite imagery covering Saudi Arabia, Jordan, Iraq, and Libya and added in areas of Egypt (especially the Eastern Desert). The conflict in the Yemen also raised that country's needs up the agenda and we have worked there too. With staff joining the project with expertise in Syria's archaeology, we also started work there, especially in Halabiye and the coastal region. The rapidly changing political situation in North Africa altered initial plans for fieldwork in some countries, but through the Trans-Sahara project the Leicester-based personnel have been working in the field in Morocco.

3 Preliminary Results

The following section highlights examples of endangered archaeology in those countries where work has taken place so far. Although our focus has, by the nature of the project, been on the archaeological and cultural heritage, there is no question that in those countries where there are conflicts the most important issue is the unfolding humanitarian crisis.

3.1 Jordan

The Aerial Archaeology in Jordan project and the archive (www.apaame.org) was one of the foundations and test beds for developing the EAMENA project. Using a combination of historical aerial imagery (the 1953 Hunting Aerial Survey in particular), Google Earth imagery, and an active aerial reconnaissance programme (for over 18 years, 1997 to 2015) thousands of sites have been photographed and recorded in Jordan; many are new discoveries. The overwhelming impression from this work has been the rapidly changing nature of the landscape. The pace of change is also accelerating, with a huge and recent rise in population in Jordan, the demand for more land for agriculture and for road and house building is having a direct and negative impact on important archaeological sites.

The focus of the EAMENA project in Jordan has, so far, been on recent road building; some years ago we photographed as much as we could of the planned southern by-pass of Amman (Kennedy and Bewley 2010). More recently we were alerted to the intended construction of a by-pass for the Azraq; and in 2014 we saw (by chance) the beginnings of a by-pass road for Irbid, and therefore made this a focus for our aerial reconnaissance in 2015 (see www.apaame.org).

For the EAMENA project, however, we wanted to try to begin surveys in advance of any construction work starting. After consultation with the Department of Antiquities we examined a corridor of land through which the Madaba ring road would be constructed. In total, 141 potential archaeological sites were recorded during this rapid investigation. Of these, 41 are site features or sub-sites, mostly of the city of Madaba (29) and Khirbet al-Mukhayyat (6). As many as eleven sites will be directly affected by the ring road and development in its immediate vicinity (within a buffer zone of 500 m on either side of it). Many of the sites are 'new' to the record; of the 141 sites examined, 86 do not have records in the MEGA-Jordan database (http://megajordan.org). We provided a report for the Jordanian Department of Antiquities to enable them to develop mitigation strategies in advance of the construction of this road (Fig. 2).

3.2 Syria

There is no question that the archaeological sites of Syria, many of them World Heritage sites (Burns 1999), are under the greatest threat because of the five-year long conflict there. At the time of writing, very important sites and individual temples and structures at Palmyra have been destroyed as part of the so-called Islamic State's publicity programme. In addition we have also seen many large, important sites, and other smaller sites, subject to systematic looting for artefacts (Stone 2015). More research is required on the timing and stimuli for the illicit trade in artefacts, but there can be no doubt that as state control diminishes, or is totally absent, looting of archaeological sites increases (but see http://traffickingculture.org for more information). We have seen significant changes to sites in connection with looting activities in Egypt, Iraq, and Yemen. In Syria the most often quoted example has been the

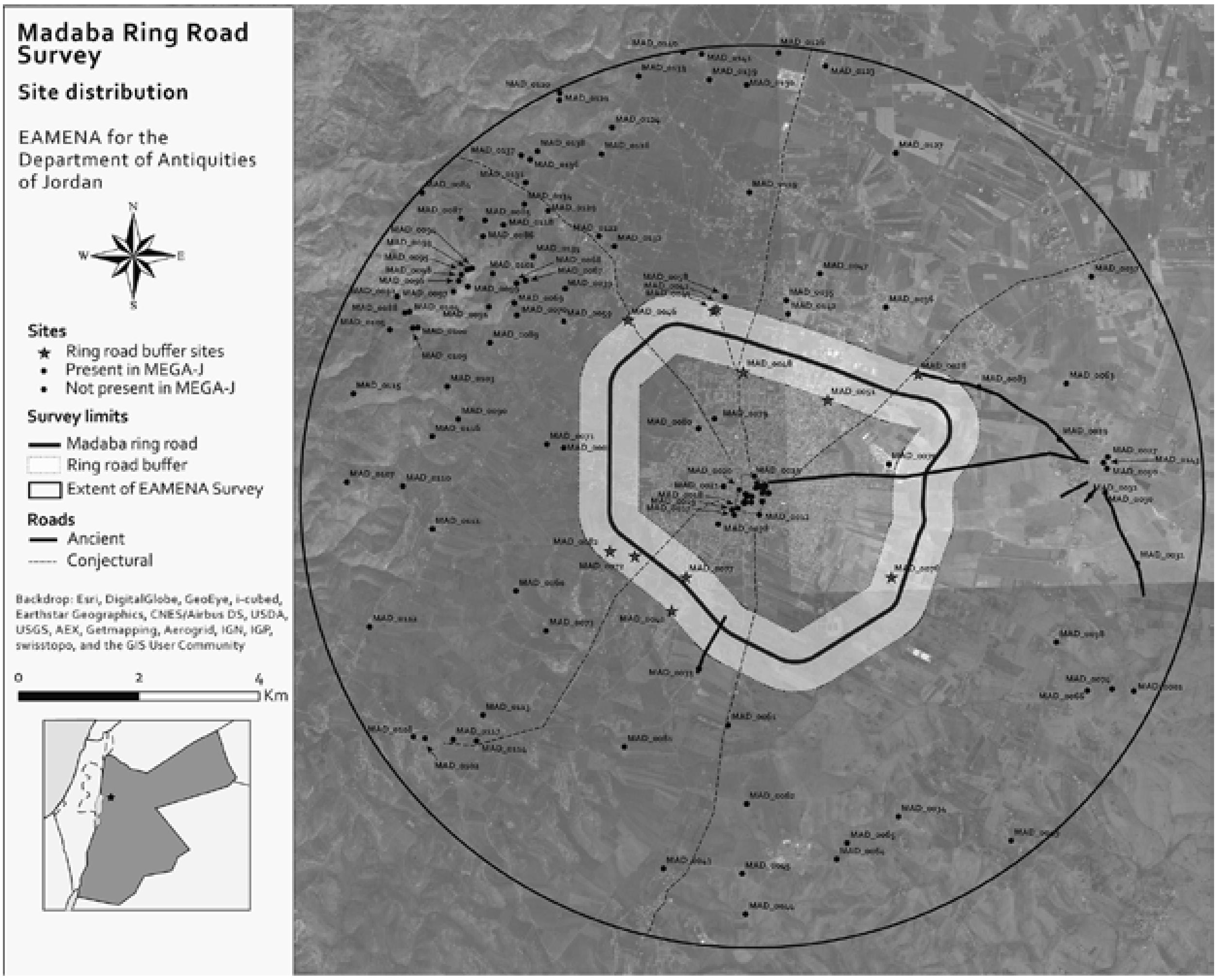

Fig. 2. The hinterland of Madaba, Jordan showing the distribution of potential cultural assets and the ring-road buffer zone (shaded).

illegal excavations at the Roman city of Apamea (see Casana 2015: fig. 8; Cunliffe 2014). Equally significant have been the changes at Dura Europos (see Casana 2015: fig. 2).

The project's approach towards data collection in Syria has aimed at filling in existing gaps in knowledge, given the extent of previous surveys (e.g. Braemer *et al.* 2009; Casana and Wilkinson 2005; Castel 2007; Geyer 2001; Matthiae and Marchetti 2013; Meyer 2013; Poidebard 1934; Ur and Wilkinson 2008; Wilkinson 2003; Wilkinson *et al.* 2012, 2014). Two main areas have so far been targeted by the EAMENA project: the Halibye Plateau and the coastal strip, from the Turkish border in the north to the Lebanese border in the south.

The Halibye region (*c.*2500 km^2), prior to the ongoing conflict in Syria, was marked for a dam project that was intended to affect more than 2000 km^2. This region is particularly rich in archaeological sites, with more than 4000 having been identified in the zone that is expected to be destroyed during construction. Mapping has focused on using Google Earth imagery, supported by the available imagery on Bing Maps and CORONA where necessary. Rescue excavations and surveys had been planned by the Syrian authorities for nine sites (some of which were already recorded) and in the plateau area, but neither these investigations nor the dam project could be carried out once the conflict started.

The coastal strip, *c.*9000 km^2, in contrast, has been heavily developed since the mid-20th century. Our mapping here has focused on using a variety of different imagery and map sources (e.g. Corona and Google Earth) to explore the changes and threats to archaeological sites along this coastline since the 1950s. Detailed records currently exist for over 1600 potential archaeological sites from this region (Fig. 3).

Other sites in Syria have remained untouched, remarkably, and we are also investigating these further, so that a better record can be made of them, just in case they do become targets for looters. At this stage it is better not to name them in a publication until the current conflict has been resolved. In Syria 6094 sites have been recorded, in an area of *c.*11,200 km^2.

3.3 Yemen

Since March 2015, the beginning of the recent conflict, the monitoring of Yemen's cultural landscape has become a

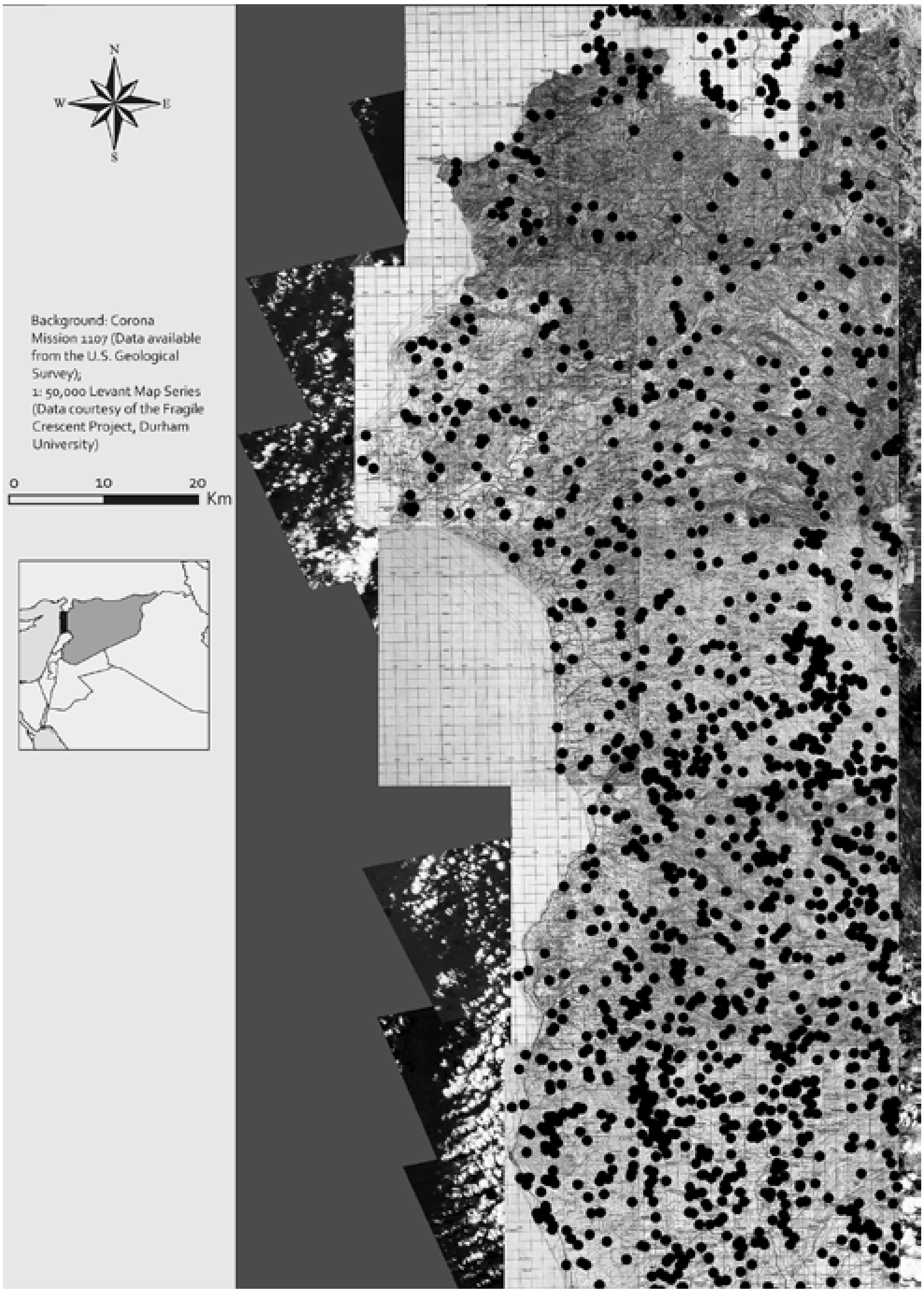

Fig. 3. Distribution of potential archaeological sites in the EAMENA survey area along the Syrian coast.

priority for EAMENA (Fig. 4). The campaign of airstrikes has concentrated in the areas controlled by the Houthis, most importantly San'a and its hinterland, but also the northern and central highlands (from Sa'dah in the north to Ta'izz in the south). These regions were therefore the priority for our investigations.

Systematic investigation of over 61,885 km^2 resulted in the recording of 34,752 sites. While many of them appear to be in good condition, there have been some notable examples of destruction caused as a result of human action: conflict, agricultural development, construction, and looting, and there is also evidence of destruction by natural events (e.g. flash flooding).

Among the sites affected by the ongoing conflict, the Baraqish city wall, the Dhamar Regional Museum, the al-Qahira fortress in Ta'izz, and the Ma'rib dam deserve special mention. Damage to the city wall of Baraqish, a site occupied from the 13th to the 1st c. BCE as well as between the 13th and the 18th centuries CE (Schiettecatte 2011: 51–57 for a broad overview), were reported on 18 August 2015 and again on 14 October 2015.[1] Ground photos also appear to suggest that the temple of Nakrah, a site of worship in use from the 7th to the 1st c. BCE (de Maigret 2004) was severely affected by bombing.[2] The Dhamar Regional Museum, which contained more than 12,000 archaeological objects, was razed to the ground in

1 Khabar News Agency 2015a, online; 2015b, online.
2 Al Montasaf 2015, online.

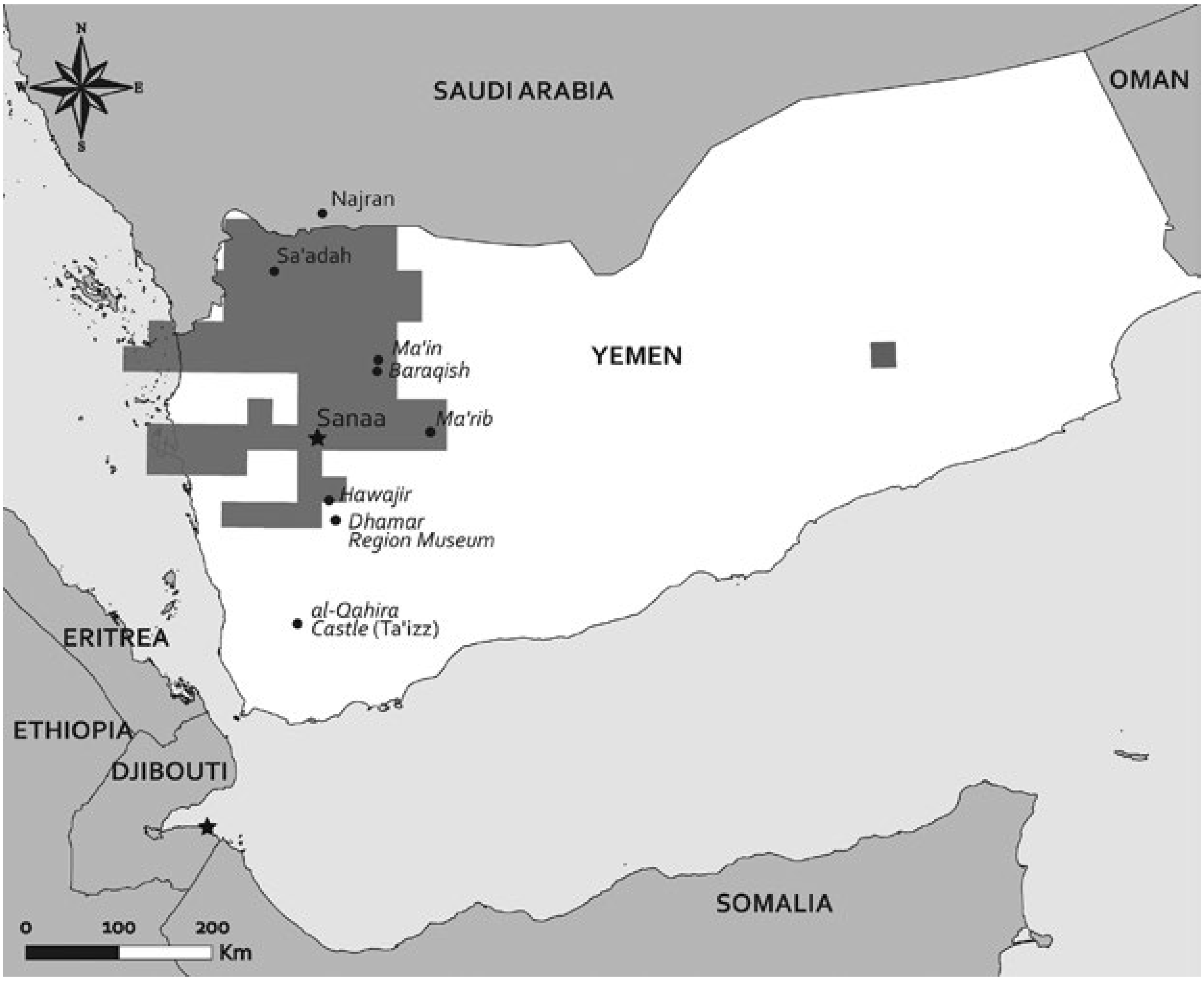

Fig. 4. Extent of EAMENA coverage in Yemen (as of October 2015) and location of sites.

June 2015:[3] only *c.*1500 objects could be retrieved from the rubble by the Yemeni General Organisation of Antiquities and Museums (GOAM).[4] The al-Qahira fortress of Ta'izz, a site settled since pre-Islamic times, was a prominent fortress under the Ayyubids and, especially, the Rasulids (13th to 15th c. CE), who made Ta'izz their capital. Ta'izz was taken over by Houthi rebels in March 2015 and its fortress subsequently bombed by the Arab coalition in May 2015.[5] Figure 5 clearly shows up to five impact craters (marked by dashed lines), which flattened several structures along the access ramp to the south of the castle, part of the rampart and the core of the castle building.

Ma'rib, the ancient capital of the kingdom of Saba, was continuously settled between the 7th c. BCE and the 7th c. CE (Schiettecatte 2011: 104–116). Water management infrastructure in Wadi Dhana is attested since the beginning of settlement in the area, although the standing features of the great dam of Ma'rib are probably no earlier than the 3rd century CE (Vogt 2004). The northern sluice of the dam was reportedly bombed on 31 May 2015.[6] So far, only one ground photograph of the damaged structure has appeared: [7] the acquisition of satellite imagery post-dating the air raid, which is currently underway, will make it possible to clarify further the extent of damage.

While destruction and damage by conflict have been brought to the fore by hostilities in Yemen, a much more pervasive, and long-term factor of threat is that related to agricultural and infrastructural development (such as road building). For example a group of pendant burials, *c.*14 km SE of Baraqish, has been severely damaged by the construction of an 8 m wide dirt road. These structures, which are generally believed to have had a funerary function, have come under increasing scrutiny in recent years (Kennedy and Bishop 2011).

Agricultural intensification has caused the irreversible loss of a group of regularly spaced cairns located in the northernmost sector of the Hajjah province, only 5 km south of the Saudi border. These were still extant in August 2004, but have been subsequently bulldozed to establish a network of agricultural fields. A combination of ploughing and looting has severely increased damage, between 2004 and 2010, at the site of Hawajir in the Dhamar region, which was dated by ground surveys to

3 Khalidi 2015, online.
4 Antonini de Maigret and Gerlach 2015: 41.
5 Al Arabiya News 2015, online.
6 Romey 2015, online.

7 UNESCO 2015, online.

Fig. 5. Ta'izz Castle. The al-Qahira citadel between March 2000 and May 2015. Imagery from 2003, 2006, and 2014 shows the progress of restoration works, and the last image shows the impact of the air strikes.

the second half of the 2nd millennium BCE (Wilkinson 1999–2000: 66–67). On the other hand, looting of large fortified structures and tell sites does not appear to have significantly increased over the last 10 years. For example, comparison of satellite imagery from August 2003 and September 2013 for the site of Ma'in (ancient Qarna in the Jawf region), an important centre between the 7th and 1st century BC (Breton 1994: 105-8; Tawfiq 1951), shows very little evidence of new looting activity during that decade.

Our work in Yemen has already produced the largest site inventory of cultural heritage sites for the country. Future work will be in the southern highlands and, more importantly, establishing partnerships with the GOAM, UNESCO, and archaeological teams with field experience in the country in order to add further details to our site records.

3.4 Saudi Arabia

The pilot study of high-resolution satellite imagery of a limited area near Jeddah, Saudi Arabia, was instrumental for this project in defining the scope and methodology. Despite the arid and daunting landscape, the results were dramatic. Within a randomly chosen survey area of 1240 km^2, which had high-resolution imagery, 1977 sites were recorded (Kennedy and Bishop 2011: 1284–1293). More recently a study of the Harret Khaybar area, relying solely on satellite imagery, from Google Earth and Bing has been published (Kennedy, Banks and Dalton 2015).

The EAMENA team has scrutinized satellite imagery covering an area of 14,700 km^2 spread over three areas in the northern, central, and southern parts of the country. This had led to the identification of 22,385 archaeological sites or site components, including dense concentrations of prehistoric settlements and burial evidence. These include cairns, pendants, desert kites, wheels, and settlement complexes, with exceptional levels of preservation occurring on the basalt lava fields in the west of the country. There is no primary threat so far identified to the archaeology of Saudi Arabia, in contrast with the situation in areas such as the Eastern Desert of Egypt, but there are localized threats such as large infrastructure projects, seismic exploration for oil, and centre-pivot field irrigation systems (Fig. 6).

3.5 Egypt

Our work on the Eastern Desert of Egypt has focused primarily in two areas, at risk in different ways: one from planned urban development that has not yet happened, and the other from uncontrolled looting and surface mining. In these two areas together we have recorded *c.*18,000 sites across more than 65,000 km^2.

The first lies just south-east of the Nile Delta in advance of a proposed eastward expansion of Cairo (*BBC News Online* 2015, online). While reported plans for the establishment of a 'New Cairo' in this area within the next few years seem to have been postponed, there is little doubt that future developments and expansion of the city eastwards will occur over the coming years and decades, posing a serious threat to any archaeological sites in the area.

The second region is an area of the Eastern Desert further to the south, where three major routes run from the Nile cities of Qift (*Coptos*) and Edfu (*Apollinopolis Magna*), connecting them to the Red Sea ports of Quseer (*Myos Hormos*), Marsa Nakari, and *Berenike*. This region is rich in natural resources, including gold, gems, and marble, and several previous archaeological projects have recorded abundant evidence of ancient mining

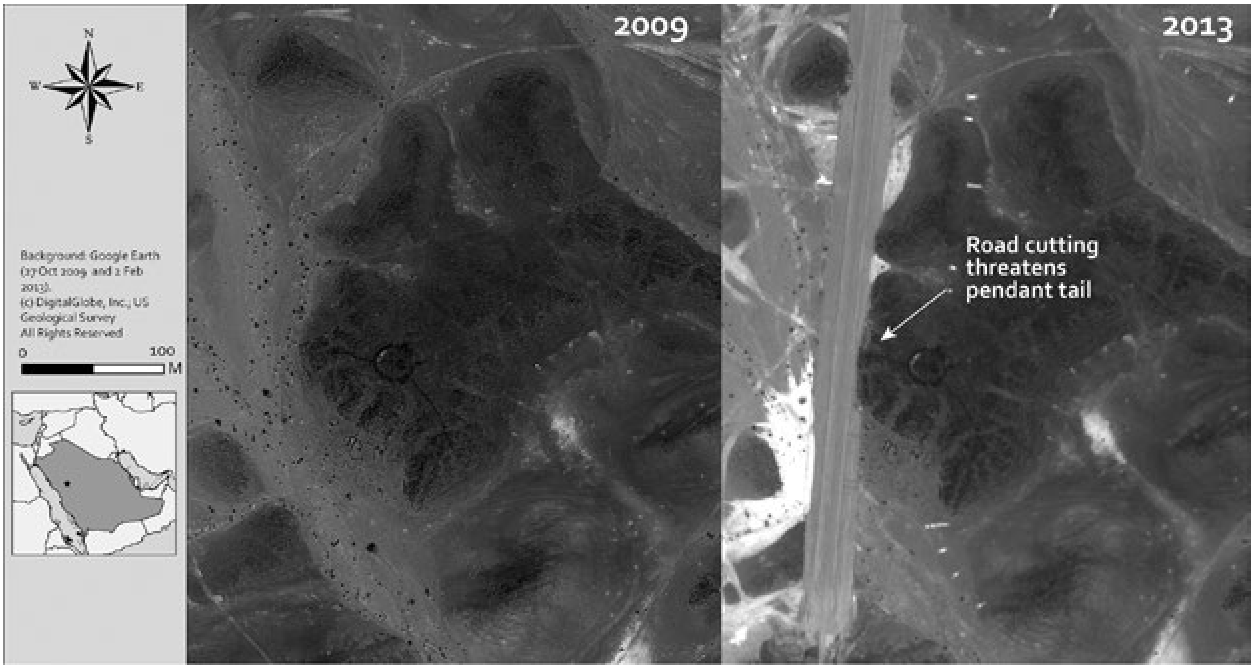

Fig. 6. Saudi Pendant. A pendant burial in 2009 (left) and 2013 (right), showing damage by road construction.

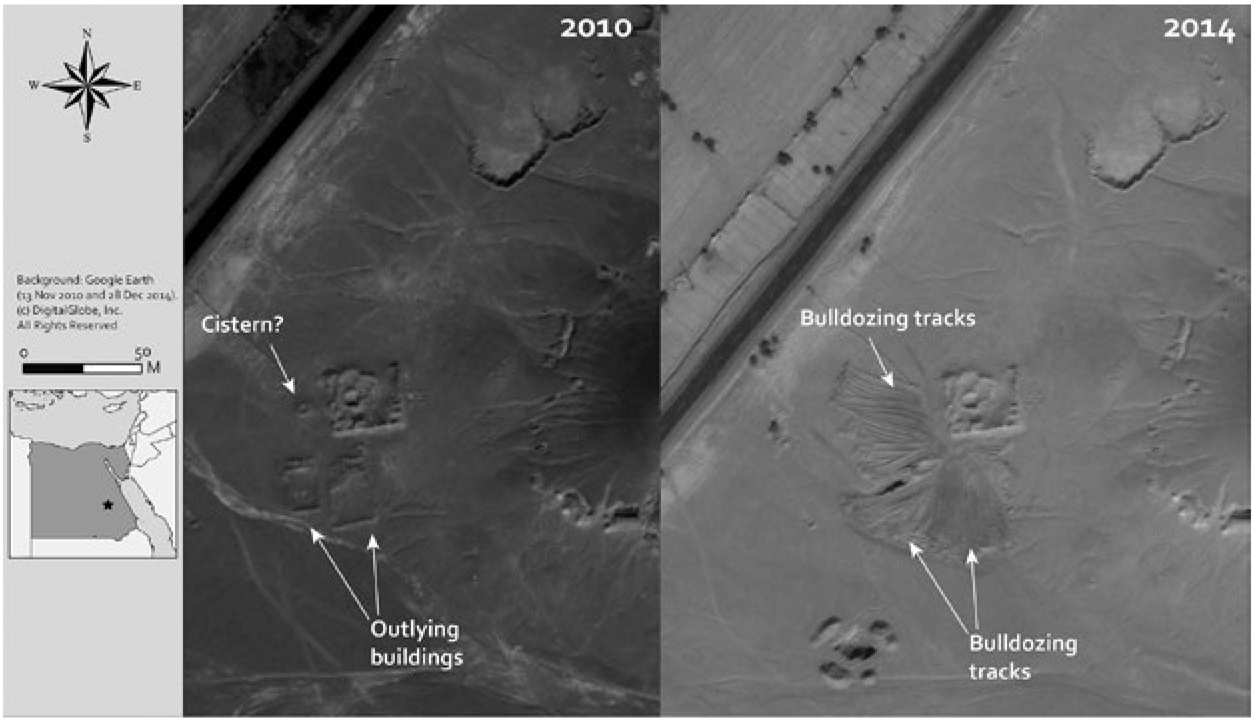

Fig. 7. Bir Abbad: the road station of Bir Abbad in 2010 (left) and 2014 (right).

settlements and activities. Furthermore, during Ptolemaic and Roman times, forts, road stations, fortified wells, and other military installations lined the routes through the region (Prickett 1979; Sidebotham and Wendrich 1995; 1996; 1998; 1999; 2000; 2006; Sidebotham and Zitterkopf 1998; Cuvigny 2003; Shaw 2007; Harrell and Storemyr 2009; Morrow and Cherry 2010; Klemm and Klemm 2011; Bragantini and Pirelli 2013, 2015). In addition to the many previously recorded sites, EAMENA has now identified several hundred previously unrecorded sites.

Many of these sites are now threatened with damage and destruction from modern mining activities. Before the Arab Spring foreign mining companies had begun large-scale

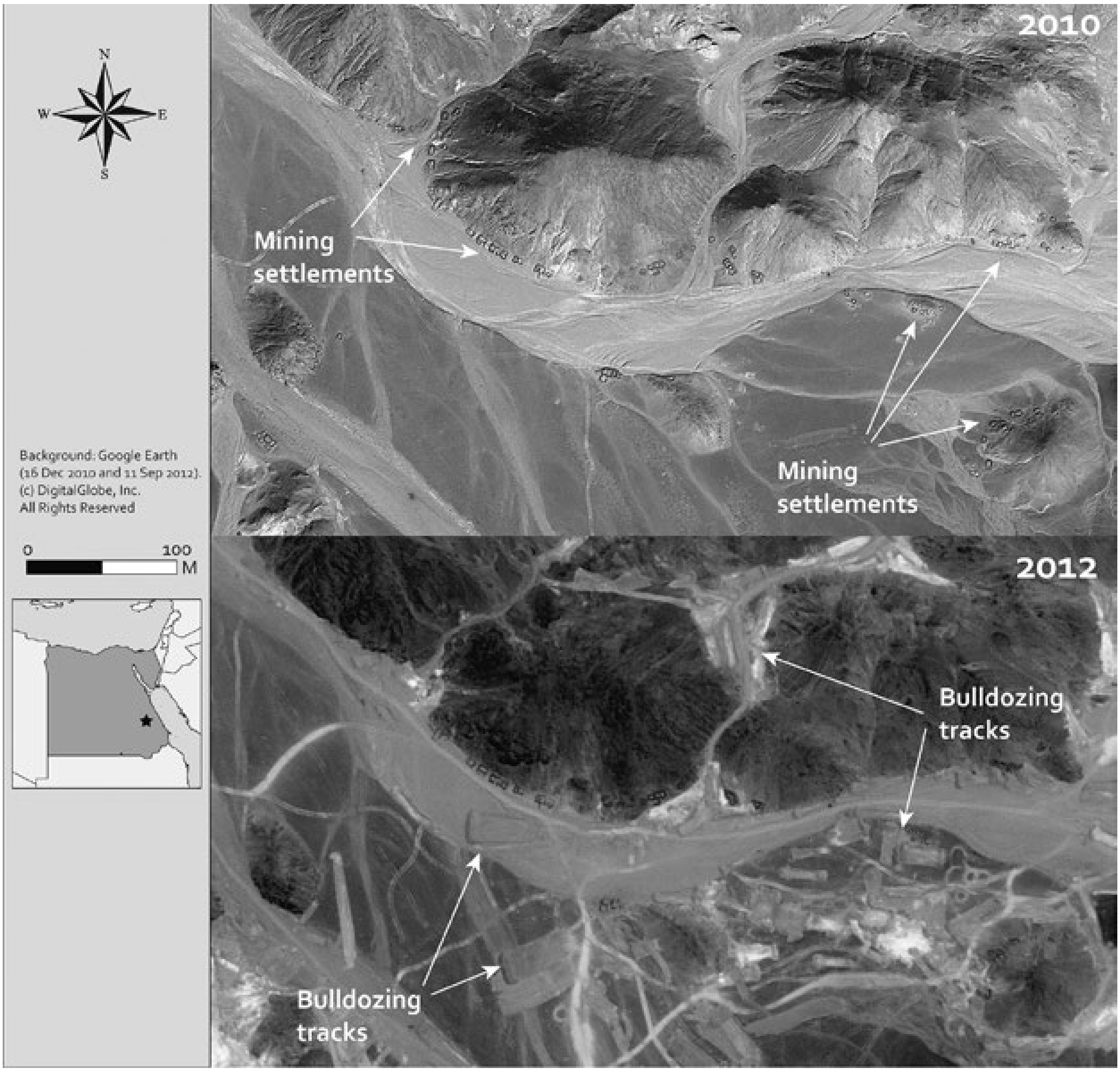

Fig. 8. A mining settlement in the Eastern Desert of Egypt in 2010 (above) and 2013 (below).

industrial extraction of gold at a number of the sites (as, for example, Centamin at Sukari). Mining at some of those sites has continued or resumed since 2011. In addition, many sites appear to have been disturbed or destroyed by local people using metal detectors and bulldozers to search for the precious metals and probably also in some cases, archaeological artefacts to sell (illegally). One site that has suffered severe damage is Bir Abbad (*c.*20 km NE of Edfu), a road station, probably of the Roman period, where two outbuildings have been completely demolished by bulldozers (Fig. 7). In another example, a probable mining settlement of unknown date (*c.* 95 km E of Edfu) has also suffered extensive damage from bulldozers (Fig. 8).

3.6 Libya

The Leicester team has a long involvement in the mapping of archaeological sites in Libya, from the UNESCO Libyan Valleys Survey of the pre-desert area (Barker *et al.* 1996a/b), to the Barrington Atlas sheets which underlie the Pleiades data (Mattingly 2000), to major surveys of desert sites in the region of Fazzan, south-west Libya (Mattingly 2003; 2007; 2010; 2013; Sterry and Mattingly 2011). The Trans-Sahara Project, with funding from the European Research Council, has extended the scope of this sort of work across a much wider geographical area (see e.g. Mattingly *et al.* 2013).

As well as consolidating the results of this work in a single database, the EAMENA project has been focusing on detailed mapping of a number of key case studies, where the archaeology has been identified as particularly understudied or under threat. To test the methodology, an initial study focused on the al-Jufra oasis group, to the south-west of the Gulf of Sirte. Three oasis towns of early modern date are known here — Sokna, Hun, and Waddan — but hitherto virtually nothing has been recorded of the long-term archaeological heritage of the oasis

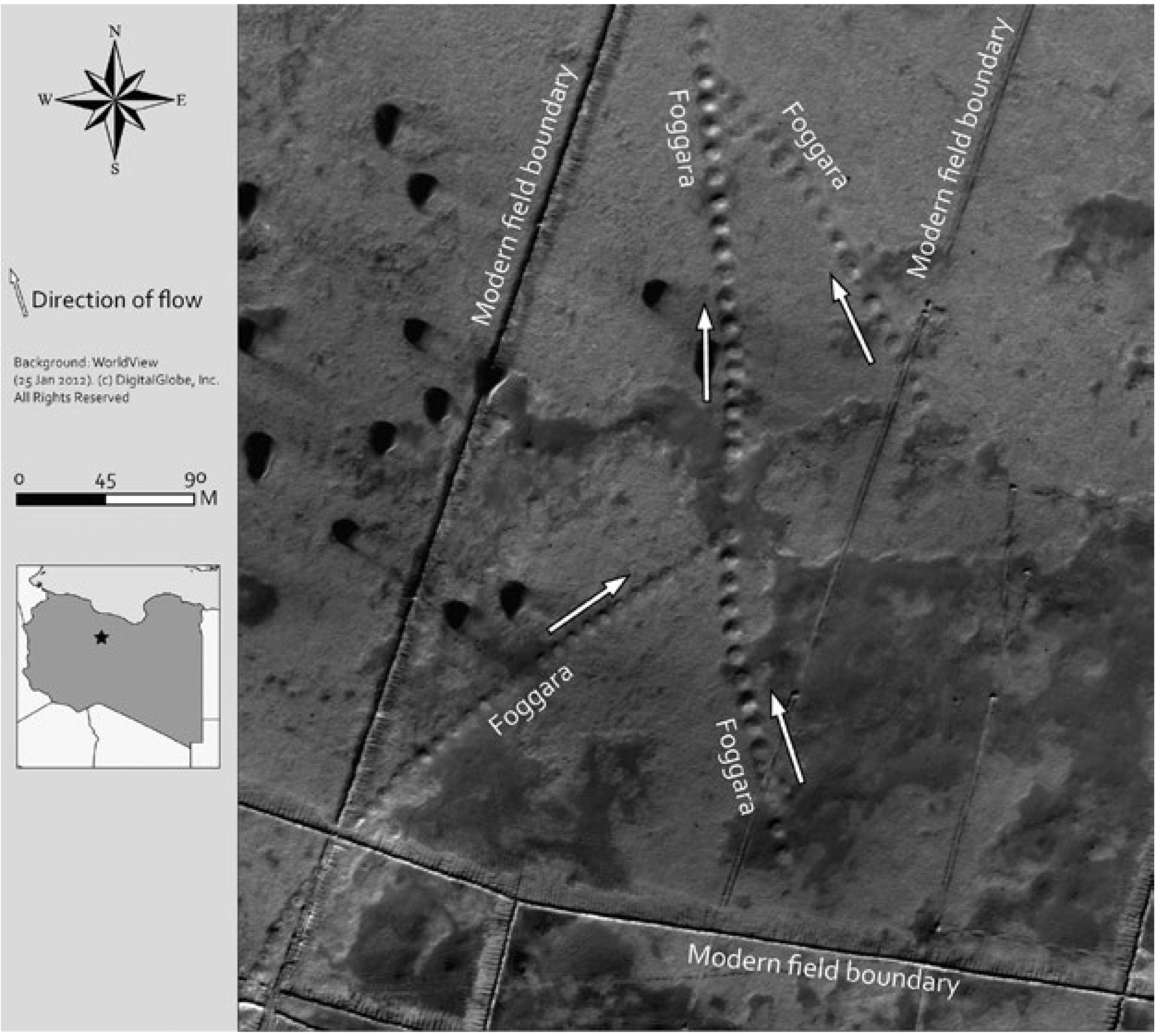

Fig. 9. Foggaras in the vicinity of Waddan damaged by modern field systems.

(Scarin 1938). Our examination and interpretation of satellite imagery has enabled us to identify around twelve urban-scale sites, representing successive phases of the development of the three main oasis centres. Several of these sites have been damaged in recent years and others are under serious threat. We have also mapped extensive evidence of other settlement sites and pre-Islamic cemeteries as well as ancient irrigation systems (foggaras), which have been largely obliterated in the last decade.

Aerial photographs (Scarin 1938), WorldView, Corona images, and Google Earth were used to map sites and a classification of Landsat images was undertaken in order to quantify the impacts of cultivation intensification. The cultivated area increased by about 5400 ha between 1975 and 2011, supported by modern irrigation. Features including foggaras have been completely removed from some parts of al-Jufra by agricultural expansion since the 1930s aerial photographs and 1960s Corona images were collected. The more recent images show other areas of foggaras, which are at immediate risk of destruction due to the introduction of new fields (Fig. 9).

The resulting site map of the area's archaeology is thus completely transformed. These results have been communicated to the Libyan Department of Antiquities to enable them to enhance protection of the heritage before it is further degraded or lost.

A second case study involves the area around the UNESCO World Heritage Site (WHS) of Cyrene in eastern Libya. Despite its WHS status, the protection of this world-famous site is seriously compromised by the presence of a burgeoning urban settlement of Shahat, just outside the ancient city's walls (see Cherstich 2008). The main impact is on the suburban landscape of cemeteries, religious sanctuaries, suburban villas, and other productive buildings, the ancient roads and aqueducts.

3.7 Morocco

Our work in southern Morocco has been designed to tie in with the results of fieldwork undertaken by the Middle Draa Project of the University of Leicester. This is another Saharan oasis zone, where the archaeological record is poorly understood and

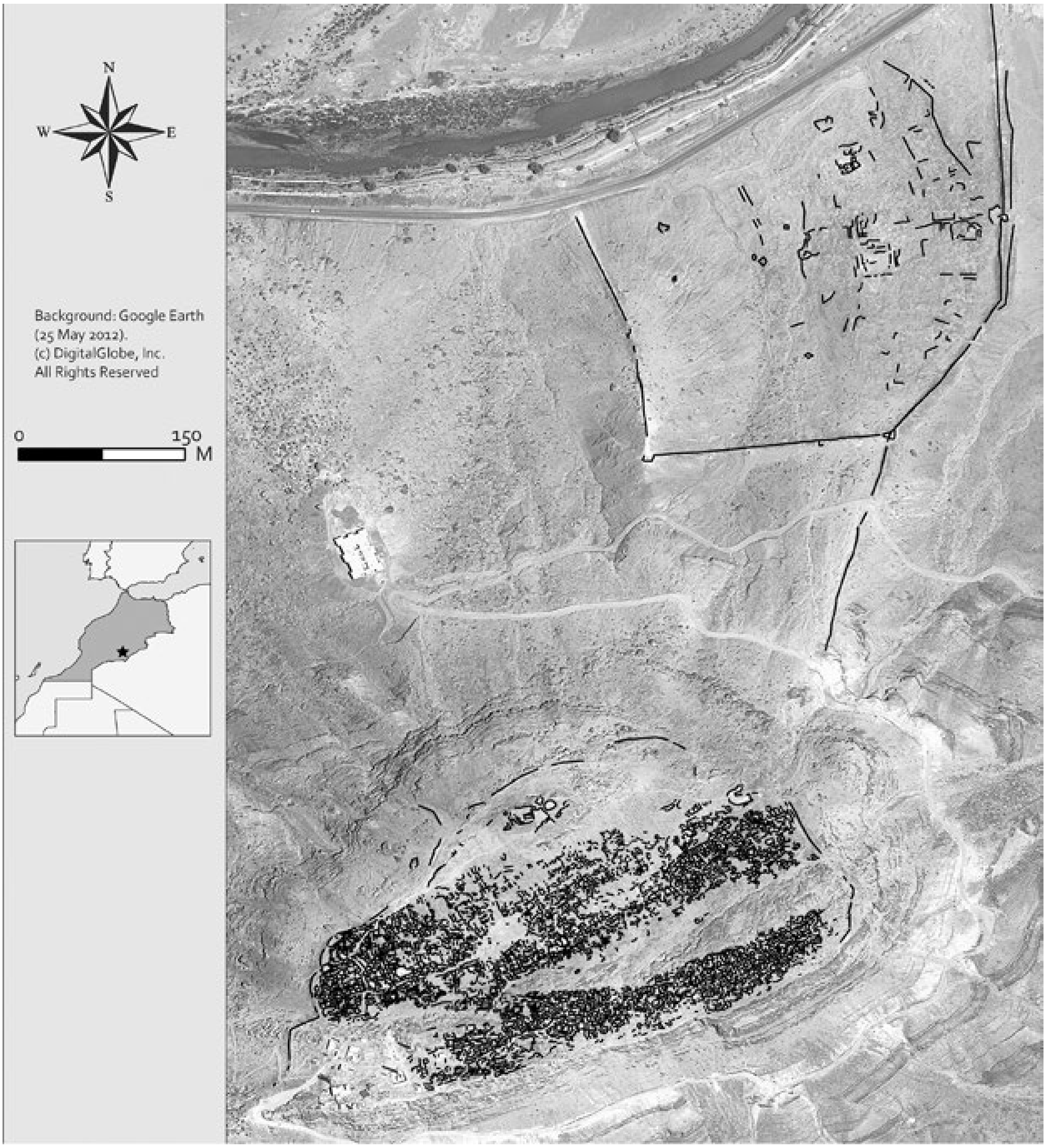

Fig. 10. The hilltop site and irrigation systems of Zagora, Morocco.

even less well protected. The detailed recording of parts of the Draa Valley from the available Google Earth satellite imagery has already produced impressive results, with hundreds of hitherto unrecorded settlements identified, along with traces of many irrigation features and thousands of pre-Islamic burial monuments. The project is also closely collaborating here with the Moroccan antiquities service (Institut National des Sciences de l'Archéologie et du Patrimoine – INSAP).

The main modern oasis settlements and cultivation are located on the flat land adjacent to the river, irrigated partly by water management schemes constructed since the 1970s. In these areas the earlier phases of activity are substantially masked or obliterated by the more recent cultivation and development. While damage is not apparent at some of the more remote hilltop sites, closer to the river the construction of new buildings and changes in irrigation and cultivation strategies have affected the preservation of sites. For example, areas of the hilltop site of Zagora have been bulldozed and some new structures built (Fig. 10). In areas where modern oasis cultivation is less intense, we have identified earlier phases of sites and irrigation systems. Although these have not, as yet, been closely dated, it is thought that the origin of oasis cultivation in Morocco dates to the pre-Islamic era. This area was selected as a detailed case study because of the contrast between the good preservation of some sites and the impact of modern activity on others, all within the same region. Vehicle tracks are apparent across several sites and some cairns have been looted.

3.8 Iraq

As a trial exercise, the maps from two surveys for the heavily farmed alluvial plain of lower Mesopotamia, extending south-east of Baghdad were digitized (Adams and Nissen 1972; Adams 1981). Using this information the available satellite imagery for the area was assessed to see whether looting was visible. A total of 2995 records were created, with 397 sites showing definite signs of looting. This work also showed how much the landscape has changed, as 765 of the sites could not be reliably located as a result of the effects of agricultural development, water management, and sand movements that have occurred since the original surveys were done.

4 Conclusions

The philosophy underlying this project is that by discovering and recording archaeological sites the information thus created will provide for better conservation and protection of the region's heritage. The responsibility for protecting sites lies with the national or regional authorities in each country and we are working with as many of the Department of Antiquities as we can to target areas within each country, which may be under threat from planned infrastructure projects, so as to mitigate the possible damage. The majority of the sites we record have not been systematically recorded before; their destruction is irreversible. This project is therefore a-once-in-a-generation opportunity. We are acutely aware that only a small sample of sites will be protected but we are, at least, improving the knowledge base so that informed decisions can be made. Only by knowing the nature of the threats to ancient sites can archaeologists advise national authorities to plan how to salvage a vital part of our shared human heritage. The preservation of the archaeological remains should not take priority over the lives of those having to live in areas of conflict. Once the conflicts do end, the destruction of the archaeological sites should diminish, and the preservation and conservation of those sites that have been affected can be improved. It is important that for the post-conflict era, however far in the future that is, the rebuilding phase does not destroy the fragile heritage any further. This a key reason why the EAMENA project and others too (Casana 2015) have an important role to play in not only recording the archaeological sites as they are today, but also providing this information in a usable form for those with the responsibility for their future protection in each country.

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Bibliography

Adams, R. McC. 1981. *Heartland of Cit*ies, Chicago and London, University of Chicago Press.

Adams, R. McC. and Nissen, H. J. 1972. *The Uruk Countryside*. Chicago and London, University of Chicago Press.

Antonini de Maigret, S. and Gerlach, I. 2015. Dimenticare l'Arabia Felix? *Archeo* 365: 36–46.

Baraqish, one among the most ancient cities in Yemen, is destroyed by the Saudi-led Arab coalition airplanes. *Khabar News Agency*. 18 August 2015. 26 October 2015. http://www.khabaragency.net/news32590.html (in Arabic).

Barker, G. W., Gilbertson, D. D., Jones, G. D. B., Mattingly, D. J. 1996a. *Farming the Desert The UNESCO Libyan Valleys Archaeological Survey. Volume 1, Synthesis*. Paris/London, UNESCO, Soc. for Libyan Studies.

Barker, G. W., Gilbertson, D. D., Jones, G. D. B., Mattingly, D. J. 1996b. *Farming the Desert The UNESCO Libyan Valleys Archaeological Survey. Volume 2, Gazetteer and Pottery*. Paris/London, UNESCO, Soc. for Libyan Studies.

Breton, J. F. 1994. *Les fortifications d'Arabie Méridionale du 7e au Ier siècle avant notre ère*. (ABADY 8). Mainz, Philipp von Zabern.

Burns, R. 1999. *Monuments of Syria. An Historical Guide*. London, I.B. Tauris.

Braemer, F., Genequand, D., Dumond Maridat, C., Blanc, P. M. *et al.* 2009. Long-term management of water in the Central Levant: The Hawran case (Syria). *World Archaeology* 41/1: 36–57.

Bragantini, I. and Pirelli, R. 2013. The Archaeological Mission of 'L'Orientale' in the Central-Eastern Desert of Egypt. *Newsletter di Archeologia CISA* 4: 47–156.

Bragantini, I. and Pirelli, R. 2015. Preliminary Report on the Second Season of the Italian Archaeological Mission in the Eastern Desert of Egypt. *Newsletter di Archeologia CISA* 6: 165–77.

Casana, J., and Wilkinson, T. J. 2005. Settlement and landscapes in the Amuq region. In K. Aslihan Yener (ed.), *The archaeology of the Amuq Plain*: 25–65, 203–80. Chicago, Oriental Institute Publications 131.

Casana J. 2015. Satellite Imagery-based analysis of archaeological looting in Syria.

Near Eastern Archaeology. Special Issue: the Cultural Heritage Crisis in the Middle East 78/3: 142-52.

Castel, C. 2007. Stratégies de subsistance et modes d'occupation de l'espace dans la micro-région d' al Rawda au Bronze ancien final (Shamiyeh). In D. Morandi Bonacossi (ed.), *Urban and natural landscapes of an ancient Syrian capital: Settlement and environment at Tell Mishrifeh/Qatna and in central-western Syria. Proceedings of the international conference held in Udine, 9–11 December 2004*: 283–94. Udine, Forum Editrice.

Cherstich, L. 2008. 'From looted tombs to ancient society: a survey of the Southern Necropolis of Cyrene', *Libyan Studies* 39: 73-93.

Cunliffe, E. 2014. Archaeological Site Damage in the Cycle of War and Peace: A Syrian Case Study. *Journal of Eastern Mediterranean Archaeology and Heritage Studies* 2 (3): 229-47.

Cuvigny, H. 2003. *La route de Myos Hormos: l'armée romaine dans le désert oriental d'Egypte*. Cairo, Institut français d'archéologie orientale du Caire.

De Maigret, A. 2004. *Baraqish, Minaean Yathill. Excavation and Restoration of the Temple of Nakrah*. Napoli.

Cowley, D. C., Standring, R. A., Abicht, M. J. 2010. *Landscape through the Lens. Aerial Photographs and Historic Environment*. Occasional Publication of the Aerial Archaeology Research Group No. 2.

Egypt unveils plans to build new capital east of Cairo. *BBC News Online: Business*. 13 March 2015. 28 October 2015. www.bbc.co.uk/news/business-31874886.

Fresh air strikes target Houthi militias in Yemen. *Al Arabiya News*. 24 May 2015. 26 October 2015. http://english.alarabiya.net/en/News/middle-east/2015/05/24/Fresh-air-strikes-target-Houthi-militias-in-Yemen-.html.

Geyer, B. 2001. *Conquête de la steppe et appropriation des terres sur les marges arides du Croissant fertile*. Lyon, Maison de l'Orient et de la Méditerranée Jean Pouilloux.

Glueck, N. 1939. *Explorations in Eastern Palestine, III.* AASOR XVIII-XIX, 1937-1939. New Haven.

Harrell, J. A. and Storemyr, P. 2009. Ancient Egyptian Quarries - an illustrated overview. In N. Abu-Jaber, E. Bloxam, P. Degryse, T. Heldal (eds.), *QuarryScapes: ancient stone quarry landscapes in the Eastern Mediterranean*. Geological Survey of Norway Special Publication 12: 7–50. Norway, NGU, Geological Survey of Norway.

Kennedy, D. L. and Bewley, R. H. 2004. *Ancient Jordan from the Air*. London, CBRL.

Kennedy, D.L. and Bewley, R. H. 2010. Archives and aerial imagery in Jordan: rescuing the archaeology of greater Amman from urban sprawl. In D. C. Cowley, R. A. Standring, M. J. Abicht (eds.), *Landscapes through the Lens: Aerial Photographs and the Historic Environment*: 193-206. Oxford, Oxbow Books.

Kennedy, D. and Bishop, M. C. 2011. Google earth and the archaeology of Saudi Arabia. A case study from the Jeddah area. *Journal of Archaeological Science* 38: 1284–93.

Kennedy, D., Banks, R., Dalton M. 2015. Kites in Saudi Arabia. *Arabian Archaeology and Epigraphy* 26, 2: 177-95.

Khalidi, L. 26 June 2015. Yemen Heritage, Saudi Vandalism. *The New York Times Online*. 26 October 2015. http://www.nytimes.com/2015/06/27/opinion/yemeni-heritage-saudi-vandalism.html.

Klemm, D. and Klemm, R. 2011. *Gold and gold mining in ancient Egypt and Nubia: geoarchaeology of the ancient gold mining sites in the Egyptian and Sudanese eastern deserts.* Berlin, Springer.

Matthiae, P. and Marchetti, N. 2013. *Ebla and its landscape: early state formation in the ancient Near East*. Walnut Creek, Left Coast Press.

Mattingly, D. J. 2000. Tripolitana; Garama; Syrtica; Cyrene; Ammon. In R. Talbert (ed), *Barrington Atlas of the Greek and Roman World*, Princeton (2000): maps 35-38, 73 and Map-by-Map Directory: 529-69; 1108-16.

Mattingly, D. J. 2003. *The Archaeology of Fazzan. Volume 1, Synthesis.* London: xxvi and 430.

Mattingly, D. J. 2007. *The Archaeology of Fazzan. Volume 2, Site Gazetteer, Pottery and Other Survey Finds.* London: xxx and 522.

Mattingly, D. J. 2010. *The Archaeology of Fazzan. Volume 3, Excavations carried out by C.M. Daniels.* London: xxvi and 574.

Mattingly, D. J. 2013. *The Archaeology of Fazzān. Volume 4, Survey and Excavations at Old Jarma (Ancient Garama) carried out by C. M. Daniels (1962-69) and the Fazzān Project (1997-2001).* London.

Mattingly, D. J. and Sterry, M. 2013. The first towns in the Central Sahara. *Antiquity* 85 (336): 503-18.

Mattingly, D. J., Sterry, M., Leitch, V. 2013. Fortified farms and defended villages of Late Roman and Late Antique Africa. *Antiquité Tardive* 21: 167-88.

Meyer, J. C. 2013. City and hinterland. Villages and estates north of Palmyra. New perspectives. *Studia Palmyreńskie* 12: 269-86.

Morrow, M. and Cherry, P. 2010. *Desert RATS: rock art topographical survey in Egypt's Eastern Desert: site catalogue.* Oxford, Archaeopress.

Photos: Historical 'Baraqish' is damaged by raids. *Al Montasaf.*14 September 2015. 26 October 2015. http://almontasaf.net/news25452.html (in Arabic).

Poidebard A. 1934. *La trace de Rome dans le desert de Syrie: le limes de Trajan* à la *conquête arabe: recherches aériennes (1925-1932).* Paris, P. Geuthner.

Prickett M. 1979. Quseir Regional Survey. In Whitcomb D. and Johnson J. (eds.), *Quseir al-Qadim 1978. Preliminary Report*: 257–352. Cairo, American Research Center in Egypt, Inc.

Romey, K. 3 June 2015. 'Engineering Marvel' of Queen of Sheba's City Damaged in Airstrike. *National Geographic Online*. 26 October 2015. http://news.nationalgeographic.com/2015/06/150603-Yemen-ancient-Sheba-dam-heritage-destruction-Middle-East-archaeology/.

Scarin, E. 1938. *La Giofra e Zella: Le Oasi del 29 degrees parallel della Libia occidentale*. Firenze, G. C. Sansoni.

Schiettecatte, J. 2011. *D'Aden à Zafar: villes d'Arabie du sud préislamique*. (Orient and Mediterranée, 6). Paris, De Boccard.

Shaw, I. 2007. Late Roman Amethyst and Gold Mining at Wadi el-Hudi. In T. Schneider and K. Szpakowska (eds.), *Egyptian Stories: A British Egyptological Tribute to Alan B. Lloyd on the Occasion of His Retirement*: 319–28. Münster, Ugarit-Verlag.

Sidebotham, S. and Wendrich, W. 1995. Berenike 1994: *Preliminary Report of the 1994 Excavations at Berenike (Egyptian Red Sea Coast) and the Survey of the Eastern Desert*. Leiden, CNWS, University of Leiden.

Sidebotham, S. and Wendrich, W. 1996. *Berenike 1995: Preliminary Report of the 1995 Excavations at Berenike (Egyptian Red Sea Coast) and the Survey of the Eastern Desert*. Leiden, CNWS, University of Leiden.

Sidebotham, S. and Wendrich, W. 1998. *Berenike 1996: Report of the 1996 Excavations at Berenike (Egyptian Red Sea Coast) and the Survey of the Eastern Desert*. Leiden, CNWS, University of Leiden.

Sidebotham, S. and Wendrich, W. 1999. *Berenike 1997: Report of the 1997 Excavations at Berenike and the Survey of the Egyptian Eastern Desert, including Excavations at Shenshef.* Leiden, CNWS, University of Leiden.

Sidebotham, S. and Wendrich, W. (eds.) 2000. *Berenike 1998: Report of the 1998 Excavations at Berenike and the Survey of the Egyptian Eastern Desert, including Excavations in Wadi Kalalat*. Leiden, CNWS, University of Leiden.

Sidebotham, S. and Wendrich, W. 2006. *Berenike 1999/2000: Report on the Excavations at Berenike, including Excavations in Wadi Kalalat and Siket, and the Survey of the Mons Smaragdus Region*. Los Angeles, Cotsen Institute of Archaeology.

Sidebotham, S. and Zitterkopf, R. 1998. Survey of the Via Hadriana: the 1997 season. *Bulletin de l'Institut Français d'Archéologie Orientale* 98: 353–65.

Sterry, M. and Mattingly, D. J. 2011. DMP XIII: reconnaissance survey of archaeological sites in the Murzuq area. *Libyan Studies* 42: 103-16.

Stone, E. C., 2015. An Update on the looting of Archaeological Sites in Iraq. *Near Eastern Archaeology. Special Issue: the*

Cultural Heritage Crisis in the Middle East 78, 3: 178-86. Special Issue: the Cultural Heritage Crisis in the Middle East.

Tawfiq, M. 1951. *Les monuments de Ma'in, Yemen*. (Études sud-arabiques, 1). Cairo: IFAO.UNESCO Director-General condemns airstrikes on Yemen's cultural heritage. *UNESCO*. 2 June 2015. 26 October 2015. http://whc.unesco.org/en/news/1291.

Ur, J. A. and Wilkinson, T. J. 2008. Settlement and economic landscapes of Tell Beydar and its hinterland. In Lebeau, M. and Suleiman, A. (eds.), *Beydar Studies 1*. *Subartu 21*: 305-27. Turnhout, Brepols.

Vogt, B. 2004. Towards a new dating of the great dam of Marib. Preliminary results of the 2002 fieldwork of the German Institute of Archaeology. *Proceedings of the Seminar for Arabian Studies* 34: 377–88.

Wilkinson, T. J. 1999. Project for the archaeology of Yemeni terraced agriculture. *OI Annual Report*: 62–9.

Wilkinson, T. J. 2003. *Archaeological Landscapes of the Ancient Near East*. The University of Arizona Press, Arizona

Wilkinson, T. J., Galiatsatos, N, Lawrence, D., Ricci, A. *et al.* 2012. Late Chalcolithic and Early Bronze Age Landscapes of Settlement and Mobility in the Middle Euphrates: A Reassessment. *Levant* 44/2: 139-85.

Wilkinson T. J., Philip G., Bradbury, J., Dunford, R. *et al.* 2014. Contextualizing Early Urbanization: Settlement Cores, Early States and Agro-pastoral Strategies in the Fertile Crescent During the Fourth and Third Millennia BC. *Journal of World Prehistory* 27/1: 43-109.

Yemen: invading air force cause great damage to the historical site of Baraqish. *Khabar News Agency*. 14 October 2015. 26 October 2015. http://www.khabaragency.net/news38833.html (in Arabic).

Enhancing Multi-Image Photogrammetric 3d Reconstruction Performance on Low-Feature Surfaces

George Ioannakis[(1)]
gioannak@ee.duth.gr

Athanasios Tsaouselis[(2)]
atsaouselis@ipet.gr

Anestis Koutsoudis[(2)]
akoutsou@ceti.gr

Fotis Arnaoutoglou[(2)]
fotarny@ceti.gr

Blaž Vidmar[(3)]
blazvidmar@student.uni-lj.si

Christodoulos Chamzas[(2)]
chamzas@ee.duth.gr

[1] Faculty of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece
[2] Athena Research and Innovation Centre, Xanthi's Division, Multimedia Research Group, Xanthi, Greece
[3] Faculty of Civil and Geodetic engineering, University of Ljubljana, Ljubljana, Slovenia

Abstract: Generation of 3D digital replicas based on Structure-from-Motion and Multiple View Stereovision (SFM-MVS) has become a popular solution within the cultural heritage domain. Its applicability relies on the existence of discernible features on the surface of the photographed object, which are used to match corresponding views in image sequences. Unfortunately, some monument surfaces are almost featureless and the obtained 3D models tend to be very noisy. In this work, we use an image collection phase variant that utilizes a projector and a controlled noise function to enrich surfaces and enable the SFM-MVS pipeline to reconstruct the object properly. We apply our SFM-MVS modification on the Turkish bath (hammam) situated in the old town of Xanthi in Greece. This monument provides a lot of texture information on its exterior surface. Its interior surface, by contrast, has an insufficient number of discernible features and simultaneously complex geometrical characteristics that had to be reconstructed.

Keywords: Structure-from-Motion/Multiple View Stereovision, Low feature surfaces, Wavelet noise pattern

Introduction

The generation of 3D digital replicas based on Structure-from-Motion and Multiple View Stereovision (SFM-MVS; Engels 2006; Robertson 2009) is a popular solution within the cultural heritage domain. Some major aspects of SFM-MVS are its cost effectiveness in terms of hardware equipment and relatively low background knowledge requirements. The data collection phase is more efficient in terms of time requirements when compared with other 3D digitisation methods. In addition, the quality of 3D models produced by SFM-MVS satisfies the requirements of a vast range of digitisation projects (Koutsoudis 2014). As with all 3D digitization methods, the SFM-MVS pipeline has its limitations. It belongs to the family of targetless photogrammetric methods and inevitably relies on detecting features on object surfaces. Using SFM-MVS on featureless surfaces, therefore, may result in image misalignment or extremely noisy 3D models.

The monument we chose to digitize is a Turkish hammam, which is situated in the back yard of the Folklore Museum in the old town of Xanthi, in the Greek region of eastern Macedonia and Thrace. The Turkish bath reflects the concern of people for individual cleanliness combined with socialization, as hammams were places for gatherings. The hammam was operating until the 1970s.

In this work we created a 3D replica of the Turkish bath using the SFM-MVS pipeline, in order to use it in iGuide, an enriched Mobile Tourist Guide. The challenge was to reconstruct the interior of the monument, which did not provide enough surface features. Thus the traditional SFM-MVS pipeline produced a noisy reconstruction or even failed to detect features from the interior image sequences, and retained the SFM-MVS procedure from calculating the intrinsic and extrinsic parameters of the camera in order to compute the relevant positions of the images in 3D space and thus produce an acceptable (in terms of accuracy) 3D reconstruction. To overcome the restriction of the traditional pipeline, we implemented an image collection phase variant (Koutsoudis 2015) that uses a noise function-based pattern projected onto the object's surface in order to enrich it with artificial features. In this manner we lost the automation of the traditional SFM-MVS pipeline, but nevertheless managed to enable feature extraction algorithms such as SIFT (Lowe 2004) or SURF (Bay 2008) to detect and match the corresponding features and determine their 3D coordinates. Apart from this modification of the data-collection phase, we had to introduce additional steps in the data-processing phase which were: the separate reconstruction of each area with the images having the noise function-based pattern; the swapping of the artificial texture (pattern) with the original texture of the monument; and finally the aligning of these parts with the rest of the model.

The rest of the paper is organized as follows. In section 2, we discuss the data-collection phase and the differences in contrast to the usual image-collection phase that was implemented in order to achieve a reconstruction of the whole monument. In section 3, we present the data processing and the modifications we had to perform in order to create the 3D model. Finally, in section 4, we present our conclusions.

1 Data Collection

It is common knowledge that the image collection phase should be performed under specific lighting conditions. For outdoor photo shooting, the ideal case is a cloudy (overcast) day when direct light and shadows are minimal. Otherwise, the shadows produce features that under ideal weather and lighting conditions do not exist, and therefore generate errors and misalignments of the images, leading finally to an inaccurate reconstruction of the 3D monument.

The terrestrial photo shooting of the exterior was performed using a mirrorless DSLR camera, the Samsung NX1000, a common DSLR, the Nikon D3200, and a projector. For the camera, we used a remote control in order to eliminate the vibrations introduced by the triggering of the camera by hand. We used also a monopod in order to capture the monument from different heights, within a range of 1-5 meters. For the exterior part we implemented the traditional workflow for the creation of the image sequences. The hammam's exterior provided sufficient texture information in order to extract features for the matching phase. The image collection of the exterior of the monument consisted of 718 images. In contrast, the interior part of the Turkish bath was completely different in terms of surface features. Its surface was almost completely grey, with very few features and its geometry was not flat but with arches and a dome. The geometrical characteristics and details such as the arcs, the dome, and the holes for the windows of the interior had to be captured. Moreover, deterioration and discoloration provided texture information in some areas that was helpful, but this was not the case for most of the interior. For the inner parts, where there was a lack of features, we had to implement the discussed image-collection phase variant, where a noise function-based pattern was projected onto the surface of the object. Thus the surface was artificially enriched with features that the feature extraction algorithm could detect.

In our case, we used a wavelet noise function-based pattern since it has some characteristics that make it suitable for use in procedural texturing. This noise pattern is truly band-limited and therefore minimizes the aliasing effect (Cook 2005; Fig. 1). In addition, the reconstruction performance of this noise function-based pattern was evaluated and proved to provide the best reconstruction quality, in terms of accuracy.

The data acquisition set-up for the image-collection phase consisted of a mirrorless DSLR, a projector, and two tripods, one for the camera and one for the projector, respectively. For each viewpoint, we obtained two images, one with the noise pattern and one without it. The image sequence with the noise pattern on it was used to generate the geometry by performing the ordinary SFM-MVS method. Then we used the second sequence of images, those without the noise function-based pattern in order to generate the actual texture again. At this point, it is important to mention that the procedure was time-consuming, since for each projector position in 3D space we had to capture a new image sequence that had to be separately reconstructed later. The image collection of the interior consisted in a total of 531 images.

Evidently, the image-collection phase time was increased due to the introduction of the proposed methodology in order to overcome the limitations of the SFM-MVS workflow that relied on the existence of feature points on the surface.

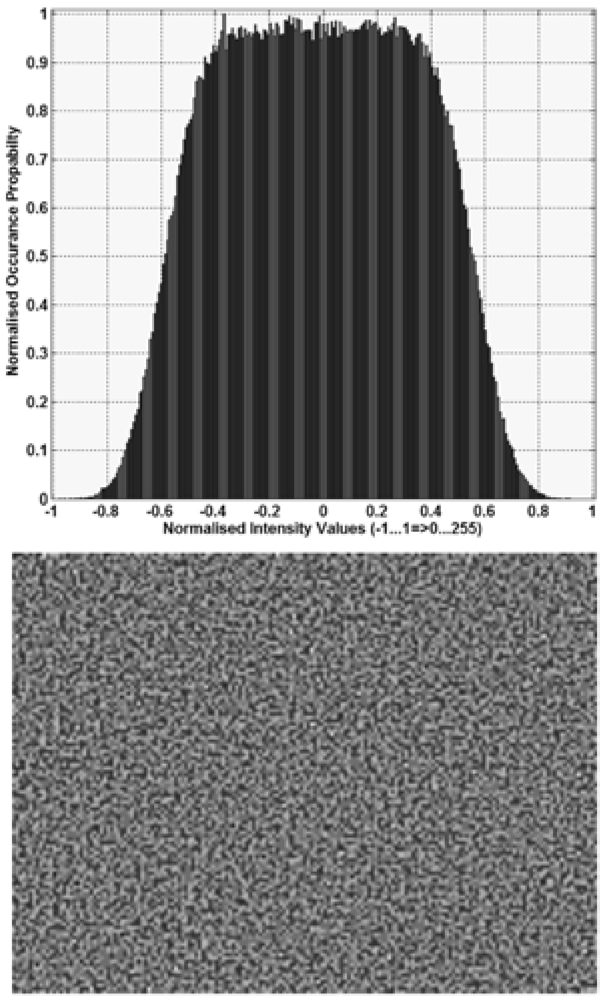

Fig. 1. Wavelet noise pattern and the normalized occurrence probability greyscale intensity values.

More analytically, for the ordinary image collection we spent approximately three hours of photo shooting in order to cover the whole exterior, and for the parts where we had to implement the image-collection phase variant, we spent more than four hours to create the appropriate image sets.

To conclude, the time effort spent for the creation of the proposed image collections with the use of the noise function-based pattern reflects the difficulties encountered. Moreover, it is important to mention that the time consumed was also related to the projector's field of view and the projector's positioning in 3D space, in other words the goal was to cover an area as wide as possible on the surface of the object being documented.

2 Data Processing

The data-processing phase was split into two different pipelines, one for the ordinary SFM-MVS pipeline and another for the workflow, in order to deal with the image sequences that derived from the image-collection phase variant. It is important to mention that the automation of the reconstruction procedure was lost and in addition required the user's intervention to produce the final 3D model. Within the cultural heritage domain, however, this will not often be the case due to the fact that most monuments suffer from deterioration, erosions, and discoloration and thus provide sufficient features on their surface. Nevertheless, when such an object comes up the proposed workflow constitutes a viable solution.

2.1 Traditional SFM-MVS pipeline

The SFM-MVS pipeline, a known technique within the cultural heritage domain, was implemented for the image sequences that were produced following the traditional image-collection procedure. More analytically, the first step was the feature detection procedure that was performed with a feature extraction algorithm. These techniques extract points or regions with characteristic texture information on the images, which would later be used in the matching phase in order to define the corresponding points among the unordered set of images. Consequently, the sparse 3D reconstruction of the hammam was performed using bundle adjustment, which is an optimization process that relies on the 3D structure and viewing parameters and the reduction of noise that derives from the images. Bundle adjustment can be defined as the problem of simultaneously refining the 3D coordinates describing the scene geometry as well as the parameters of the relative motion and the optical characteristics of the cameras employed, according to an optimality criterion involving the corresponding image projections of all points, for the given set of images depicting a number of 3D points from different viewpoints (Triggs *et al.* 1999). A dense point-cloud model was subsequently produced, which was based on the estimated camera positions and on the calculation of the depth information from each camera, which were combined in order to produce a single point cloud. Finally a triangulated mesh was produced from the dense point cloud.

2.2 SFM-MVS variant

On the other hand, the produced noise function-based image sequences had to be treated differently. More analytically, the SFM-MVS was implemented as described above with the added necessity of replacing the texture of the created mesh with its original texture. In this step we used the image sequences that were captured from the same viewpoints without the noise function-based pattern projected on the surface of the hammam. The swapping of the noise function-based texture with the original was performed within the software used for the 3D reconstruction. Finally, we had to align the parts created during the SFM-MVS image collection phase variant with the rest of the 3D model that derived from the traditional pipeline.

The improvement in the reconstruction of the 3D scene is shown in Figure 2, where the part of the 3D scene that was created using the Wavelet noise function-based pattern is highlighted (marked with black border). The reconstruction around the area where noise function-based pattern was projected was very noisy and thus not appropriate for the documentation of the hammam.

It is important to mention that in almost every case the feature extraction algorithm failed to detect features on the featureless areas without the noise function-based pattern projection and as a consequence could not proceed to the matching of corresponding points and the 3D reconstruction. In other cases where the algorithm succeeded in extracting features, it was not possible to create an accurate polygonal mesh due to the ambiguity during the matching of the corresponding point phase that led to misalignments.

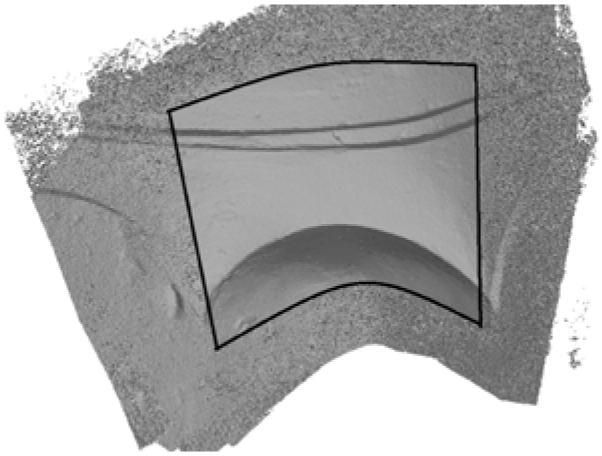

Fig. 2. Reconstruction based on the artificial features provided by the wavelet noise pattern.

Finally, the completion of the SFM-MVS pipeline and the proposed method to deal with featureless surfaces led to the creation of separate polygonal meshes. In order to create the whole polygonal model we had to align the separate meshes manually by picking the corresponding points. This process was performed using MeshLab (MeshLab 2005), an open source mesh-processing software. The outcome of the whole workflow is shown in Figures 3 and 4.

Conclusions

The SFM-MVS pipeline relies on the extraction of features and the detection of corresponding features among images in image sequences. The number of corresponding points matched is strongly related to 3D data quality and accuracy. In this work, we point out the limitation of the traditional SFM-MVS pipeline, while reconstructing the 3D polygonal mesh of the Turkish hammam. In order to overcome this restriction we implemented an image-collection phase variant with the aid of the wavelet noise function-based pattern that was proved to perform better in terms of accuracy and quality of the 3D data. This method increased the data-collection as well as the data-processing time and effort but enabled us to reconstruct the monument. This project confirms that the data-collection phase variant constitutes a viable solution within the cultural heritage domain, when there are no other digitization options available.

Acknowledgements

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TAB. 1. RECONSTRUCTION RESULTS.

	Nr of images	Sparse Point cloud (pts)	Polygonal Model (faces)
NP image collection	1249	1,663,573	30,557,374
Additional wavelet image collection	100	55400	26,916,004

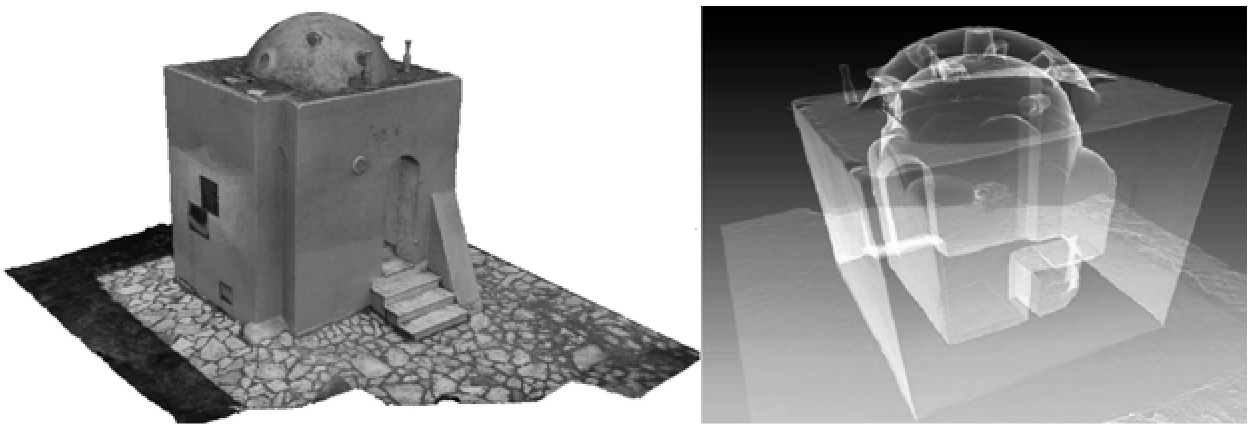

FIG. 3. TURKISH HAMMAM RECONSTRUCTION OVERVIEW.

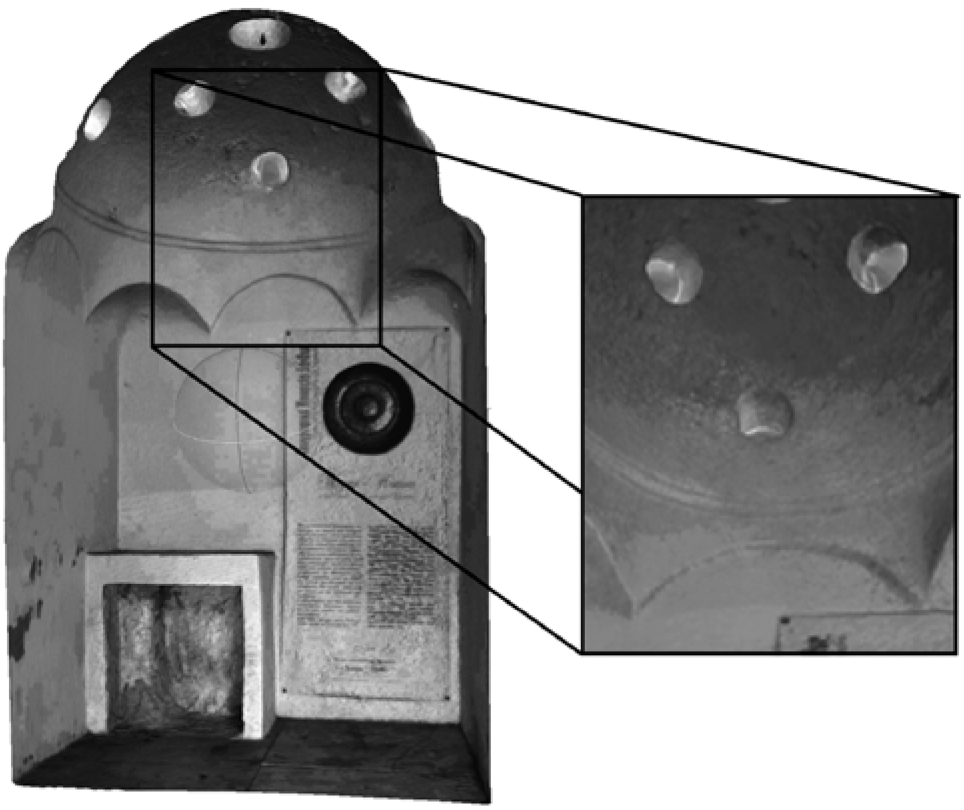

FIG. 4. INTERIOR RECONSTRUCTION OVERVIEW.

Bibliography

Bay, H., Ess, A., Tuytelaars, T., Gool, L. V. 2008. SURF: Speeded Up Robust Features, *Computer Vision and Image Understanding 110:* 346-359.

Cook, R., Derose, T. 2005. Wavelet noise. In *ACM SIGGRAPH 2005 Papers (SIGGRAPH '05)*: 803-811.

Engels, C., Stewénius, H., Nistér, D. 2006. Bundle adjustment rules, In *The photogrammetric computer vision conference, ISPRS, Bonn, Germany, September 20–22 (2006)*.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., Chamzas, C. 2014. Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*. 15(1): 73-79.

Koutsoudis, A., Ioannakis, G., Vidmar, B., Arnaoutoglou, F., Chamzas, C. 2015. Using noise function-based patterns to enhance photogrammetric 3D reconstruction performance of featureless surfaces. *Journal of Cultural Heritage*.

Lowe, D. 2004. Distinctive Image Features from Scale-Invariant Keypoints. *Journal of Computer Vision 60*: 91-110.

MESHLAB 2005. [Online] http://meshlab.sourceforge.net. [Accessed: 25th June 2015].

Robertson, D. P., Cipolla, R. 2009. Structure from motion, *Practical image processing and computer vision, John Willey and Sons Ltd* 2009.

Triggs, B., Mclauchlan, P., Hartley, R., Fitzgibbon, A., 1999. Bundle Adjustment — A Modern Synthesis. *ICCV '99: Proceedings of the International Workshop on Vision Algorithms*: 298–372.

Combination of RTI and Decorrelation — an Approach to the Examination of Badly Preserved Rock Inscriptions and Rock Art at Gebelein (Egypt)

Piotr Witkowski
pwit@wp.pl
Polish Centre of the Mediterranean Archaeology, University of Warsaw

Julia M. Chyla
julia.chyla@gmail.com
Antiquity of South-eastern Europe Research Centre, University of Warsaw

Wojciech Ejsmond
wojtek.ejsmond@wp.pl
Antiquity of South-eastern Europe Research Centre, University of Warsaw

Abstract: This paper presents the results of a combination of two imaging techniques — RTI and decorrelation. Both techniques were used during epigraphic survey of Gebelein in Egypt. The combination helped in the discovery of new graffiti and dipinti, and in the understanding and examination of those already known.

Keywords: RTI, Decorrelation, Egypt, Graffiti

1 Epigraphic survey at Gebelein

The Gebelein archaeological site complex is located in Upper Egypt, *c.*28 km south-west of Luxor on the western bank of the Nile. Archaeological sites in the area are dated from the Middle Palaeolithic to the Middle Ages. The place was an important centre in Egyptian history but its exact role and significance is not yet explained (Ejsmond, Chyla and Witkowski, in press; Ejsmond, in preparation).

There is a long history of research at Gebelein: the first official examination was undertaken in 1885 (Fiore Marochetti 2013), but so far most of the results of the excavations have not been published. The current research project was initiated in 2013 (Ejsmond, Chyla and Baka, in press). Due to threats to the archaeological heritage and limited knowledge of this important site complex, the aims of the ongoing project are to document all recognizable archaeological features and study archaeological records related to Gebelein. The area of the archaeological survey is large (*c.*4 x 5 km) and complicated. The dominating features of the landscape are two rocky mounds, which gave the place its ancient Egyptian name (Inerti), as well as the contemporary Arabic name (Gebelein) — 'two rocks'.

The tombs are the dominant archaeological features, but there are also many graffiti and dipinti,[1] which are concentrated mainly in two areas (Fig. 1). They are dated from the prehistoric to modern times. Motifs were executed in different techniques, such as engravings, sunk reliefs, and paintings.

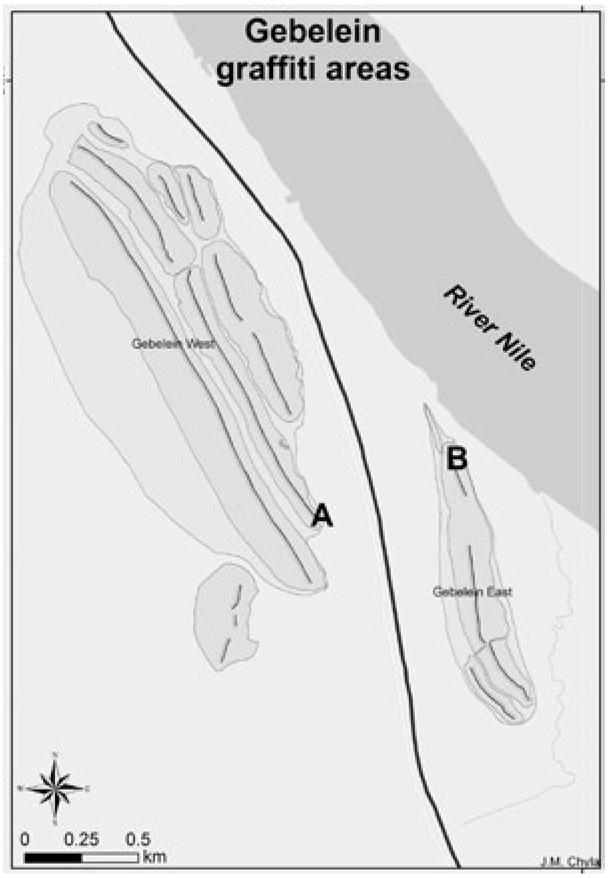

Fig. 1. A map of Gebelein: A. location of graffiti and dipinti; B. Hathor temple and speos.

[1] In the archaeology of Egypt, a graffito (pl. graffiti), is a deliberate mark made by scratching on a large surface such as a wall. The marks may form an image or writing. In popular culture it is sometimes confused with dipinto (pl. dipinti), which is painted mark(s) on large surfaces of objects (like a worker's dipinti on stone blocks in pyramids or temples) (see H.-J. CH. 1977: 880–2).

Fig. 2. View to the north-west of graffiti and dipinti discovered in the southern part of the western rock. Light areas indicate the location of the rock arts.

Fig. 3. The small part of the rock art palimpsest with overlapping engravings created at a different period.

The first area is located in the south-eastern part of the western hill (Fig. 1/A, Fig. 2). Most graffiti were made on the eastern wall of rocks, *c.*1.5 m above the ground and cover an area of *c.*7.5 x 1.8 m (main panel 6 x 2 m and side panel 1.5 x 1.8 m). The main panel of graffiti is inclined at *c.*50° to the ground. It is some kind of palimpsest — a few graffiti and dipinti from different periods are represented here on the same surface. Some of them have been destroyed to make space for new ones, others overlap each other (Fig. 3). Other inscriptions — one from the time of Ramesses IV (Wieczorek, in press), another, very fragmentary, is a preserved hieroglyphic inscription with the sign of the goddess Hathor) — are located a few metres to the south, covering the southern face of the hill (Fig. 4).

The second set of inscriptions is on the eastern slope of the northern part of the eastern mound (Fig. 1/B). It consists of a heavily damaged decoration on the walls of a speos constructed during the 18th dynasty. Several metres above the speos, on

Fig. 4. View on graffito from the time of Ramses IV (left), and the inscription with the sign of the goddess Hathor (right).

the rock cliff there is a narrow, less than 1 m wide, shelf with a small cave at the end. Both carved and painted inscriptions were placed *c.*3 m above the shelf.

2 Documentation and the idea of combining RTI and decorrelation

Some of the discovered graffiti are located in places that are difficult for documentation and the dynamic lighting conditions very quickly became unfavourable (at approx. 10 a.m., in some cases even earlier, the sun's rays no longer reach the engravings and certain elements become poorly visible or even invisible). The rock surface is uneven, fragile, cracked, and rough and therefore traditional techniques of documentation with the use of transparent plastic foil and direct tracing are often inefficient and troublesome. Furthermore, the foil reduces shadows and attaching transparent paper on the stone surface can destroy more fragile parts. Many graffiti and dipinti are very poorly preserved due to their exposure to the elements and anthropogenic damages.

In order to avoid further destruction of the rock surface and to save time, after the initial use of transparent plastic foil it was decided to apply indirect, non-invasive recording techniques, one of them being to trace on digital photography (Domingo 2014; Pagi, Miles and Uueni 2015). The source images are generated by the imaging technique RTI (Reflectance Transformation Imaging).

RTI (more exactly Polynomial Texture Mapping, which is the first kind of RTI) was developed in 2000 at Hewlett-Packard Laboratories (Malzbender *et al.* 2000). The result is an interactive image created from a set of photos taken with a stationary camera. Each photo is taken under the same circumstances, with the only variable being the movement of light — all the points in which the light is placed should create a hemisphere. The settings of the camera also stayed the same for each image. Then, the algorithm of specialized software mathematically recreates the surface from the recorded data. It is important to point out that the result is not a 3D object. Following this, one can open the digital version of the documented fragment in a dedicated viewer and manually re-illuminate it in an interactive manner. This helps to reveal the characteristics of the examined object, which might be poorly visible or even invisible to the naked eye (Malzbender, Gelb and Wolters 2001; Diaz-Guardamino and Wheatley 2013). RTI is already a known technique in rock art archaeology (Diaz-Guardamino and Wheatley 2013; Tumi *et al.* 2014) and in Egyptology (Piquette 2014; Serrano *et al.* 2014).

To record the photos we used a Canon EOS 500D (15 megapixels), the standard zoom lens with the focus set at 35 mm, a tripod, a Fomei Panther 600 mini (strong portable flash), a pole, two blackballs, a measuring tape, and string. Each of the registered set was composed of 35–90 images (RAW + JPG). The smaller number of images in the collection means it was not possible to create a full hemisphere using the lamp.

In 2014, a few months after the completion of the fieldwork, while browsing through photos on the computer, Piotr Witkowski noticed a small fragment of the surface near the graffito of Ramesses IV. After strengthening the colours of the image in a graphics program, the fragment revealed the clearly visible hieroglyph of the goddess Hathor. In addition, a few others signs also became visible. No one saw this fragmentary inscription in the field even though all the project members were present. A comparison of the drawing on transparent foil and the results of digital colour enhancement show that the latter technique gave a clearer picture of the inscription than the classical technique of documentation, that is, direct tracing (Fig. 5).

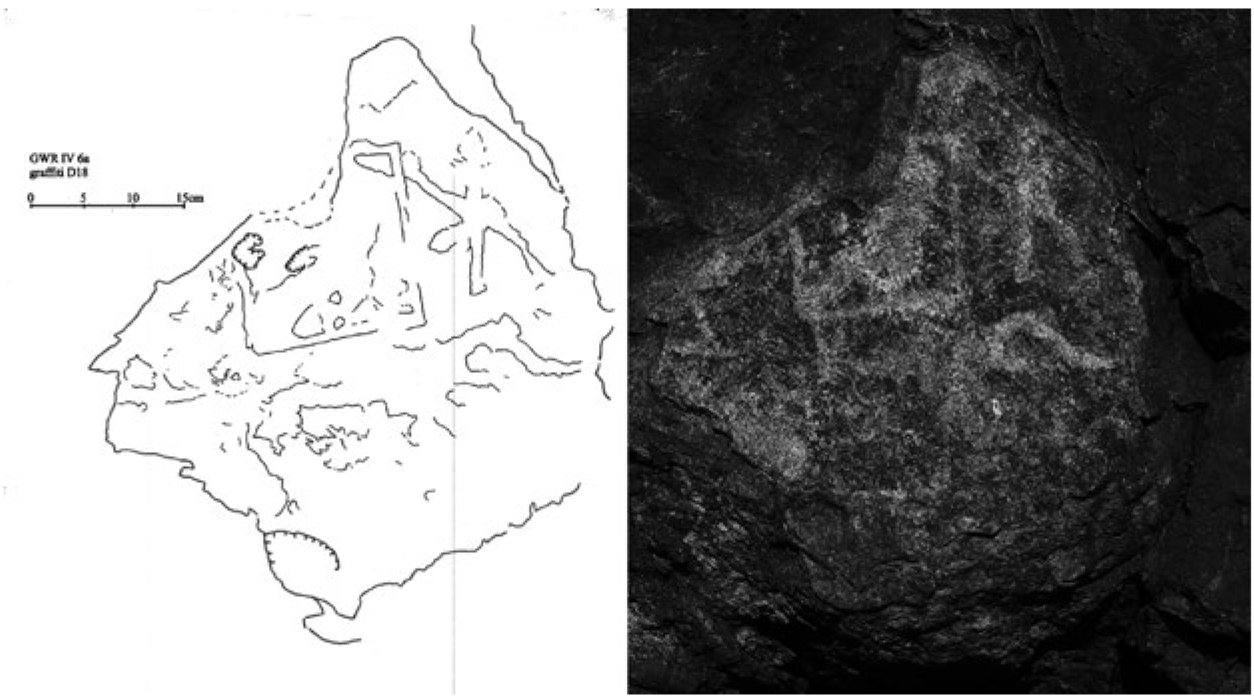

Fig. 5. Comparison of different methods of documentation: direct tracing (left) and digital enhancement image (right).

ImageJ software and DStretch[2] plug-in were applied for the post-processing of the images of the rock. DStretch is a set of decorrelation algorithms that reinforces the differences in the hue of neighbouring pixels. The chosen technique was used earlier not only in rock art documentation but also in remote-sensing analysis (Harman 2008), where it gave interesting results, which is the reason it was decided to use it in our research. The work with the plug-in is intuitive and fully automated (it is also possible to specify one's own settings). Caution should be taken while using the plug-in, however, as it is easy to over-enhance the colour, which may not give a true representation of the artefacts on the photo (on the picture elements that were not recorded during the shooting of the image might be added or raise so much noise that the image becomes unreadable).

The discovery of the overlapping and faded engraved and almost invisible painted elements on the eastern rock, as well on the western rock, gave the idea of combining the two techniques of RTI and colour enhancement/decorrelation. Another stage was added to the process of creating an interactive RTI file. After capturing, photos were processed in a DStretch plug-in or another graphics program (Photoshop or Gimp). The resulting digitally enhanced images were then loaded into RTIBuilder software.

- The combination of these two techniques was also based on several assumptions:
- faded elements should become much more visible
- it is possible to find additional elements which are not visible to the naked eye
- the images after digital enhancement should be high-quality photos
- each image of the set is enhanced identically (with the same options and parameters)

3 Results

After trying each automatic option implemented in DStretch for the reinforcement of colour, we chose the option that best strengthens white and black colours (LAB) and best fulfils our assumptions. The results of the combination of the RTI and decorrelation techniques are visible in Figures 6 and 7. It was possible to obtain high-quality photos, and the painted elements of the graffiti became much more visible. Furthermore, previously invisible elements can now be seen on the images; for example, there are red traces crisscrossing the engraved figure of a human (Fig. 7).

It was a pleasant surprise to see that the differences in the patina colours became much clearer, and thus improved the clarity of the gazelles and others animals, which were depicted in shallow sunk relief. Moreover, traces of damage on the rock surface are more visible. One can also observe two zones with different patina colours (Fig. 7). One can speculate that a lighter hue in the lower right half of the image (it is also visible in other parts of the graffiti) shows that at some time, part of the palimpsest was subject to exposure to a different environment (e.g. buried under ground?).

4 Conclusions

The results of combining RTI and DStretch confirmed the possibility of a better visualization of faded elements. It also helped to detect elements not visible to the naked eye or using

2 ImagesJ website is http://rsb.info.nih.gov/ij/index.html; information about DStretch could be found at www.dstretch.com.

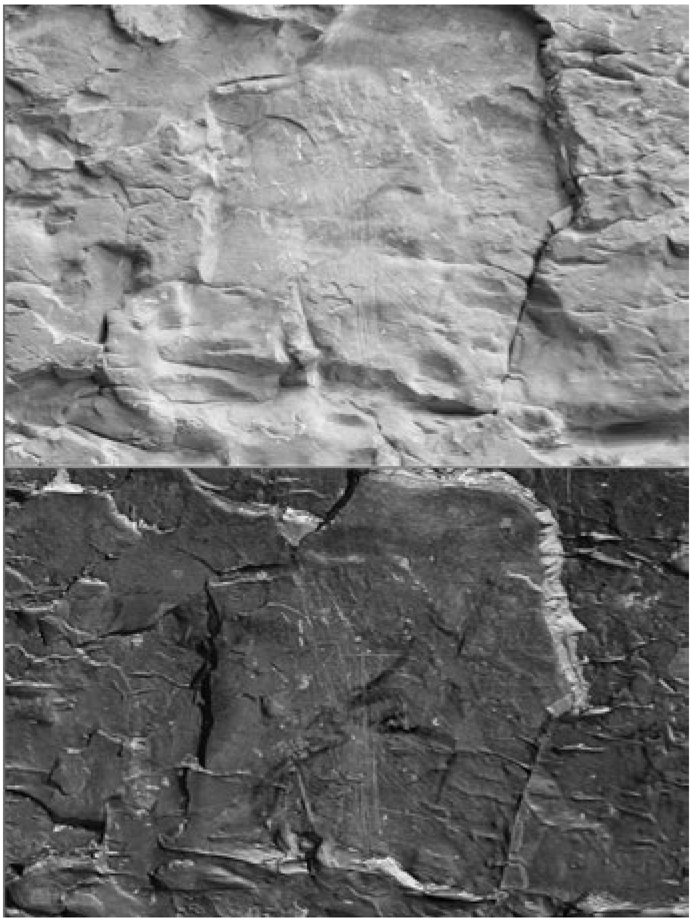

Fig. 6. Screenshots of the small part of the rock art palimpsest (western rock, southern part of the main panel) viewed with the traditional RTI method (top) and the RTI connected with DStretch plug-in (bottom).

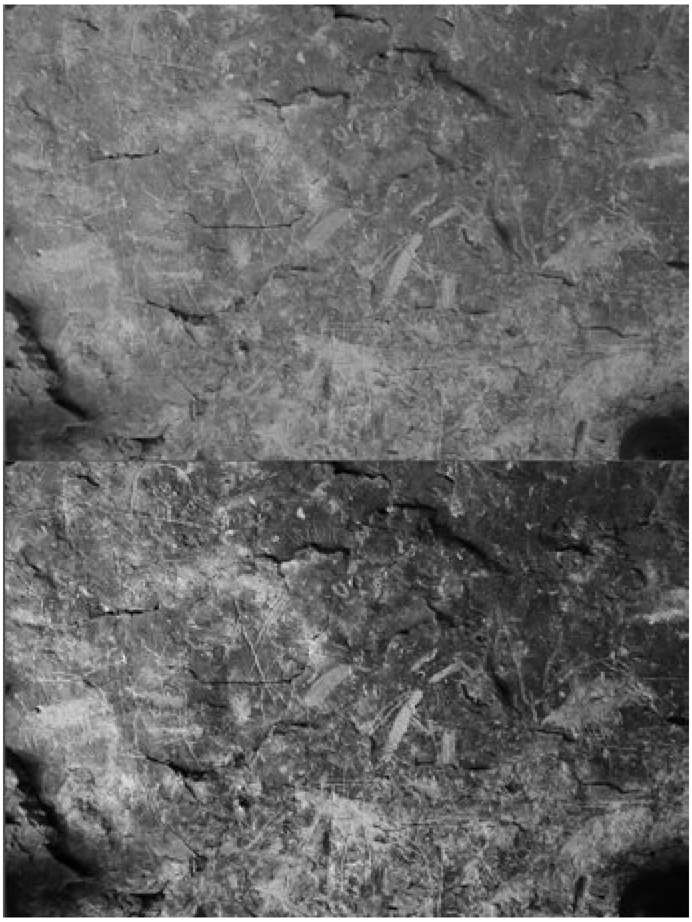

Fig. 7. Screenshots of the small part of the rock art palimpsest (western rock, middle part of the main panel) viewed with the traditional RTI method (top) and the RTI connected with DStretch plug-in (bottom).

only one technique. Such a combination of techniques also allows the documentation and investigation of the relationship between the almost invisible painted motifs and engraved depictions of the rock art. The outcome of the post-processing of photos mentioned above enabled the epigraphic researchers to continue their work after the field season with more detailed, as well as new data.

It would appear that the same approach can provide good results during research on the decoration of temple walls where reliefs are frequently supplemented with painted elements. These were often the first to be removed and replaced with successive reliefs or painted motifs.

Acknowledgements

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Bibliography

Diaz-Guardamino, M. ,Wheatley, D. 2013. Rock art and digital technologies: the application of Reflectance Transformation Imaging (RTI) and 3D laser scanning to the study of Late Bronze Age Iberian stelae. *MENGA. Journal of Andalusian Prehistory*, 4: 187-203.

Domingo, I. 2014. Rock Art Recording Methods: From Traditional to Digital. In Smith, C. With (ed.), *Archaeology of Art section. Encyclopedia of Global Archaeology.*

Ejsmond, W. (in preparation). Developments and Declines - the Archaeological Site Complex of Gebelein. *Journal of Egyptian Archaeology*.

Ejsmond, W., Chyla, J. M. and Baka, C. (in press). Report from Field Reconnaissance at Gebelein, Khozam and el-Rizeiqat. *Polish Archaeology in the Mediterranean* 24/25.

Ejsmond, W., Chyla, J. M. and Witkowski, P. (in press). Results of Recent Field Research at Gebelein. In Miszk, Ł., Kajzer, G. and Wacławik, M. (eds.), *The Land of Fertility. South-East of Mediterranean from the beginning of The Bronze Age to the Muslim Conquest. Proceedings from The 1st International Post-graduate Conference*, Kraków-Cambridge: Cambridge Scholar Publishing.

Fiore Marochetti, E. 2013. Gebelein. In Wendrich, W., Dielman, J., Ford E. and Baines J. (eds.), *UCAL Encyclopedia of Egyptology*, Available from: https://escholarship.org/uc/item/2j11p1r7. [Accessed: 30th of June 2015]

Harman, J. 2008. *DStretch Algorithm Description.* [Online] Available from: http://www.dstretch.com/AlgorithmDescription.html. [Accessed: 28 of June 2015].

H.-J. CH. 1977. Graffiti. In W. Helck and E. Otto (eds.), *Lexikon der Ägyptologie* vol. 2, Wiesbaden: O. Harrassowitz: 800–2.

Malzbender T., Gelb D., Wolters H., and Zuckerman, B. 2000. Enhancement of Shape Perception by Surface Reflectance Transformation. *Hewlett-Packard Technical Report HPL-2000-38*.

Pagi H., Miles J. , Uuen A. 2015. *Re-Illuminating the Past. Introduction to Reflectance Transformation Imaging,* Daguerreotype 2/2015: 15-21.

Serrano A. J. *et al.* 2014. *Projecto Qubbet el-Hawa: Las tumbas 33, 34aa Y 34bb Sexta Compaña*, Boletín de la Asociación Española de Egiptología No. 23: 7-48.

Piquette, K. E. 2014. *Scribal Practice and an Early Dynastic Stone Vessel Inscription: Material and aesthetic implications*. In Dodson, A. M., Johnston, J. J. and Monkehouse, W. (eds.), A Good Scribe and an Exceedingly Wise Man: studies in honour of W.J. Tait: 241–50.

Wieczorek, D.F. (in press). A Ramesside Rock Inscription at Gebelein – an unknown expedition of Ramesses IV. *Etude et Travaux* 27.

Tumi G., Lopez E., Nieves A. 2014. Reflectance Transformation Imaging (RTI) at two petroglyph sites in Peru: manufacturing techniques, deterioration and conservation. In Zhang Ya Sha (ed.), A monograph of Rock Art Research and Protection: 204-26.

Geophysical-Archaeological Experiments in Controlled Conditions at the Hydrogeosite Laboratory (CNR-IMAA)

Felice Perciante
felice.perciante@imaa.cnr.it

Luigi Capozzoli L.
luigi.capozzoli@imaa.cnr.it

Valeria Giampaolo
valeria.giampaolo@imaa.cnr.it

Antonella Caputi
antonella.caputi@imaa.cnr.it

Raffaele Luongo
raffaele.luongo@imaa.cnr.it

Gregory De Martino
gregory.demartino@imaa.cnr.it

Enzo Rizzo
enzo.rizzo@imaa.cnr.it

CNR-IMAA, Laboratorio Hydrogeosite, Marsico Nuovo (PZ), Italy

Abstract: Geophysical techniques are an important contribution to archaeological research without needing invasive excavation. The study of geophysical parameters increases the knowledge of archaeological contexts for protection and preservation of the cultural heritage. Several research papers show the importance of geophysical techniques in archaeological context for a broad variety of environments. For each site condition the right geophysical method has to be appropriately chosen, however, because one of the most important principles in applying geophysical techniques is a good knowledge of their limits as the geophysical parameters could hide a true or highlight a false target. In order to improve the obtained results it has become a tested practice to use a multi-methodological approach based on the integration of different geophysical techniques (Gabrielli and Piro 2009; Goodman and Piro 2013). Nowadays, the use of these techniques is very important in the research and definition of archaeological sites thanks to their characteristics of low cost and rapidity in the restitution of the data.

The main goal of this paper is to analyse in laboratory experiments the contribution of two geophysical techniques commonly applied to the archaeological context, GPR and ERT, to investigate an archaeological site characterized by lacustrine and/or high water content conditions.

Keywords: Archaeogeophysics, Geoarchaeology, GPR, ERT, Analogue archaeological site

Introduction

In order to assess the capability of geophysical techniques in detecting archaeological remains placed in humid or water-saturated subsoil, an experiment was conducted at the Hydrogeosite Laboratory. By reconstructing a small, buried archaeological site, the goal of this experimental activity was to enhance the ability of interpreting geophysical data and refine field methods for their application in archaeological investigations.

The large-scale Hydrogeosite Laboratory at CNR-IMAA consists of a pool shape structure measuring 230 m^3, where an archaeological reconstruction (consisting of walls, tombs, roads, columns, and a mosaic floor) were installed; buried by sediments it characterizes variable degrees of water saturation in order to simulate lacustrine and wetland conditions, or extreme events (e.g. an underwater landslide, fast naturally eroding coast, etc.). In detail, inside the Hydrogeosite Laboratory pool, an archaeological framework relative to both a living and burial environment of Roman times was built. For this purpose some representative elements of a building were reconstructed, defined by a 'structural frame' consisting of two dividing walls joined at an angle; a 'roman' mosaic floor; a collapse with material uprooted and a column; a paved road; three different types of burials (a capuchin tomb, a case tomb made with clay tiles, an *enchytrismos* tomb). The types of structure, construction techniques, and materials used, as well as their installation were in accordance to the standards of architecture by Vitruvius and more recent scientific publications.

The case study analysed the capability of two well-known geophysical techniques widely applied in the field of archaeological research: Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) (Cammarano *et al.* 1997a, 1997b, 1998a, 1998b; Sambuelli *et al.* 1999; Sarris and Jones 2000; Rizzo *et al.* 2005; De Domenico *et al.* 2006; Böniger and Tronicke 2009; Campana and Piro 2009; Cavalieri and Pace 2011, Giavarini *et al.* 2006; Orlando 2013, 2015). Their ability to individuate an archaeological *target* depends mainly on the subsoil characteristics, on the water content in the soil, and physical properties of the analysed medium. In both cases numerical simulations were carried out for comparison with the real data collected in the field. The objective was twofold: on the one hand we tried, through the integration of data, to overcome the limits of each technique in humid/saturated conditions, especially in terms of resolution and depth, on the other the potential technological enhancement in

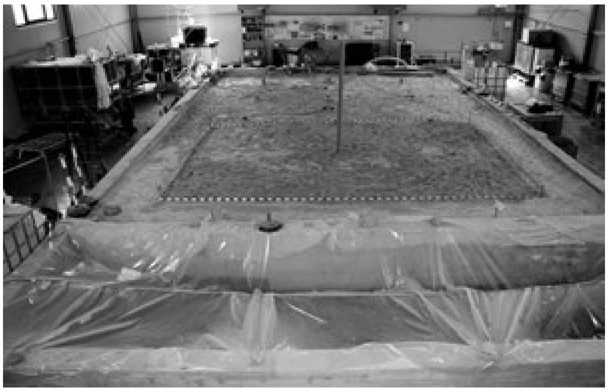

Fig. 1. The Hydrogeosite Laboratory.

Fig. 2. Reconstruction of the archaeological context.

the integrated use of GPR and ERT in three-dimensional mode was investigated.

1 Test site

The Hydrogeosite is a research laboratory of the pole CNR-IMAA in Marsico Nuovo (PZ, southern Italy), created in 2006 to study under controlled conditions the contamination phenomena of soil and groundwater with geochemical and geophysical analysis (Fig. 1).

The presence of a system of tanks and wells (n = 17) allows the simulation of different elevations of groundwater, by saturating the sand to a desired height through a water pumping controlled system (Cuomo *et al.* 2005). It therefore allowed us to simulate some archaeological remains buried by sediments in different water saturation conditions, simulating typical lacustrine and wetlands conditions. Furthermore, even extreme events, as for example submarine landslide, fast coast natural erosion, etc. can be tested.

The pool, filled with silica sand, is approximately 240 m^3 (12 x 7 x 3 m), and the Hydrogeosite Laboratory thus offers the advantage of obtaining controlled results in scales comparable to experiments in the field. In particular, for this experiment we used a surface area of around 6.20 x 4.60 m, reaching an excavation depth of –1.10 m at the boundaries, and a minimum depth of –1.60 m where tombs and structures were buried. To make a realistic reconstruction the structures were executed at a reduced scale of 1:25. In this archaeological context, we tried to identify and validate the effectiveness of the geophysical methods currently used in archaeology, under unfavourable conditions (high water content). At each stage and for the different water table positions, GPR and ERT surveys were performed together with the same configuration and grid of acquisition, with the aim of identifying the influence of the increasing subsoil water content (tap water with electric conductivity of 0.3 S/m) on the EM response of the case study.

2 Materials and methods

The first phase of this laboratory experiment concerned the study of different archaeological features typical of the archaeological sites located in the Agri Valley. We analysed the settlement types and the exploitation of natural resources from prehistory to the present, focusing our attention on the adopted material, construction types, and techniques (Giardino 1983; Giardino and De Siena 1999; Rocchetti 2002; Russo et al. 2007; Gualtieri 2009; Tarlano 2009, 2010, 2013, 2014). Furthermore, we examined the Roman architectural techniques that followed the standards reported by ancient sources as those set by Vitruvio (De Architectura) and various recent scientific publications (Giovannoni 1925; Lugli 1957; Adam 1988; Giuliani and Ferretti 1997; Giuffrè 1999; Le Pera 1999; Caleca 2000; Rocchetti 2002; Giuliani 2006).

In order to analyse the ability of geophysical techniques to operate in humid and saturated soil conditions, we designed and in some cases realized several targets characterized by different shapes and materials. For this reason we adopted stylistic and structural elements belonging to different historical periods, places, and *ethnos* that find their coexistence in the middle Republican age and in the Late Imperial phase and even employed in more recent times, such as the capuchin tombs and 'box-graves' composed of large clay *tegulae* (tiles) used in the 4th–3rd century BC and in the Imperial period, or the *opus caementicium* continuously employed from its invention to the present.

In particular, the project involved the construction of two different environments, one for the living context and one representing the funerary world (Fig. 2). Three burials are located along the western margin: a capuchin (F), an *Enchytrismos* in a pot (E), and a tiles burial (B). The eastern portion was used for the construction of a paved road fragment and part of a building (C). The latter, defined by two dividing walls converging to form a corner, incorporated a mosaic-covered floor; in this case, a small collapse near the structure was simulated (D). Finally, a marble column was placed (A) along the western edge of the mosaic floor.

3 GPR investigations

The GPR investigations were performed on the surface of the simulated archaeological site at different groundwater levels, in order to define the quality of the GPR results for increasing subsoil water content. The investigated area has a surface of about 4.60 x 6.20 m, and the GPR acquisition lines were carried out each 0.20 m both along axes X and Y (Fig. 3).

Thus, 56 acquisition lines were carried out, 24 along the X axis and 32 along the Y axis. The GPR utilized was the GSSI SIR

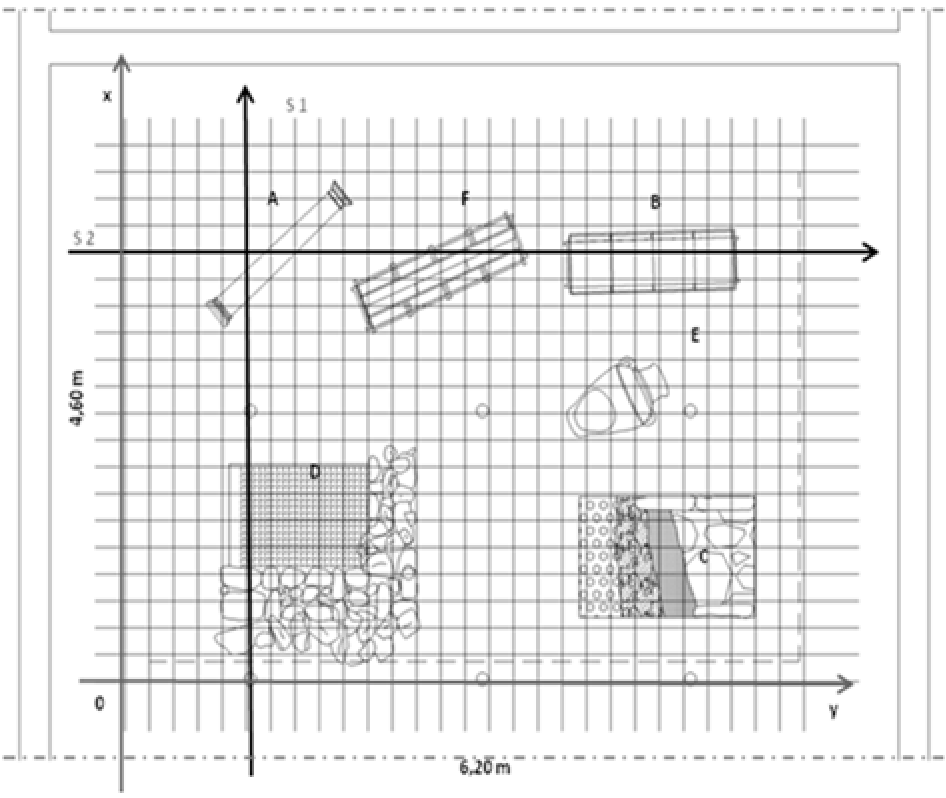

FIG. 3. SKETCH OF THE GPR GRID ACQUISITION.

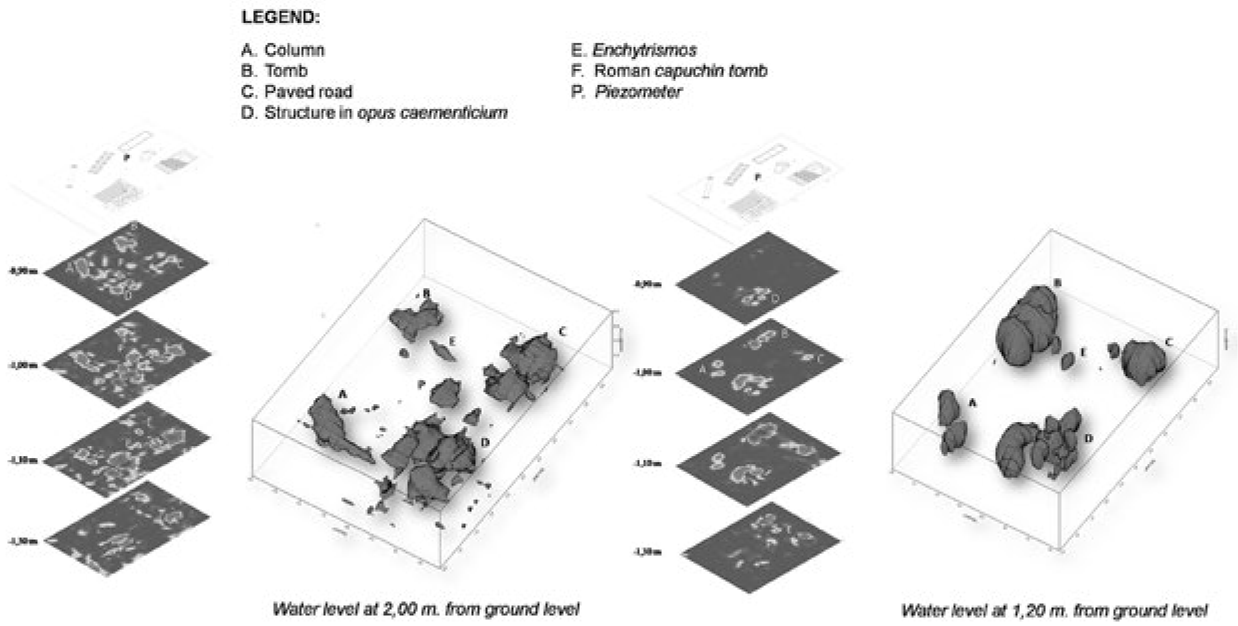

FIG. 4. TIME SLICES AND RENDERING 3D DATA.

3000 coupling to the antenna with a central band frequency of 400 MHz. The collected data were processed and displayed using the software ReflexW.

Figure 4 shows the GPR results obtained with two different piezometric levels of the groundwater (2 m and 1.2 m below ground surface). Moreover, the results are shown as time slices and 3D visualization, where only the main reflections are highlighted. The two images show very clearly the reflections due to the archaeological buried target. Furthermore, it can be observed that the variation of the groundwater surface affects the EM reflection of the archaeological targets

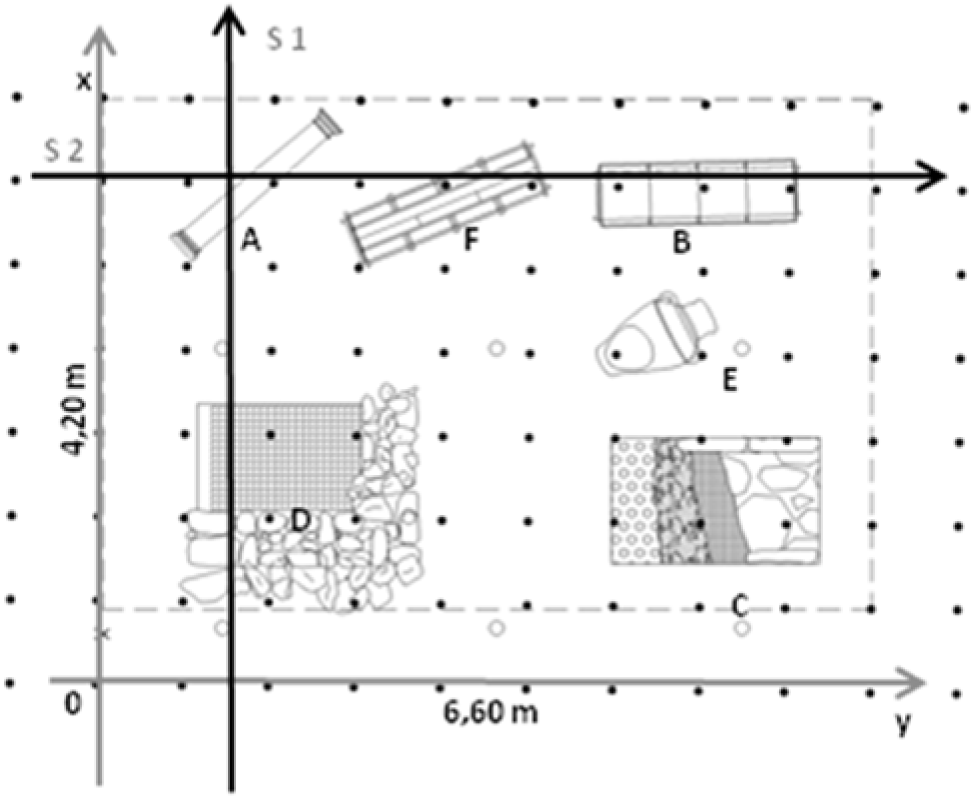

Fig. 5. Sketch with the location of electrodes for 3D ERT acquisitions (black circles on the map) and 2D ERT survey lines (black arrows labelled as S1 and S2).

causing both an increase of the EM signal attenuation and a slowdown of the propagation velocity of the EM waves. The different electromagnetic responses are related to the changes of the physical properties of the soil, in particular dielectric permittivity and electrical conductivity, due to the variations of the water content of the sand (Fig. 4).

4 Geoelectrical investigations

A 3D geoelectrical survey was carried out in the archaeological test site. A grid of 96 steel electrodes distributed over an area 7 x 4 m with a mesh of size 0.60 x 0.60 m was defined (Fig. 5). The electrodes were connected to a georesistivimeter Syscal Pro Switch 96 of Iris Instruments. This grid ensured coverage of the entire area to be investigated, acquiring 2D and 3D resistivity data. Moreover, different kinds of arrays were deployed: Dipole–Dipole, Dipole–Dipole Equatorial, Wenner-Schlumberger, and the Cross-Diagonal Pole–Pole. All the acquisitions were performed over a number of different stages, corresponding to the varying groundwater levels.

Figure 6 shows the Dipole–Dipole Equatorial resistivity results with a piezometric level placed at about 0.5 m from the surface. The apparent resistivity acquired data were inverted by RES3Dinv (Geotomo software) and the 3D images were visualized by Voxler software (Golden Software). Thanks to the presence of water, the 3D ERT showed low resistivity values distributed in all the investigated soil volume; nevertheless, it is possible to observe an increase of the resistivity values in depth, between 0.5 and 1.50 m, corresponding to the portion of soil relevant to the archaeological remains.

In order to improve the archaeo-geophysical interpretation, 2D ERTS were also acquired along two lines and the results were compared to GPR data. Figure 7 shows the comparison between the same profiles S1 and S2. Profile S1 intercepts the column (A) and the wall (D) while profile S2 intercepts the column and two of the three burials (A, F, and B). The results of S1 highlight a concurrence between GPR and ERT anomalies related to the presence of the column (A) and the wall (D). Along S2, relative resistive values are observed where strong reflections are defined along the radargram due to the column (A) and the burial features (B).

5 Conclusions

The geophysical techniques applied are a huge contribution to archaeological research, due to their capability of detecting a buried target before excavation. Indeed, the use of geophysical methods in archaeology has recently increased in order to improve knowledge of a site investigation. Nevertheless the geophysical approach cannot be considered as a magic wand that can solve problems for the archaeologist, such as the individuation of a site or the definition of its shape and dimension; false interpretations of the geophysical data on an archaeological target are, in fact, quite common.

In order to assess the capability of geophysical techniques to detect archaeological remains placed in humid or water-saturated subsoil, a buried archaeological site was simulated under real environmental conditions and was investigated by the geophysical techniques GPR and ERT. The experiment highlighted the complex relationship between the physical

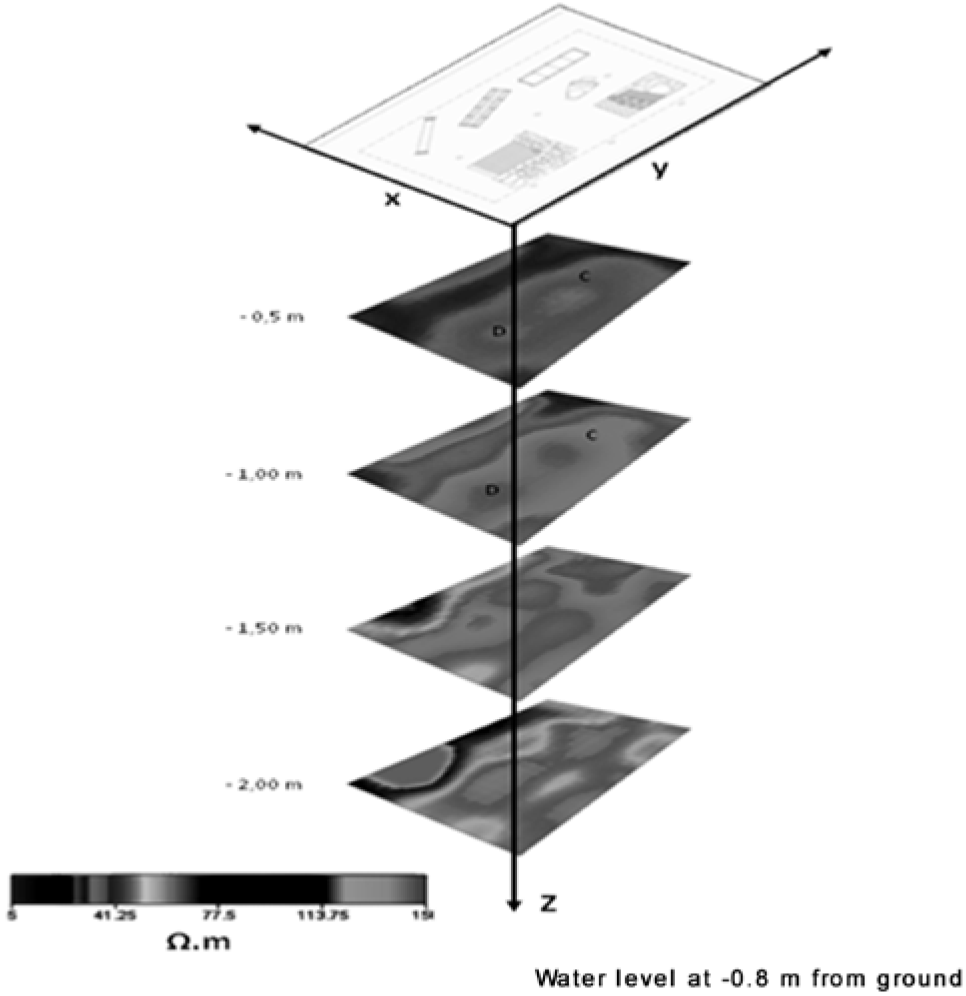

FIG. 6. 3D ELECTRICAL RESISTIVITY IMAGE AT DIFFERENT DEPTHS (DEPTH SLICES).

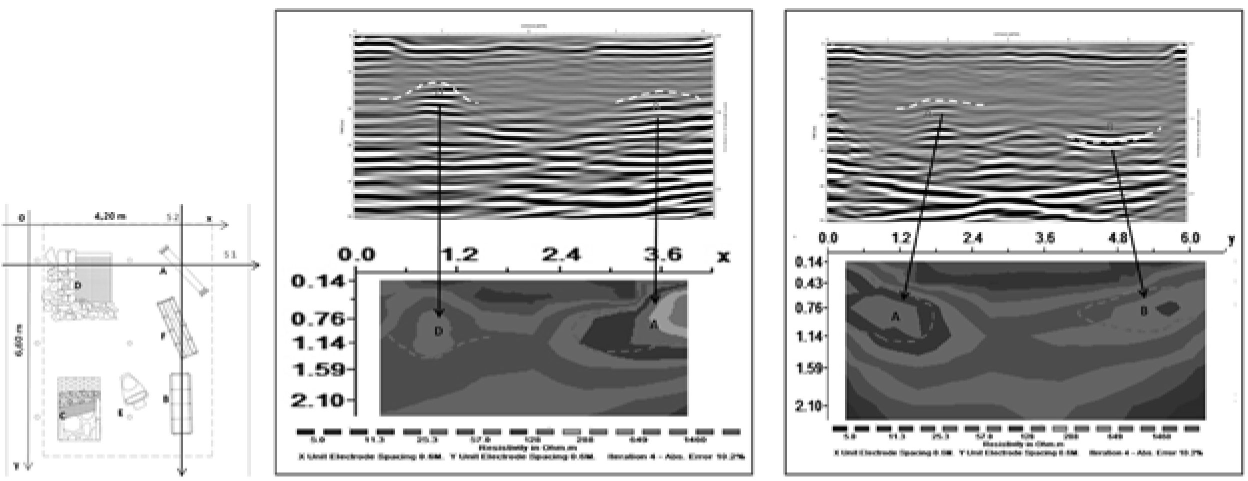

FIG. 7. COMPARISON BETWEEN GPR DATA AND RESISTIVITY DATA ACQUIRED ALONG THE SAME PROFILES S1AND S2.

characteristics of the target and the geophysical responses. From the experiment it was possible to note that the characteristics of the objects (shape, size, and material) have a strong influence on the capability of geophysics to discover them. From a condition of an absence of water to a condition of saturation, GPR data show the geometries of buried targets in detail, but they then disappear. This situation is caused by a strong attenuation of the electromagnetic signal due an increase of the conductive behaviour of the soil. Under the same situation the ERT survey provides better results under saturation conditions, reaching a great depth. Moreover, the larger or smaller spacing between electrodes strongly influences the larger or smaller depth-screening power of ERTs.

The lower resolution of the ERT did not enable a definition of the geometric characteristics of the remains. In this scenario an improvement of the results in term of detecting the geometry could be obtained with an integrated approach that combines GPR and ERT information.

Acknowledgements

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Bibliography

Adam, J. P. 1988. *L’arte di costruire presso i romani*. Milano.

Böniger, U., Tronicke, J. 2009. Integrated Remote Sensing Techniques Für Archaeological Prospection. *Archaeological prospection*, Wiley.

Caleca, L. 2000. *Architettura tecnica*. Flaccovio editore.

Cammarano, F., Mauriello, P., Patella, D. and Piro, S. 1997a. Integrated geophysical methods for archaeological prospecting. In Cortini, M. and De Vivo, B. (eds.), *Volcanism and Archaeology of the Mediterranean Area*. Trivandrum, India, Research Signpost.

Cammarano, F., Mauriello, P., Patella, D. and Piro S 1997b. Geophysical methods for archaeological prospecting: a review. *Science and Technology for Cultural Heritage* 6, 2: 151-73.

Cammarano, F., Mauriello, P., Patella, D., Piro S., Rosso, F. and Versino, L. 1998a. Integration of high resolution geophysical methods. Detection of shallow depth bodies of archaeological interest. *Annali di Geofisica* 41, 3: 359-68.

Cammarano, F., Mauriello, P. and Piro, S. 1998b. High resolution geophysical prospecting with integrated methods. The case of ancient Acropolis of Veio (Rome, Italy). *Archaeological Prospecting* 4: 157-64.

Campana, S., Piro, S. 2009. *Seeing the unseen – Geophysics and landscape archaeology*. London, CRC Press.

Cavalieri, M., Pace, G. 2011. Metodologie geofisiche a confronto presso la villa tardoantica di Aiano-Torraccia di Chiusi (Siena): qualche nota su efficacia e limiti. *Archeologia e calcolatori 22*: 283-306.

Cuomo,V., Fiore, S., Lapenna, V. and Rizzo, E. 2005. HYDROGEOSITE: nuovo laboratorio a grande scala per applicazioni geofisiche ambientali. In *Atti del 24° Convegno Nazionale del GNGTS, Roma, 15-17 November 2005*.

De Domenico, D., Giannino, F., Leucci, G., Bottari, C. 2006. Integrated geophysical surveys at the archaeological site of Tindari (Sicily, Italy). *Journal of Archaeological Science* 33: 961-70.

Gabrielli, R., Piro, S. 2009. Multimethodological approach to investigate chamber tombs in the Sabine Necropolis at Colle del Forno (CNR, Rome, Italy). *Archaeological Prospection* 16: 1-14.

Giardino, L. 1983. *La viabilità nel territorio di Grumentum in età repubblicana ed imperiale*. In AA.VV., *Studi in onore di D. Adamesteanu*: 195-217. Galatina.

Giardino, L., De Siena, A. 1999. *La costa ionica dall’età del ferro alla fondazione delle colonie: forme e sviluppi insediativi*. In Barra Bagnasco, M., De Miro, E., Pinzone, A. (eds.), *Magna Grecia e Sicilia. Stato degli studi e prospettive di ricerca*: 23-38. Messina.

Giavarini, C., Ferretti, A. S., Santarelli, M. L. 2006. Mechanical characteristic of roman ‘opus caementicium’. In Kourkoulis, S. K. (ed.), *Fracture and Failure of Natural Building Stones*: 107-20. Springer.

Giovannoni, G. 1925. *La tecnica delle costruzioni presso i romani*. Roma.

Giuffrè, A. 1999. *Letture sulla meccanica delle murature storiche*. Roma.

Giuliani, C. F. 2006. *L’edilizia nell’antichità*. Roma.

Giuliani, C. F., Ferretti, A. S. 1997. Opus cementicium. Il materiale e la tecnica costruttiva. Atti del seminario (Roma, facoltà di Ingegneria, 11 june 1997). In *Materie e Strutture* 2-3. Roma, L’Erma di Bretschneider.

Goodman, D., Piro, S. 2013. *GPR remote sensing in archaeology*. London, Springer.

Gualtieri, M. 2009. *La romanizzazione del territorio: Grumentum e l’alta Val d’Agri nel contesto della Lucania romana*. In Mastrocinque, A. (ed.), *Grumentum Romana. Atti del convegno di studi, Grumento Nova, 28-29 june 2008*: 217-33. Moliterno.

Le Pera, S. 1999. *Come costruivano gli antichi romani: brevi note di tecnica edilizia*. Roma.

Lugli, G. 1957. *La tecnica edilizia romana*. Roma, Bardi ed.

Orlando, L. 2013. GPR to constrain ERT data inversion in cavity searching: Theoretical and practical applications in archeology. *Journal of Applied Geophysics* 89: 35–47.

Orlando, L. 2015. Characterization of a pre-Trajan wall by integrated geophysical methods. *Archaeological prospection* 07/2015, 22(3): 221-32.

Rizzo, E., Chianese, D., Lapenna, V. 2005. Integration of magnetometric, GPR and geoelectric measurements applied to the archaeological site of Viggiano (Southern Italy, Agri Valley-Basilicata). *Near Surface Geophysics* 3: 13-9.

Rocchetti, D. 2002 *Aree sepolcrali a Metaponto*. Available from: http://consiglio.basilicata.it/consiglioinforma/files/docs/10/15/42/DOCUMENT_FILE_101542.pdf

Russo, A., Gargano, M. P., Di Giuseppe, H. 2007. Dalla villa dei Bruttii Praesentes alla proprietà imperiale. Il complesso archeologico di Marsicovetere - Barricelle (PZ). *Siris* 8: 81-119.

Sambuelli, L., Socco, L. V., Brecciaroli, L. 1999. Acquisition and processing of electric, magnetic and GPR data on a Roman site (Victimulae, Salussola, Biella). *Journal of Applied Geophysics* 41: 189–204.

Sarris, A., Jones, R. 2000. Geophysical and related techniques applied to archaeological survey in the Mediterranean: a review. *Journal of Mediterranean Archaeology* 13, 1: 3–75.

Tarlano, F. 2009. Il territorio grumentino e la Valle dell'Agri nell'antichità. In *Atti della giornata di studi Grumento Nova, Potenza. 25 Aprile 2009*. Bologna 2010.

Tarlano, F. 2010. Note sulla via Herculia e la viabilità nella zona di Grumentum. In Quilici, L., Quilici Gigli S. (ed.), *Atlante Tematico di Topografia Antica*. *ATTA* 20: 79-101.

Tarlano, F. 2013. Alcune riflessioni sul rapporto tra geomorfologia e popolamento in alta Val d'Agri tra la romanizzazione e l'alto medioevo. In Mastrocinque, A. (ed.), *Grumentum e il suo territorio nell'antichità*: 233-40. British Archaeological Reports Internetional Series. Oxford, Archaeopress.

Tarlano, F. 2014. Le aree interne della Basilicata meridionale tra mondo lucano e romanizzazione: l'alta valle dell'Agri. In Dall'Aglio, P. L., Franceschelli, C., Maganzani. L. (eds*.), Atti del IV Convegno Internazionale di Studi Veleiati*: 285-98. Bologna.

Colour and Space in Cultural Heritage in 6Ds: the Interdisciplinary Connections

Anna Bentkowska-Kafel
anna.bentkowska@kcl.ac.uk
Department of Digital Humanities, King's College London, UK,

Julio M. del Hoyo Melendez
jdelhoyo@muzeum.krakow.pl
Laboratory of Analysis and Non-Destructive Investigation of Heritage Objects,
National Museum Kraków, Poland

Lindsay W. MacDonald
lindsay.macdonald@ucl.ac.uk
3DIMPact Research Group, Faculty of Engineering, University College London, UK

Aurore Mathys
aurore.mathys@africamuseum.be
Scientific Heritage, Royal Belgian Museum of Natural Sciences, Brussels and Collection Management,
Royal Museum of Central Africa, Tervuren, Belgium,

Vera Moitinho de Almeida
veramoitinho@gmail.com
Science and Technology in Archaeology Research Center (STARC),
The Cyprus Institute, Cyprus

Abstract: Documentation of material cultural heritage is a core common interest to the participants of the network 'Colour and Space in Cultural Heritage' (www.COSCH.info), supported by the European Cooperation in Science and Technology (COST) between 2012 and 2016. Although COSCH is a trans-domain Action in Materials, Physics and Nanosciences (TD1201) many of the over 200 participants are not scientists. Perspectives on the material cultural object are many within this diverse, interdisciplinary group. Despite this kind of collaborative research being well established, defining research questions of common interest and basic terms of communication is far from easy. This paper shares some observations drawn upon the COSCH experience and looks at the issues of colour and space in cultural heritage in six dimensions: disciplines and digital technology involved, data, documentation, development, and diffusion. To highlight the danger of assumed understanding, the term 'dimensions' is used here both as a mathematical term, indicating results of measurement, as well as figuratively, as a multitude of perspectives or views. The paper introduces a case study of ancient Roman coins, being undertaken by a group of ten researchers from different academic institutions, museums, and scientific laboratories in eight countries. The novelty of this exploratory study lies in the breadth of approaches and examination methods, applied to the same objects for effective comparison and evaluation. The paper does not present the results of the study, still in progress at the time of writing. The authors aim instead to highlight the challenge of articulating and understanding the multiplicity of interdisciplinary questions involved.

Keywords: Cultural heritage, Documentation, Digital technology, Interdisciplinarity

1 Background

In 2014 a group of researchers involved in the network 'Colour and Space in Cultural Heritage' (www.COSCH.info) undertook to conduct a two-year study with the aim of testing and comparing a number of specialist digital recording techniques, by applying them to specific heritage objects, namely silver coins believed to be ancient Roman. The project is one of seven case studies of material culture being conducted within the COSCH framework. Reflecting on the experience gained in the course of the exploratory examination and recording of Roman silver coins (in progress), the authors note some key areas of this collaborative interdisciplinary study and communication that often demand stepping outside one's own discipline in order to gain an unfamiliar understanding of a familiar concept. The recognition of this need is critical for the success of the study and promises results that are transparent and useful to different end users. Concepts as common as data and documentation have different meanings to different stakeholders. No meaning should be taken for granted; otherwise effective communication is at risk.

The test objects for this study were two silver denarii (coins A and B) portraying Empress Faustina I, wife of Antoninus Pius, believed to be posthumous deification issues of AD 141. The obverse of both coins shows the bust of the empress, facing right, with the raised inscription DIVΛ FΛUSTINΛ. The portrayal on coin A (Fig. 1) is rather more flattering to a lady who was famous for her beauty. The designs on the reverse are different: coin A shows Aeternitas (or perhaps Urania) holding a globe in her right hand, with the palla billowing out around her head, and is inscribed ΛETER-NITΛS; coin B shows Vesta,

Fig. 1. Visualization of obverse of coin A through the Hewlett-Packard PTM viewer software, with virtual light source at left, in specular enhancement mode. (Lindsay MacDonald 2015).

holding the palladium in her right hand and the sceptre in the left, and is inscribed VES-TΛ. Each coin is approximately 17 mm in diameter and 1.5 mm in thickness. The two coins were specifically chosen for study in a network of laboratories across Europe, as part of the COSCH programme, to establish how well various 3D recording methods can support the analysis and comparison of features and properties.

The COSCH case study presented here involves research that aims to:

- Assess how numismatics are currently documented and presented to both specialists and the public;
- Determine access to 3D spatial and spectral techniques; how such techniques are used in current museum practice; assess the interest in their wider adoption;
- Determine the best possible approach to scientific documentation of coins using selected spectral and spatial techniques; review and evaluate earlier research in this area;
- Apply a range of non-invasive techniques to record silver coins and evaluate the results;
- Test possible techniques for 3D visualisation and presentation of multimodal results with metadata and paradata;
- Establish what kind of research questions and conservation needs may be supported by the methods and techniques used;
- Conduct targeted consultation to assess the study and evaluate its results;
- Disseminate the results; and
- Identify questions for future research.

2 Disciplines

COSCH is a trans-domain Action in Materials, Physics and Nanosciences (TD1201) supported by the European programme for Cooperation in Science and Technology (COST). Many participants are heritage scientists specializing in optical, spatial, and spectral measurement techniques. Conservators and other museum professionals, archaeologists, academic art historians, and digital humanities scholars also participate in this COST Action. The coin study benefits from access to the latest technology and world-class expertise, as well as valuable contributions from postgraduate and post-doctoral researchers.

The study of Roman coins, like other objects of cultural heritage, requires wide-ranging expertise. The number of original proposers of the study has since been augmented by other colleagues, each expressing interest in a particular aspect of research. The study requires involvement of many scientific and non-scientific disciplines, including:

- Archaeology (numismatics)
- Art History (numismatics)
- Archaeometallurgy
- Chemistry
- Conservation
- Documentation, archiving and digital preservation
- Education
- Engineering

- Metrology
- Museology
- Optoelectronics
- Photography, imaging, and visualization
- Photonics
- Physics

Numismatic interests provide the background to the case study, which aims to define the value of what other disciplines can bring. Every discipline has its discrete canons, which are continually redefined through interdisciplinary collaboration. The issue for interdisciplinary projects is that although they bring together multiple disciplines, with an additive effect, they are also pulling in different directions in what each wants out of the project, which may not be additive. Each discipline has different motives for research, methods of investigation, measures of quality, metrics of assessment, means of documentation, and standards. Traditionally, the tendency is to set science and technology apart from the arts and humanities. The goal of this particular interdisciplinary collaboration is to be able to reduce these gaps in communication and knowledge. This is a challenge, but science can be successfully communicated to non-specialists if the benefits are explained.

Numismatic research in the past has typically consisted of stylistic and/or compositional studies conducted by specialists with art historical and natural science backgrounds, respectively, as shown in a study of a representative group of Polish medieval coins issued by the rulers of the House of Piast at the turn of the 10th century. For instance, Buko (2007) and Suchodolski (1967) discussed these coins in their archaeological, historical, and stylistic contexts, while compositional studies of a group of related coins were conducted in parallel (Młodecka 2010). More recently, research efforts have focused on the correlation of archaeological and chemical data. Expert groups of diverse and complementary specialist backgrounds have been set up. Although current research trends indicate the need for interdisciplinary work in this field, initiatives similar in scope to the present project are still very limited. An innovative aspect of this wide-ranging study is the use of optical recording in conjunction with analytical physico-chemical techniques to support the archaeological and historical records. The present study has compiled a bibliography of a significant body of earlier research and will make it widely available.

3 Digital Technology

The methodological shift resulting from widespread use of digital technologies has affected all disciplines, bringing them closer and facilitating interdisciplinary research. The present study supports this argument. Data in digital formats are open to reuse and a wide range of applications and enhancements. Digital technology also facilitates collaboration that would otherwise be difficult, if not impossible. The range of technologies involved in the COSCH coin study is broad. They include:

- Depth sensing
- Digital microscopy
- IR reflectography
- Laser scanning
- Multiband/multispectral imaging
- Photography
- Photostacking
- Polynomial texture mapping (PTM) with dome illumination
- Reflectance transformation imaging (RTI)
- Scanning electron microscopy (SEM)
- Structure from Motion (SfM)/Photogrammetry
- Structured light scanning
- Survey drawing vectorization
- UV fluorescence
- X-ray fluorescence (XRF)
- X-ray spectroscopy (XRS)
- X-ray microtomography

The coin study benefits from access to the latest technology and world-class expertise, as well as valuable contributions from researchers at an early stage of their careers. The coins are interesting objects for this kind of multimodal investigation, as well as a convenient and practical choice for shipping from one European laboratory to another.

4 Data

All research deals with data, but the term 'data' is relatively new to the terminology and epistemology of arts and humanities. The coins used in the present study are a source of historical and social information. In art studies it has traditionally been assumed that 'data' are obtained through scientific work, for example in the course of the examination of artworks. This is made clear in the title of the article 'Beyond a Collection of Data: What We Can Learn from Documentary Sources on Artists' Materials and Techniques' (Carlyle 1995), in which information contained within text documents is not considered as data. Digitization has radically changed this situation. 'Data' have become more diverse and of interest to non-scientists: in interdisciplinary cultural heritage studies, an object may be represented through distinct types of data, including digital data, metadata, and paradata. What these data entail, however, is understood differently depending on a field of study. Consequently, an approach based on a range of datum types and formats has been adopted for the current case study, including:

- 2D/3D object data
- Digital/non-digital data

- Input/output data
- Metadata
- Missing data
- Numerical/textual/symbolic data
- Paradata
- Pre-/post-processed data
- Qualitative/quantitative data
- Raw (captured)/analysed/interpreted data
- Reference data

Different technologies tend to require distinct methods and/or techniques. Even for the same technology, different methods and/or techniques may generate distinct data. One of the objectives of the study is to present in detail the particular workflows for each different method and technique from data acquisition to data post-processing and analysis. It is proving difficult to locate established ways of recording such complex workflows. Much effort is therefore being put into agreeing the scope and granularity of metadata (i.e. data about the data content) and paradata (i.e. data about the process of survey data collection, processing, and analysis), as well as an effective format for their presentation. An Excel spreadsheet is a starting point (Fig. 2).

There is a challenge of standardization of policies and strategies for long-term digital preservation and access to 3D digital data (DCMI 1995; CIDOC-CRM 2006; 3D-COFORM 2009; London Charter 2009; CARARE 2012; 3D ICONS 2014). Metadata and paradata (Couper 1998) can provide more insight into the models and connected files, by overlaying them with increasingly meaningful information. One should bear in mind that 'scientific data cannot be understood without knowledge about the meaning of the data and the ways and circumstances of their creation' (Doerr and Theodoridou 2011: 1; Doerr *et al*. 2014). The procedure for creating the final dataset of all the generated digital files associated with each object is partially ensured by following specific international recommendations. The present study is informed by the 3D-COFORM (2009) recommendations in conjunction with CARARE (2012), TDAR (2009), English Heritage/Historic England (Barber and Mills 2011), GMV (2011), and Europeana (2013) schema and data fields. In the near future the intention is to map our dataset to CIDOC-CRM (2006), which takes into account additional requirements for semantic element description, relationship, and linkage of cultural heritage objects.

In this case study, metadata and paradata are meant to:

- be useful for the transparency, reproducibility, and reusability of both our work and data;
- enable comparison and evaluation of results within and between methods and techniques for recording silver coins;
- be useful for producing guidelines for good documentation practice;

Roman silver coins — XRF (X-ray fluorescence spectrometry)

Inventory No.	Survey date	Institution author	Survey location	Survey location characteristics	Survey type	Hardware portability	Hardware	Software	Parameters of measurement
COIN A	01/12/2014	Julio del Hoyo	The National Museum in Kraków	Laboratory	Invasive / Non-invasive	Yes / No	Artax 800 (Bruker)	Spectra 5.3 (Bruker)	voltage 45 kV; current 500 uA; time 30 s; step size 1mm
COIN B	01/12/2014	Julio del Hoyo	The National Museum in Kraków		Invasive / Non-invasive	Yes / No	Artax 800 (Bruker)	Spectra 5.3 (Bruker)	voltage 45 kV; current 500 uA; time 30 s; step size 1mm

EDX (energy-dispersive X-ray spectroscopy)

Inventory No.	Survey date	Institution author	Survey location	Survey type	Hardware portability	Voltage	Hardware	Software	Parameters of measurement
COIN A	01/11/2014	Miroslav Hain	Institute of Measurement Science, Slovak Academy of …	Invasive / Non-invasive	Yes / No				
COIN B	01/11/2014	Miroslav Hain	Institute of Measurement Science, Slovak Academy of …	Invasive / Non-invasive	Yes / No				

microCT (X-ray microtomography m…

Inventory No.	Survey date	Institution author	Survey location	Survey type	Hardware portability	Hardware
COIN A	01/10/2014	Miroslav Hain	Institute of Measurement Science, Slovak Academy of …	Invasive / Non-invasive	Yes / No	Phoenix Nanotom 180 (GE)
COIN B	01/10/2014	Miroslav Hain	Institute of Measurement Science, Slovak Academy of …	Invasive / Non-invasive	Yes / No	Phoenix Nanotom 180 (GE)

Fig. 2. Preliminary record of coin measurements (detail of a screenshot). (Originated by Vera Moitinho de Almeida, COSCH Coin Study, 2014–16).

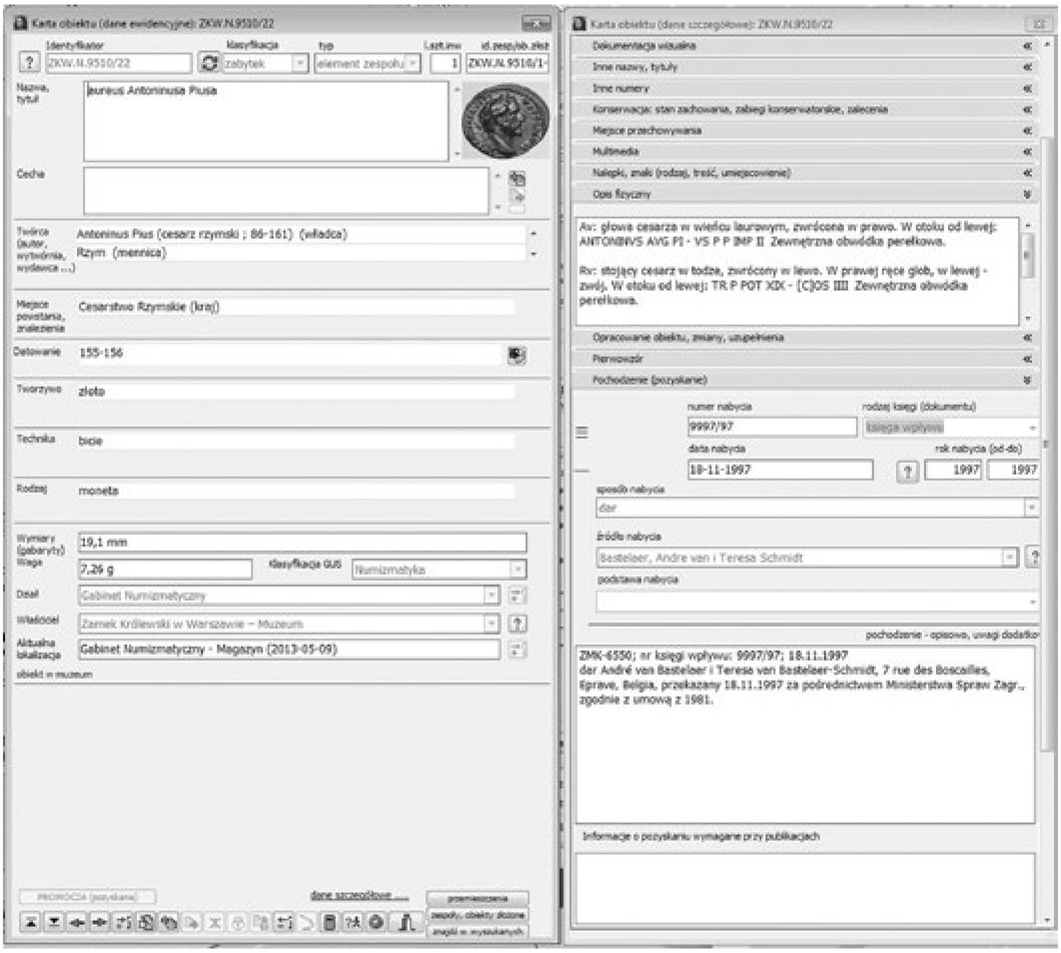

Fig. 3. Example of a typical museum record of a coin. Aureus of Antonius Pius, Rome 155–156. Royal Castle, Warsaw. (Reproduced by kind permission).

- test possible techniques for 3D visualization and presentation of multimodal results with meta- and paradata;
- be submitted to the COSCH Knowledge Representation App. (see section 'Diffusion', below)

Professionals from diverse areas are interested in discussing and comparing their results with the aim of making adequate qualitative and quantitative interpretations of the data. This joint approach will serve to understand the advantages and limitations of each technique at the time of assessing different geometrical, physical, and chemical properties of the coins that can provide insights in terms of their manufacturing, provenance, and authenticity. These results will constitute the first step towards the creation of a database that, in conjunction with published works on similar coins and reference data therein, could help to discriminate a genuine coin from a forged one, among other issues.

5 Documentation

Documentation is a process of collecting information and making it accessible. Alongside the generic understanding of documentation as documentary evidence, each of the disciplines represented in the COSCH study of Roman coins has a particular understanding of its scope, formats, and how they originate. It is not unusual for scientific discourse to refer to the datasets resulting from 3D measurements as 'documentation', for example in the context of structured-light and laser scanning applications (Mara *et al.* 2007; Faro 2015). Documentation of material cultural heritage includes archaeological, historical, and conservation records and is particularly complex. The intangible aspects of material culture — to do with its original purpose and ownership, subsequent transformations, and use — are important yet often not possible to record adequately. Examination of physical and chemical properties, however, may offer invaluable insights into an object's provenance and use, not just its current condition.

Mara *et al*. (2007: 1) noted the persistent use of manual drawing 'to document archaeological finds' and 'to abstract them [coins] from photographs'. The standard object record established through age-long museum practice has also changed little in recent decades, and even with the latest technology the object records in databases tend to follow traditional models. Whether still recorded on a paper index card or in a collection database, the museum object record consists of information about its type, subject and meaning, provenance (together with the accession number), materials and techniques (Fig. 3). The object is described and a visual record, typically a photograph, is included. There are still collections throughout Europe, both large and small, that have not been fully

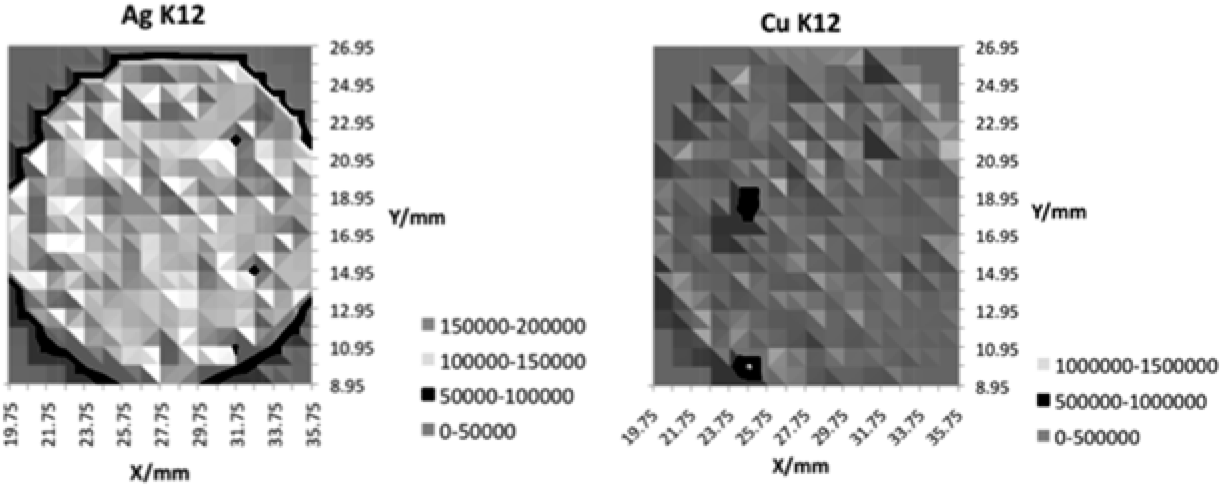

Fig. 4. XRF maps obtained for silver (Ag) and copper (Cu). The legends indicate the net peak area ranges obtained after deconvolution of the spectra. (Julio M. del Hoyo Melendez 2015).

catalogued and photographed for lack of adequate resources. Sometimes dimensions are only approximate, based on hand measurements. If the object underwent conservation the results of examination and description of treatment would be held by the conservation lab and would not necessarily be included with the main object record.

Image-based numismatic studies and resources that include 3D visual records of coins are widely available (Hedrich *et al.* 2010; Athens 3D 2012; Huber-Mörk 2013; Kavelar *et al.* 2014), but few follow a multi-method approach that involves the use of advanced spatial and spectral techniques. Given adequate resources and know-how, it is now technically possible for museums to augment traditional documentation (Zambanini *et al.* 2009) with state-of-the-art spatial and spectral information. The authors believe that comprehensive documentation requires this complementarity of scientific data and historical or other descriptive information about the object. For example, techniques involving X-rays can provide a new dimension to the documentation of coins, giving information about the specific location of chemical elements. An initial approach involves chemical mapping through the use of XRF spectrometry and SEM with EDS microanalysis. A comparison of the data generated by these two techniques allows a full understanding of the surface properties of a coin. These maps can be complementary to other forms of documentation and will definitely serve to expand the diversity of description. X-ray fluorescence maps obtained for one of the coins used in the present COSCH study show the surface distribution of two elements, silver and copper (Fig. 4). The colour scale provides a way of comparing the net peak areas obtained for each element, allowing to visualize its distribution over the evaluated surface. Micro XRF analyses were conducted using a Bruker (Karlsruhe, Germany) Artax 800 spectrometer equipped with an Rh tube and a polycapillary lens that provides a spatial resolution of about 80 μm. The X–ray generator was operated at 45 kV and 500 μA. The acquisition time and the step size used were 30 s and 1.0 mm, respectively.

In the present COSCH study, X-ray microtomography (microCT) has also been applied, using a Nanotom 180 (GE) measuring device, to examine the inner structure of coins and assess cracks and areas of corrosion. The resulting visualization is revealing and should be considered not only as scientific conservation data, but also as part of the object's general iconography (Fig. 5).

Another technique already tested on the coins is photogrammetry (Fig. 6). This technique, arising from computational imaging, enabled reconstruction of a 3D model of the coins from a set of photographs. The equipment used for this digitization technique was an entry-level DSLR (Canon 600D) with a 100 mm macro lens. The lens was calibrated for distortion with a lens calibration utility and a white balance calibration of the camera was performed for the illumination. The coin was placed on a turntable with a homogeneous background with a scale and using a smooth lighting set-up. Successive 10° rotations giving 36 pictures were required in order to obtain a full cylindrical coverage. The pictures were processed by photogrammetry software (Agisoft Photoscan) and automatically masked to remove the smooth background, then aligned, and a point cloud was produced. The different views were aligned and merged and a dense point cloud and mesh were generated for the full model of the coin.

Another technique employed for the coins was reflectance transform imaging (RTI) (Earl *et al*. 2010, Kotoula and Kyranoudi 2013). Each coin was placed in a hemispherical illumination device (dome) and imaged by a Nikon D200 camera with a 200mm macro lens, giving a surface resolution of 75.3 points/mm (i.e. each pixel covers 13.3 μm on the surface of the coin). A set of 64 images was captured, each illuminated by a flashlight from a different direction. A polynomial texture map (PTM) representation was constructed by the fitter software originally developed at Hewlett Packard (Malzbender *et al.* 2001), enabling interactive display of the coin as if illuminated by a virtual light source. Positioning of the virtual light source may reveal surface relief or defects such as cracks, scratches, or pits that would not otherwise be visible. This is especially true in the 'specular enhancement'-rendering mode in which the specular component of reflection is amplified (Fig. 1). The observer experiences a convincing

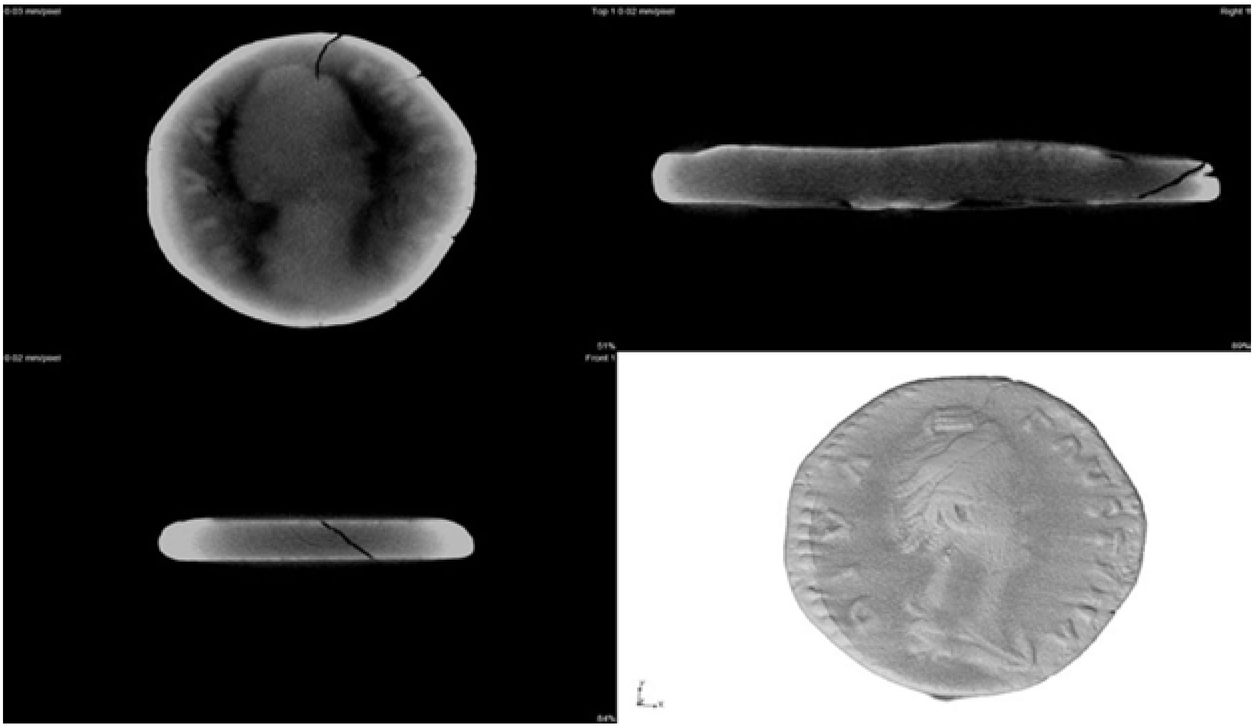

Fig. 5. MicroCT reveals cracks that are invisible to the naked eye. (Miroslav Hain 2015).

Fig. 6. Photogrammetry model of one coin, with texture on the left, without texture on the right. (Aurore Mathys *et al*. 2013).

illusion of 3D although in fact there is no underlying 3D data structure, only an approximation of how the intensity of each pixel varies with the angle of incident light. An important aspect of multi-illumination methods is that because all images are in pixel register, the representation contains much more information than a single image about the shape and properties of the object surface, and can be processed in various ways (MacDonald 2015).

The different types of data and file formats used in the study need to be aggregated before the results can be analysed and compared. An added complication is that special viewing software may be needed for each modality, for example for spatial records arising from 3D point cloud acquisition (e.g. with structured light or photogrammetry or a laser scanner) and the '2.5 D' RTI imaging techniques.

6 Development

The COSCH coin project is unconventional in its concept and development. It grew out of the initial idea of promoting the use of actual heritage objects in 3D scanning tests, rather than modern surrogates that do not expose all the intricacies of historic materials. A shiny metal coin of unconfirmed ancient (?) provenance seemed an interesting and practical choice, raising a number of scientific, historical, ethical, and legal questions (some of which are listed above). The process of applying structured light scanning and preliminary results obtained evidenced the need for further research and comparison with other methods. Expressions of interests from colleagues participating in COSCH to join such a project coincided with the Action's call for case studies in spatial and spectral documentation of cultural heritage objects. As the present study receives no funding and work is not compensated, the design of the study and schedule had to be flexible to fit within other commitments and to enable further participation and the inclusion of new methods. The work has been driven by the research interests of the participants, coupled with possibilities within their respective institutions and evaluation of current needs, as well as recognition of the value of engagement with other specialists.

Participating researchers come from several international institutions (see Acknowledgements). Each brings his or her own individual expertise and they benefit from discussing their respective working methods and ideas. As the participation of other researchers and subject specialists grows, the study may evolve into a kind of expert crowdsourcing. Each COSCH case study, however, has an expert assigned who monitors progress and offers advice. Progress is regularly reported and presented to the meetings of the COSCH network, which offers peer review. The first year of the project has been dedicated to acquisition of the data, which will be analysed, correlated, and interpreted in Year 2. User evaluation by non-specialists is envisaged later in the study.

The general workflow of recording/measuring the coin involves the interpretation of several documentation and analytical techniques:

- after acquisition by different methods, the different 3D models are compared;

- visual comparison: are the features of the coins visible on each model? Are there artefacts or noise on the model that are not present on the original object?

- alignment of models and virtual metric comparison of local/specific points;

- mapping of multispectral (or other modality) data onto the 3D model;

- interpretation of the refined representation;

- interdisciplinary evaluation of results.

Future work may involve the application of additional techniques and different ways of analysing and comparing datasets obtained in the course of the study. Many areas of this research are yet to be resolved, including the promise of direct 3D multispectral scanning; currently separate hardware and software are used to capture and process spatial and multispectral data.

7 Diffusion

'Documentation is the process of collecting and subject classifying all the records of new observations and making them available, at need, to the discoverer or the inventor' (Bradford 1948). Since this definition was proposed it has become generally accepted that the value of knowledge lies in its diffusion and debate. The COSCH coin study challenges each of the participants to communicate his or her work to other members of the group in ways that are understood to both specialist and non-specialist, clearly identifying the benefits and drawbacks of a particular approach or technique. The success of the methods adopted for the study depends on evaluation of the scientific data by a number of numismatic experts so that they can assess the value of each step.

The study aims to provide documentation of the work undertaken and offer it as an online resource and guide to good practice. One of the objectives is to develop a standard protocol for evaluating the authenticity of a coin based on results derived from several documentation and analysis techniques. The challenges here are to ensure access to reference data about coins certified to be genuine and successfully to combine multimodal results. All COSCH case studies are expected to inform the design and content of the open access COSCH Knowledge Representation App (Boochs *et al.* 2014), which is being created for heritage professionals to facilitate the choice of recording technique, depending on the type of object and other properties or conditions. A flowchart will indicate which techniques are adequate under which specific testing conditions, as well as point toward subsequent decisions based on analysis of the data. Users will have access to open source software allowing them to manipulate a dataset and interpret the results.

The authors intend to provide open access to the Roman coin data — through visualization and other presentation formats — in order to facilitate the dissemination of the results. The implications on the state of preservation of the objects under investigation and the potential changes taking place as a result of exposure to environmental elements will also be highlighted.

COSCH work in general, and the seven case studies in particular (http://www.cosch.info/web/guest/case-studies) are expected to contribute to an enhanced understanding and wider adoption of 3D spatial and spectral techniques for the recording of material cultural heritage.

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Bibliography

3D-Coform 2009. *D.2.1 – Initial version of 'User Requirement Analysis and Functional Specifications' (version 8)*. [Online] http://www.3d-coform.eu/downloads/D_2_1_User_Req_and_Fnctl_Specs_online.pdf. [Accessed: 22 June 2015].

3D Icons 2014. *Guidelines and Case Studies*. [Online] http://3dicons-project.eu/eng/Resources/D7.3-3D-ICONS-Guidelines-and-Case-Studies. [Accessed: 22 June 2015].

Athens 3D 2012. Numismatic Museum of Athens, 3D virtual gallery. [Online] http://www.nma.gr/3d2_en.htm. [Accessed: 22 June 2015].

Bradford, S. C. 1948. *Documentation,* London, Crosby Lockwood and Son.

Barber, D. and Mills, J. 2011. 3D Laser Scanning for Heritage (2nd ed.), Swindon: English Heritage. [Online] https://www.historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage2/. [Accessed: 27 June 2015].

Boochs, F., Trémeau, A., Murphy, O., Gerke, M., Lerma, J.L., Karmacharya, A. and Karaszewski, M. 2014. Towards a Knowledge Model Bridging Technologies and Applications in Cultural Heritage Documentation. In *Proceedings of the ISPRS Technical Commission V Symposium*, 23–25 June 2014, *Riva del Garda*: 81–88. Göttingen, Copernicus Publications.

Buko, A. 2007. 'Tribal' societies and the rise of early medieval trade: archaeological evidence from Polish territories (eight-tenth centuries). In Henning, J. (ed.), *Post Roman Towns, Trade and Settlement in Europe and Byzantium: The Heirs of the Roman West*, 30 *November–3 October 2004, Bad Homburg*: 431–450. Berlin, Walter de Gruyter.

Carare 2012. *CARARE Metadata schema*. [Online] http://www.carare.eu/eng/Resources/CARAREDocumentation/CARARE-metadata-schema [Accessed: 22 June 2015].

Carlyle, L. A. 1995. Beyond a Collection of Data: What We Can Learn from Documentary Sources on Artists' Materials and Techniques. In Lightweaver, C. and Hill, J. (eds.), *Proceedings of the Symposium Historical Painting Techniques, Materials, and Studio Practice, Leiden, 26–29 June 1995*: 1. Los Angeles, The Getty Conservation Institute. Available from: https://getty.edu/conservation/publications_resources/pdf_publications/pdf/historical_paintings.pdf. [Accessed: 27 June 2015].

Cidoc-CRM 2006. *The CIDOC Conceptual Reference Model*. [Online] http://www.cidoc-crm.org/. [Accessed: 26 June 2014].

Cosch 2013. Colour and Space in Cultural Heritage. [Online] http://cosch.info/home. [Accessed: 22 June 2015].

Cost, European Cooperation in Science and Technology, [Online] www.cost.eu. [Accessed: 22 June 2015].

Couper, M. 1998. Measuring Survey Quality in a CASIC Environment. In *Proceedings of the Section on Survey Research Methods of the American Statistical Association*: 41–49. Virginia, American Statistical Association.

Doerr, M. and Theodoridou, M. 2011. CRMdig: A generic digital provenance model for scientific observation. In *Proceedings of the 3rd USENIX Workshop on the Theory and Practice of Provenance (TaPP 2011), Crete, 20–21 June 2011*: 1–5. California, USENIX Association.

Available from: http://static.usenix.org/events/tapp11/tech/final_files/Doerr.pdf. [Accessed: 22 June 2015].

Doerr, M., Bekiari, C., Kritsotaki, A., Hiebel, G. and Theodoridou, M. 2014. Modelling Scientific Activities: Proposal for a global schema for integrating metadata about scientific observation. In *Proceedings of CIDOC – International Documentation Committee of ICOM: Content metadata – Administrative metadata – Technical metadata – Legal metadata (long paper) – Conference, Dresden, 6–11 September 2014, Paris*: 1–11. ICOM/CIDOC.

Available from: http://www.cidoc2014.de/images/sampledata/cidoc/papers/E-2_Bekiari_paper.pdf. [Accessed: 22 June 2015].

DUBLIN CORE METADA INITIATIVE 1995. DCMI. [Online] http://dublincore.org/. [Accessed: 22 June 2015].

Earl, G., Martinez, K. And Malzbender, T. 2010. Archaeological applications of polynomial texture mapping: analysis, conservation and representation. *Journal of Archaeological Science* 37, 8: 2040–50.

EUROPEANA 2013. *Europeana Semantic Elements Specification and Guidelines*. [Online] http://pro.europeana.eu/files/Europeana_Professional/Share_your_data/Technical_requirements/ESE_Documentation//Europeana%20Semantic%20Elements%20Specification%20and%20Guidelines%2014%20July%202013.pdf. [Accessed: 22 June 2015].

FARO 2015. 3D Documentation Conference 2015. [Online] http://www.faro.com/landingpage_eu/faro-3d-documentation-conference-2015/information. [Accessed: 22 June 2015].

GMV 2011. Geospatial Modeling and Visualization. [Online] http://gmv.cast.uark.edu/using-gmv/. [Accessed: 26 June 2014].

Hedrich, J., Paulus, D., Mäkeler, H. and Bengtsson E. 2010. Image-Based Comparison of Pre-modern Coins and Medals. In Franke, K.-H. and Nestle, R. (eds.), *Proceedings of the 16th Workshop 'Farbbildverarbeitung' 2010, 7–8 October 2010, Ilmenau*: 156–69. Ilmenau, Zentrum für Bild-und Signalverarbeitung e.V.

Huber-Mörk, R. 2013. Automatic Coin Classification and Identification. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southamptom, 26–29 March 2012*: 275–88. Amsterdam, Amsterdam University Press.

Kavelar, A., Zambanini, S., Kampel, M. 2014. Automatically Recognizing the Legends of Ancient Roman Republican Coins. In Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.), *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southamptom, 26–29 March 2012*: 241–249. Amsterdam, Amsterdam University Press.

Kotoula, E. and Kyranoudi, M. 2013. Study of Ancient Greek and Roman coins using Reflectance Transformation Imaging. *e-Conservation Magazine* 25: 74–88. Available from: http://www.e-conservationline.com/content/view/1101 [Accessed: 26 June 2015].

LONDON CHARTER 2009. *London Charter: for the computer-based visualization of Cultural Heritage (Draft 2.1)*. [Online] http://www.londoncharter.org [Accessed: 26 June 2015].

MacDonald, L. W. 2015. Representation of Cultural Objects by Image Sets with Directional Illumination. In Trémeau, A., Schettini, R. and Tominaga, S. (eds.), *Computational Color Imaging, 5th International Workshop, CCIW 2015, St. Etienne, 24–26 March 2015*: 43–56. Berlin, Springer.

Malzbender, T., Gelb, D. and Wolters, H. 2001. Polynomial Texture Maps. In *Proceedings of ACM SIGGRAPH, Los Angeles, 12–17 August 2001*: 519–528. New York, ACM SIGGRAPH.

Mara, H., Kampel, M., Niccolucci, F. and Sablatnig, R. 2007. Ancient Coins and Ceramics – 3D and 2D Documentation for preservation and retrieval of lost Heritage. In

Proceedings of the 2nd ISPRS International Workshop on 3D Virtual Reconstruction and Visualization of Complex Architectures (3DARCH), Zurich, 12–13 July 2007: 10–18. Göttingen, Copernicus Publications.

Available from: http://www.isprs.org/proceedings/XXXVI/5-W47/pdf/mara_etal.pdf˝[Accessed: 22 June 2015].

Mathys, A., Brecko, J. and Semal, P. 2013. Comparing 3D digitizing technologies: what are the differences?. In Addison, A. C., De Luca, L., Guidi, G. and Pescarin S. (eds.), *Proceedings of the Digital Heritage International Congress*, *Marseille, 28 October – 01 November 2013*: 201–4. Paris, CNRS.

Młodecka, H. 2010. Selected problems of conservation of silver coins from the gatherings of the Archaeological and Ethnographical Museum in Łódź. *Biuletyn Numizmatyczny*. 1: 63–8.

Suchodolski, S. 1967. Moneta polska w X/XI wieku. *Wiadomości Numizmatyczne* XI: 67–193.

TDAR 2009. tDAR: The Digital Archaeological Record. Digital Antiquity. [Online] http://www.tdar.org/. [Accessed: 22 June 2015].

Zambanini, S., Schlapke, M. Kampel, M. and Müller A. 2009. Historical Coins in 3D: Acquisition and Numismatic Applications. In Perlingieri, C. and Pitzalis, D. (eds.), *Proceedings of the 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, *Malta, 22–25 September 2009, Genève*: 49–52. Eurographics Association.

Integrating Low Altitude with Satellite and Airborne Aerial Images: Photogrammetric Documentation of Early Byzantine Settlements in Crete

Gianluca Cantoro[1]
gianluca.cantoro@gmail.com

Christina Tsigonaki[2]
tsigonaki@uoc.gr

Kayt Armstrong[1]
k.l.armstrong@ims.forth.gr

Apostolos Sarris[1]
asaris@ret.forthnet.gr

[1] Laboratory of Geophysical – Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranean Studies, Foundation for Research and Technology - Hellas, Rethymno, Greece
[2] University of Crete and Institute for Mediterranean Studies, Foundation for Research and Technology – Hellas, Rethymno, Greece

Abstract: The paper presents the current state of research for the DynByzCrete project ('Recapturing the Dynamics of the Early Byzantine Settlements in Crete: Old problems − New Interpretations through an Interdisciplinary Approach'), which aims to study the settlements on Crete, Greece. The project exploits the potential of imaging techniques in archaeology, such as satellite imagery, historical photographs, airborne oblique images and RPAS (Remotely Piloted Aerial Systems also known as drones or UAV, Unmanned Aerial Vehicles) low altitude photogrammetry, for the understanding of a specific chronological time-period, namely the Early Byzantine period. Indeed, the integration of all the above material, combined with traditional field survey and bibliographic search, is oriented towards a qualitative and quantitative information gathering for the GIS analysis.

The presentation of methodological aspects of the project, carried out under the framework of the Operational Programme 'EDUCATION AND LIFELONG LEARNING' (NSRF 2007-2013) and specifically the action 'ARISTEIA II', co-funded by the EU (European Social Fund) and national resources, will be the occasion for a critical approach to the specific tools used.

Keywords: Archaeological Remote Sensing, RPAS, Low altitude photogrammetry, Landscape change detection, Byzantine Crete

Introduction

Most recent archaeological projects tend to involve the study of large portions of landscapes as the place where people and the environment interact, with particular attention to the modifications to it that humans create, provoke or endure. Clearly many factors are affecting this man-landscape interaction (Tilley 1994), time and multi-stratification being just two of them. And surely a proper analysis cannot consider only geographic regional or micro-regional aspects to the neglect of social and historical factors (Gaffney and Van Leusen 1995). However, up until now the geographical factors in the settlement history of Early Byzantine Crete have gone wholly unexamined in the literature.

The focus of DynByzCrete is on the dynamics of Cretan settlements from the 4th century to the early 9th century, with a particular attention to the crisis of the 7th-8th centuries, the so-called 'Dark Ages' of Byzantium. The scientific question motivating the research concerns the identification or understanding of the reasons that caused some formerly prosperous sites on the island to disappear from the record, whilst other to persist even after the Arab occupation. This apparent 'decline' and 'collapse' of the cities as it was first formulated in the '60s, has been the object of a scientific debate in the last decades (cf. Saradi 2006). In this panorama of 'collapse' or 'transformation' of spaces and places, the island of Crete has a peculiar role as being one of the most urbanized regions of the Byzantine Empire, fully integrated in the maritime military and exploiting trade routes in the Mediterranean Sea (Tsougarakis 2011; Tsigonaki *et al*. (under publication)).

According to a widespread view, the fragmentation of the Cretan landscape, which isolate several areas, probably determined the organization of Cretan populations into several autonomous cities in antiquity, unified in the Roman period into one administration with the capital at Gortyna. Those sparse cities and major settlements, currently numbering 83 (Fig. 1), around 40 of which are identified with their historical identity, have been observed with special attention on their evolving trajectory during the crisis of the 7th-8th century and with emphasis on the involved political, social and economic factors. The modification of public spaces within the cities' boundaries during the Early Byzantine period was driven by the erection of new churches, normally wealthily decorated.

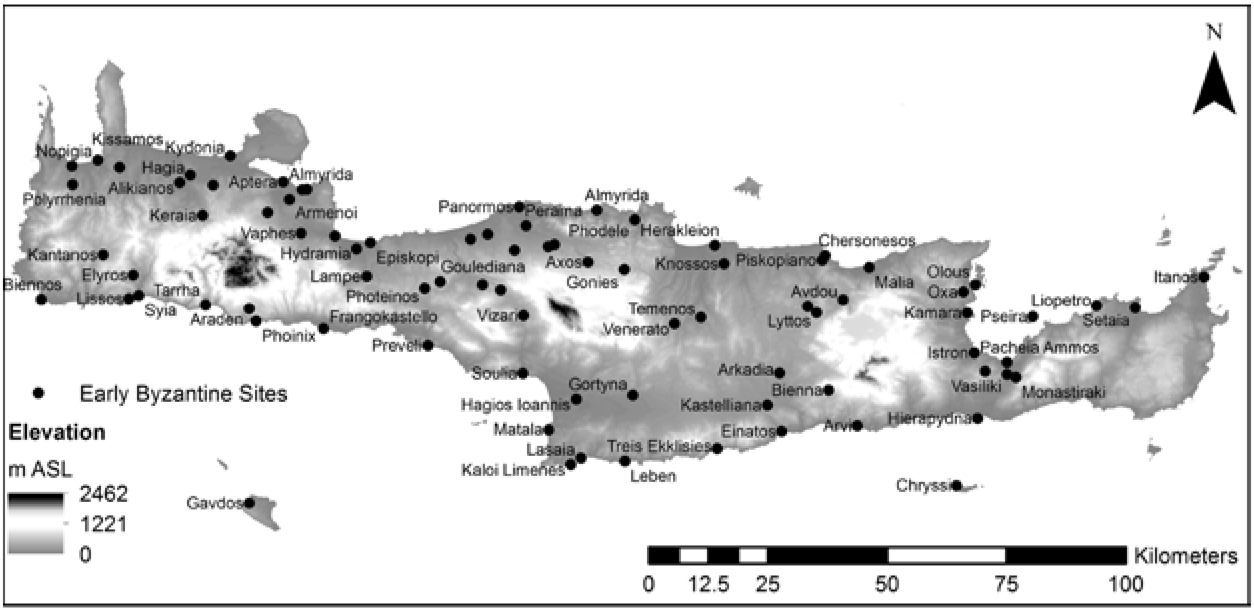

Fig. 1. Spatial distribution of the 83 sites/settlements that have been studied within the DynByzCrete project.

In this perspective, also the construction of infrastructure (fortifications, bridges and aqueducts) in the same period, does not match up with the generally argued lack of skilled labour and economic collapse (Tsigonaki 2012).

In this respect, the archaeological research topic, which is approached by DynByzCrete deals with the understanding of the degree to which the documented modification of Early Byzantine settlements is linked with geographical and geomorphological settings of their location. Furthermore, the project tries to shed light on the real chronology and function of specific infrastructure, contributing to correct dating across a uniform system of periodization and terminology.

This is where the use of new technologies in field survey becomes essential and makes a contrast with traditional approaches in Byzantine landscape archaeology.

1 Methodology

It has been argued (Cantoro and Sarris 2012) that mountainous landscapes, beside the peculiar archaeological questions related to inhospitable environments, often require a specific approach and protocol for a proper understanding. In line with this, DynByzCrete started from the creation of a relational DBMS (Data-Base Management System), where all published information on the architectural remains (fortifications, infrastructure, public and religious monuments, houses, workshops and cemeteries) could be organized and geo-tagged. When the location of features was uncertain or not clearly stated on published papers, high-precision DGPS (Differential Global Positioning System) survey was undertaken for centimetre accurate mapping of architectural structures (essential for the GIS spatial analysis).

This dataset has then been loaded into a GIS project with the addition of supplementary layers, such as coarse terrain model from the Hellenic Military Geographical Service (GYS) and thematic maps (geology, hydrology, historical maps).

Since fortifications (traditionally neglected in the study of Early Byzantine period in Crete) are considered to be the main indication of spatial re-organization of settlements during a period of insecurity, they were the main targets of the early phases of the project's topographical fieldworks. Indeed after a preliminary examination of historical aerial imagery of the selected areas, a targeted field survey was planned with differential GPS and drones equipped with digital cameras for 3D documentation and reconstruction. The examination of archive vertical photographs and satellite images was often essential in fieldwork planning. Here, areas where further investigation was needed could be outlined and pinpointed. Some persistent natural or anthropic features from historic images (collapsed buildings or field-boundaries, rock outcrops, open spaces without vegetation and so on) could also be selected as potential location for the forthcoming positioning of ground targets to be used in the photogrammetric and georeferencing processing.

Furthermore, the precise georeferencing of all aerial images (see below: AutoGR-Toolkit software) in one single system including proper archaeological photo-interpretation helped to date modern structures (visible only in recent imagery) or in the modification of the layout of standing remains. Indeed, the practice of reorganizing collapsed (sometimes historical or even archaeological) buildings to be used for temporary herd management is not uncommon in mountainous landscapes and in Crete in particular. This first data compilation from aerial and satellite imagery was then improved and integrated with targeted low-altitude photographs and photogrammetric processing.

Photogrammetry as the technique to render real objects measurable despite their distorted representation in images is quite an old discipline, paradoxically even older than photography (the first camera -as we know it- dates to 1825 and in 1851 Laussedat invented a photogrammetric device), as concepts like perspective and projective geometry date back to 1480 with the early studies of Leonardo da Vinci (for an overview on history and development of photogrammetry, see Doyle 1964; Buchanan 1993). Its digital version also has a long tradition of studies and applications, with a distinct acceleration in recent years. Indeed recently, thanks to the advent of free/affordable and easy to use amateur or professional applications, a number of scholars from various disciplines have adopted photogrammetry on large-scale artefacts in Cultural Heritage domains: vases and statues, historical buildings, arriving at the documentation of entire contemporary or historical landscapes (Cerato and Pescarin 2013).

The ease-of-use, affordability and flexibility of drones (also known as UAV, Unmanned Aerial Vehicles, or RPAS, Remotely Piloted Aerial Systems) considerably boosted the potential of low altitude aerial photography (Remondino *et al.* 2011), making it easier than ever to collect potentially endless number of overlapping photographs at variable altitude, with different light or soil conditions and for different purposes (and final ground resolution of the 3D model).

A combination of the two aforementioned hardware and software tools –the RPAS with on-board cameras and photogrammetric software for image matching, georeferencing and 3D model creation– have been exploited for the documentation and analysis of Early Byzantine settlements in Crete. In particular, historical and low altitude aerial photographs were used to:

A. refine the layout of Cretan Early-Byzantine settlements and identify further landscape elements, such as land use patterns

B. digitize the internal architectural features of them, to be used for the subsequent spatial analysis of the intra-space usage.

The combination of satellite imagery, newly acquired photographs and historical archive images aimed at highlighting differences in the physical environment and at helping to identify locations where differences may be enriched with archaeological / historical meaning. Of particular value was indeed the tracking of changes through a wide spectrum of aerial images, with different sets and scale of information derived from each involved raster object, with satellite imagery being the main source for large scale modifications and vegetation regimes notation; the historical vertical images (mainly from the fifties and afterwards) for landscape settings development across time and first coarse (the available photographic material does not allow -at the state of art- the detailed mapping of standing remains) architectural mapping; the RPAS photographic and photogrammetric session for higher detail information and three-dimensional artefact exploration and study, especially in steep-slope locations (where all other images do not provide sufficient and clear information regarding standing structures because of their nadir-view nature).

1.1 The challenges and the chosen configuration

As mentioned above, the fieldwork activities have been focused on specific features, such as the Byzantine fortifications with unclear or dubious/unconfirmed chronology. Most of these defensive structures are normally located on hilltops or in poorly accessible areas. This peculiar characteristic brought into the project some extra challenges for the complete topographic and photogrammetric documentation of built structures. Some difficulties are caused by the specific landscape, some others by the object of study. Landscapes for instance are usually unhospitable, with highly corrugated rocky surfaces, mostly covered with thick *macchia* vegetation and often with sudden and abrupt altitude differences. Beside the difficulties in reaching specific locations (especially with bulky or heavy equipment) even just for a safe take-off and landing of the drone, the geomorphology usually provokes instable flight conditions with strong wind gusts and the so called 'Venturi effect', well known to pilots operating in mountainous landscapes.

As the areas are isolated and poorly accessible, they are mostly not disturbed by agricultural activities, which in turn means also that no real field boundaries (traditionally employed in historical air-photo-interpretation) are recognizable and consequently very few existing control points can be used for 3D model and orthophoto georeferencing. The wild nature of most areas (sloping and with abrupt altitude changes, mostly covered with low bushes or high vegetation) made it often impossible to add artificial targets for the purpose of the project.

Another side effect of the thick uncultivated vegetation is that, from one side it tends to cover built structures and from the other it constantly changes the aspect of specific location, making it particularly difficult to identify the exact location of a site of interest (considering that even GPS sensors may hardly fix their 3D position). In such a case, a first integration of data is required and this is when previous aerial reconnaissance flights come to hand. In 2012, an aerial archaeological survey has been conducted in Central and Eastern Crete in an unsystematic site-oriented pathway (http://photogrammetry.ims.forth.gr/AerialRemoteSensing.php?proj=Crete). Aerial images from this survey were particularly useful to reconstruct a preliminary 3D model of the area to survey and to locate areas of interest, often not even recognizable at the resolution of freely accessible satellite images (such as the ones provided by Google, Microsoft Bing or the Hellenic Cadastre – 'Ktimatologio').

Once the first recognition of a site was made, the next phase could start, consisting of field survey with a remotely piloted aerial system and DGPS. The flight platform consisted of a custom-made DroidWorx CX4 platform (Fig. 2) equipped with DJI Wookong M navigation system and remote telemetry.

On board the RPAS, two to three cameras configurations were synchronously used. Available cameras were the GoPro Hero1 with fisheye lens, mainly used for large area coverage and as backup for the other two sensors; two similar compact mirror-less cameras - Canon PowerShot A2500 - were also employed, one in its regular (RGB) capturing format whereas the other was converted to capture Near Infrared photographs (a simple operation, for the specific and similar compact cameras, consisting in removing the standard filter from sensor stack in the lens block and replacing it with a spectrally calibrated IR sensitive one). Both Canon cameras were preferred because of their CHDK (Canon Hack Development Kit, http://chdk.wikia.com/wiki/CHDK) capabilities, a firmware update solution to

Fig. 2. The custom made RPAS platform (Droidworx CX4) in the field during the battery recharging.

extend the device configuration with specific settings and time-lapse triggering at desired intervals.

Following some experimental flights with different parameters uploaded to the flight controller and navigation system (basically flight altitude and speed, with consistent time interval for image capturing), an optimal setting was created for the autonomous flight and it was used in the following fieldwork with minor adaptations. When autonomous flight was possible using the custom-made drone, the area coverage was set to a (normally) rectangular field span of about 200 x 300 meters. The average altitude was set to 60 to 90 meters above take off point, with lower altitudes at specific conditions or for higher level of details in post-processing.

Experimental flights were also undertaken with a non-professional backup RPAS (DJI Phantom 1), with lower performance, no navigation system, reduced payload capabilities and a higher vibration rate (on average). An experimental vibration absorption device was mounted on this second flying system to counterbalance the large amount of blurry photographs due to the so called 'jello effect'. This device noticeably improved the quality of captured images, so that final outputs are averagely good (in terms of sharpness and clarity of details) despite the flight being undertaken with this auxiliary system.

A first comparison of results can be presented with respect to the chosen platforms. The specific differences identified after fieldwork concern the flight-time and actual coverage. The main difference stays in the navigation system of the two RPAS, since the Phantom1 needs to be piloted entirely in manual mode and flown in visual contact, whilst the custom-made RPAS may fly along predefined flight paths in a completely automated mode. This latter system allows better control over velocity, altitude and coverage of the vehicle through the real-time telemetric information. On the other side, the Phantom1 makes use of smaller capacity batteries (easier to transport and recharge), it is lighter and more portable and can fly for about the same length of time, although with more limited payloads.

1.2 Data processing

Regarding data processing, several software packages are currently available for photogrammetric computations, some of which are from the commercial sector and some others are free/open-source. The latter are generally more flexible and allow for a more complete control over the entire process, although they require more basic user-knowledge and integration of multi-step approaches. Commercial solutions are normally provided as a 'black-box' with all the possible output one mouse click away (Cantoro 2015). Both solutions were explored for the specific project and the resulting outputs compared. In particular, Agisoft Photoscan Professional (http://www.agisoft.com/) was preferred as commercial solution; VisualSFM (Wu 2011; Wu *et al*. 2011) with the specific modules CMVS-PMVS (Furukawa and Ponce 2010) and CMPMVS (Jancosek and Pajdla 2011) for multi-view dense reconstruction, CloudCompare (Girardeau-Montaut 2012) and Meshlab (Callieri *et al*. 2009) for the free one.

The precise georeferencing of digital models, orthophoto mosaics and single frames was achieved in several steps: one in the field and a second one in post-processing. The field activity consisted of the positioning and measuring of ground targets (when possible) at specific locations and distances to achieve specific ground resolution or simplify the georeferencing of complex surfaces. Considering the centimetric accuracy of the DGPS used for the targets' measurements, some stable features were measured as well in a wide area, so that all the available orthophotos or maps could be aligned to the best accuracy we could reach. Indeed, during the desk processing, all images were georeferenced with the use of this control points and also with the experimental use of a free software developed by the first author of this contribution, AutoGR-Toolkit (Cantoro 2012).

Besides numerous other functions, AutoGR-Toolkit allows users to georeference one given image based on another, and in a complete automation, with limited user intervention and over short timescales. This complex operation is done thanks to the use of computer vision algorithms such as SIFT, ASIFT or SURF. In the specific workflow, when the photogrammetric low-altitude model was accurately georeferenced, an orthophoto was generated and it was used as base for the improved georeferencing of other aerial/satellite material. This way the entire dataset could be precisely overlaid, with a sub-pixel accuracy derived from advanced image matching algorithms.

1.3 Selected case-studies

Veni Korphi is the modern name of a site situated on top the Veni hill, at the northern entrance of the valley of Amari (Rethymno). Various hypotheses have been put forward as to the ancient name of the location (Osmida, Phalanna), but no identification with any of the known ancient Cretan cities can be confirmed. The flat area on the hilltop is surrounded by a fortified wall. It is preserved in very poor condition. The fortification at Veni is known in the bibliography as a fortification of the Classical period. However, here the masonry indicates that parts of the wall should be dated to the Early Byzantine period, thus demonstrating the existence of an Early Byzantine settlement in central Crete, entirely unknown in the bibliography. The site seems to have been re-fortified in the Middle Byzantine

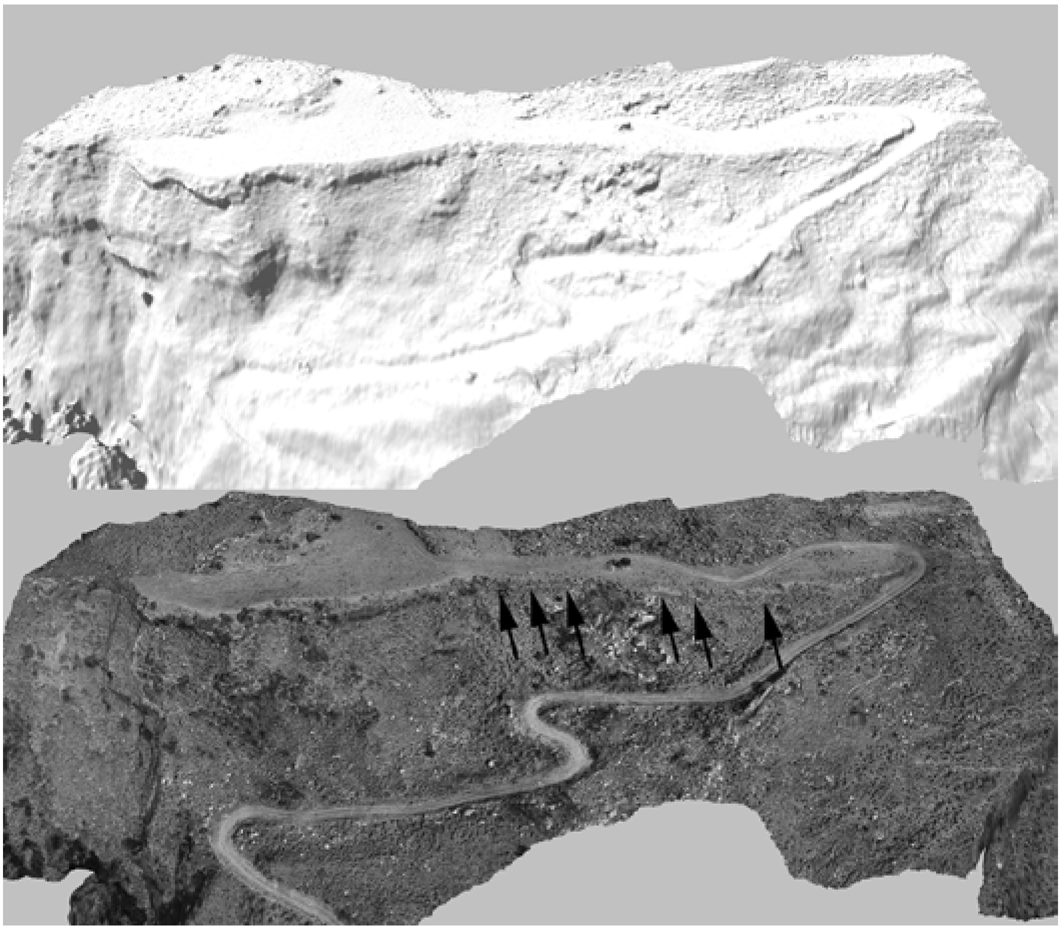

Fig. 3. Perspective view of the photogrammetric model (represented as hillshade surface and with orthophoto mosaic) of one part of the walls of the site of Veni Korphi.

period, since most of the fortification surrounding the hill can be recognized to belong to the specific period.

The digital surface model with high-resolution orthophoto (Fig. 3) was able to provide valuable information, allowing the otherwise impossible complete documentation of the most difficult and hardly accessible areas of the site. To the northern edge of the plateau the fieldwork team could see elements of fortifications but these were impossible to access and map safely with the DGPS employed for mapping accessible standing architecture. The RPAS was able to overfly this area, and from the digital model the team were able to accurately trace the fortification line, and include this in the viewshed calculations, giving important information about views over a crucial route through the upper Amari valley. Without the RPAS dataset, it would not have been possible to have enough spatial certainty of the location of the wall to generate a viewshed for this part of the site.

The viewsheds produced (Fig. 4) show that the fortified site has visual control of almost the entire hinterland of Rethymno up to the Amari area with visibility towards important Early Byzantine cities such as Syvritos. This viewshed, and the others discussed, have been created using observer locations derived from fortification structures accurately located in the RPAS datasets, with an added height specific to each case, to re-create an observer on the assumed standing height of the original structure.

The fortification at Kastelo, Varypetro is mostly known for its Middle Byzantine phase. It is situated inland, at a distance of 8km SouthWest of Kydonia (modern Chania) in a hilly terrain (Fig. 5).

An important element of the Early-Byzantine fortification is situated on the South side of the enclosure. There, a monumental tower is located with different morphological characteristics from the other towers existing on the same side. At the point where the construction has collapsed it reveals its internal compact structure. This specific prow tower (highlighted in red in Fig. 6) could only been understood with the use of high resolution (RPAS derived) orthophotos and digital model. Indeed, the steep inclination of the sides of the walls (for their intrinsic nature) are quite hard to access and therefore also the understanding of shapes and phases is only clearly understandable from the perfect (digital environment) view from above and for the peculiar capabilities of 3D models to be rotated and sectioned with ease in desk processing.

The hypothesis for the existence of an Early Byzantine tower at this specific location had been formulated for first time by Nikos Gigourtatis (Gigourtakis 2011-13: 59-60), but confirmed

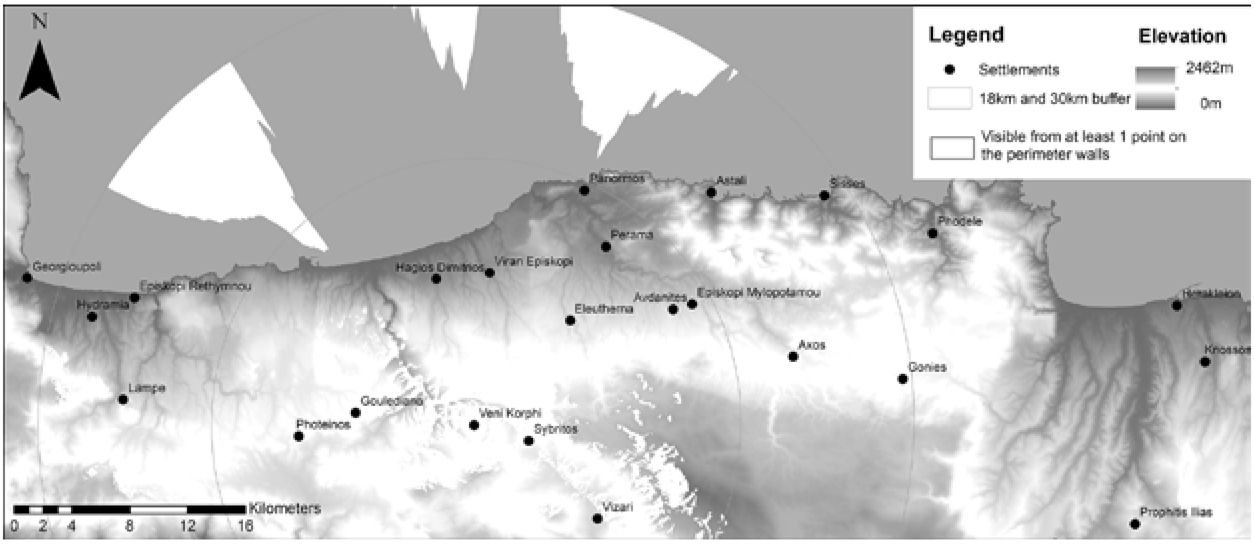

Fig. 4. Viewshed from the walls of Veni Korphi, assuming a height of 10m above present ground level.

only thanks to the innovative approach applied. More precisely, the polygonal shape of the tower revealed by the analysis of high resolution images and 3D model, indicates that the tower could be dated to the 7th century or the beginning of the 8th century.

Regardless of further results generated from the RPAS data, they form an important research output in their own right, offering for the first time accurate recording of neglected and poorly understood Early Byzantine features in their landscape settings. For example the current set of images can now be used as a benchmark to monitor the condition of these important constructions.

2 Further steps

The acquired data and the resulting output from photogrammetric image processing are becoming integral part in the GIS analysis of explored contexts. This has included Site Location Modelling (identifying common landscape elements present at Early Byzantine settlements), Site Catchment Analysis (examining the resources available for each settlement) and Territorial Models (looking at - settlement hierarchies). The GIS will also allow for an investigation of settlement networks and communication as well as their accessibility to the sea, their proximity to cultivable territories, to water sources and to sources of raw materials. Modelling and classification of the landforms will provide an insight into the naturally fortified character of certain settlements, their inter-visibility and the defence-network planning. The results of remote sensing analysis combined in the project GIS will allow an assessment of various aspects of the settlements, such as the estimation of the size of the inhabited area or the area and morphology of the enclosed urban space and the precise location and nature of fortifications.

Early results from this analysis were presented by Armstrong *et al.* (in this volume) at the CAA meeting in Siena. Preliminary examinations of the viewsheds from case study sites, as shown above, indicate a concern for watching communication links, whether they are along valley floors, or by sea, rather than a specific attempt to achieve inter-visibility with other fortified sites. The detailed terrain models produced by the aerial photogrammetry have been a key component in generating accurate viewshed models, and in re-creating wall and tower heights for this purpose. Viewsheds require two key things to provide accurate assessments of the visible areas from a location of interest: first of all the observer point must be accurately digitised or otherwise recorded, and secondly, the DTM employed must be fit-for-purpose. Though the viewsheds were generated using the 20m satellite-derived DTM, the RPAS terrain models allowed for detailed checking of the immediate topography around the observer point, and when cross-referenced with the main DTM, errors in this close to the observer points (and thus having a disproportionately large effect on the outcome) could be eliminated. They also allowed the sub-metre accurate location of structures that were inaccessible on foot, and for the reconstruction of supposed original heights, from which the viewshed could be calculated. They have also been important for understanding the extent and character of enclosed areas at the fortified sites. At sites with large enclosed areas, we can for example, identify places suitable for small scale farming within the defended area.

3 Final remarks

The project DynByzCrete, ‘Recapturing the Dynamics of the Early Byzantine Settlements in Crete: Old problems – New Interpretations through an Interdisciplinary Approach’, was set to answer specific research questions and fill a gap of knowledge in the specific field of Early Byzantine studies. To do so, a few approaches have been used, one of which being the use of novel remote sensing and digital photogrammetric techniques and their integration. The photogrammetric models have been particularly important because they allow reconstructions of fortifications, for the generation of accurate viewsheds (which can be strongly affected by DEM errors close to the source-point), and in characterising the enclosed areas of fortified sites, something not possible from the 20m resolution DEM used for the general landscape analysis. The innovative approach of automatically georeferencing the entire dataset of each site on the base of one high resolution RPAS orthophoto

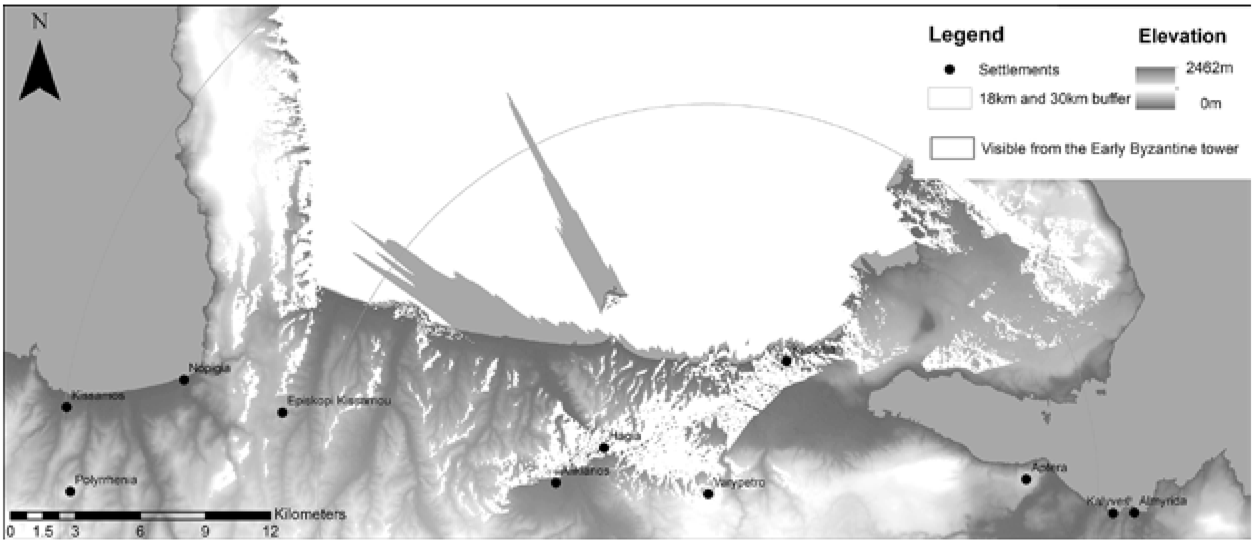

Fig. 5. Viewshed from the Early Byzantine tower at Varypetro, assuming an additional 10m in height from present.

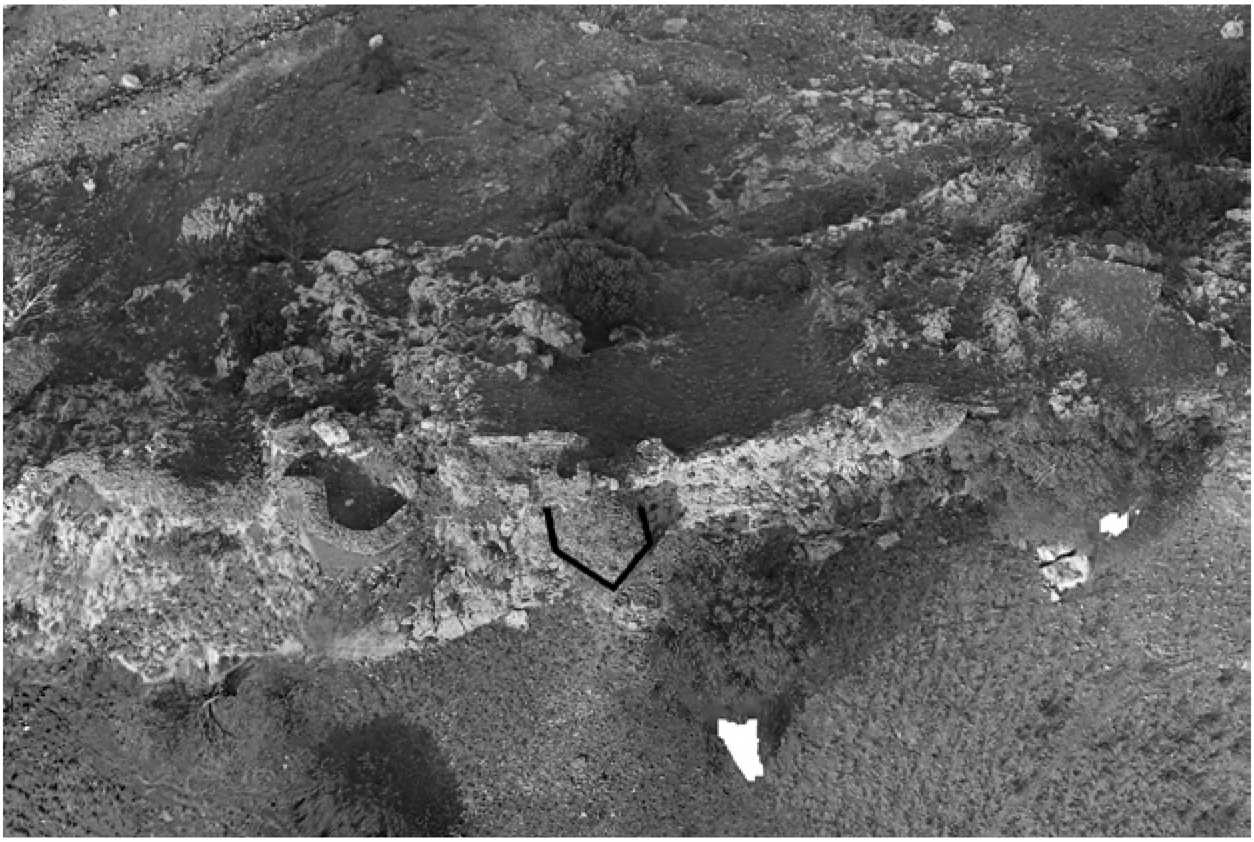

Fig. 6. Perspective view of the digital model of the south side of Varyperto fortification. In red, the outline of a polygonal tower that could be properly understood only with (low altitude RPAS) photogrammetric investigation. The abrupt inclination outside the walls has been calculated from the digital model in a 65% ca.

allowed a full exploitation of all available resources, satellite imagery, historical vertical aerial photographs and oblique images from previous aerial archaeological survey. This way, specific features could be analysed in multi-period satellite images and freely accessible orthophotos on a pixel-by-pixel scale, with the goal to reconstructing the recent biography of the area under investigation.

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Bibliography

Buchanan, T. 1993. Photogrammetry and projective geometry: an historical survey. In: Barrett, E. B. and McKeown, D. M. eds. *Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision*: 82–91. Orlando, FL.

Callieri, M. *et al*. 2009. Meshlab as a Complete Open Tool for the Integration of Photos and Colour with High Resolution 3D Geometry Data. In *Archaeology in the Digital Era Volume II, e-Papers from the 40th Conference on Computer Applications and Quantitative Methods in Archaeology, Southampton, 26-30 March 2012*: 406-16. Amsterdam, Amsterdam University Press.

Cantoro, G. 2012. Speeding up Georeferencing with Subpixel Accuracy. In: *Archaeology in the Digital Era Volume II. e-Papers from the 40th Conference on Computer Applications and Quantitative Methods in Archaeology, Southampton, 26-30 March 2012*: 752–760. Amsterdam, Amsterdam University Press.

Cantoro, G. 2015. Aerial Photogrammetry: when Archaeology meets SIFT. In *Recovering Lost Landscape*. Belgrade, Serbia [in press].

Cantoro, G. and Sarris, A. 2012. Fundamental Tools for Photo-Interpretation in Mountainous Rocky Areas: Photogrammetry and Ground-Truthing. In Perakis K. and Moysiadis A. (eds.), *Proceedings of the 32nd EARSeL Symposium*: 100–12. Mykonos, Greece.

Cerato, I. and Pescarin, S. 2013. Reconstructing Past Landscapes for Virtual Museums. In Corsi, C. *et al*. (eds.), *Good Practice in Archaeological Diagnostics*. Natural Science in Archaeology: 285–296. Springer International Publishing.

Doyle, F. 1964. The Historical Development of Analytical Photogrammetry. *Photogrammetric Engineering* XXX (2): 259–65.

Furukawa, Y. and Ponce, J. 2010. Accurate, Dense, and Robust Multiview Stereopsis. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 32 (8): 1362–76.

Gaffney, V. and Van Leusen, M. 1995. Postscript-GIS, environmental determinism and archaeology: a parallel text. In Lock G. R. and Stancic G. (eds.), *Archaeology and geographical information systems: a European perspective*: 367–382. London and Bristol, PA, CRC Press

Gigourtakis, N. 2011-13. Η οχυρωμένη Βυζαντινή Ακρόπολη της Λύκτου. Κρητική Εστία 14: 49-64.

Girardeau-Montaut, D. 2012. CloudCompare: 3D point cloud and mesh processing software - Open Source Project. [Online] Available at: http://www.danielgm.net/cc/.

Jancosek, M. and Pajdla, T. 2011. Multi-view reconstruction preserving weakly-supported surfaces. In: *2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*: 3121–8.

Remondino, F. *et al.* 2011. UAV photogrammetry for mapping and 3d modeling – current status and future perspectives –. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*: 25–31. Zurich.

Saradi, H. G. 2006. *The Byzantine city in the sixth century: literary images and historical reality*. Athens:Society of Messenian Archaeological Studies.

Tilley, C. Y. 1994. *A phenomenology of landscape: places, paths, and monuments*. Berg.

Tsigonaki, C. *et al.* (under publication). Recapturing the Dynamics of the Early Byzantine Settlements in Crete: Old Problems - New Interpretations through an Interdisciplinary Approach. In *3rd International Landscape Archaeology Conference 2014*. Rome.

Tsigonaki, C. 2012. Πόλεων ανελπίστοις μεταβολαίς: Ιστορικές και αρχαιολογικές μαρτυρίες από τη Γόρτυνα και την Ελεύθερνα της Κρήτης (4ος-8ος αι.). In Kiousopoulou, A. (ed.), Οι Βυζαντινές πόλεις *(8ος - 15ος* αιώνας): Προοπτικές της έρευνας και νέες ερμηνευτικές προσεγγίσεις. Rethymno: Faculty of Letters Publications, University of Crete. Crete, Greece.

Tsougarakis, D. 2011. Rites of passage. Από την υστερορρωμαϊκή στη βυζαντινή Κρήτη: οικιστική εξέλιξη και κοινωνικοί μετασχηματισμοί. In: *Proceedings of the 10th International Cretological Congress*, Chania, 1-8 October 2006. Chania: Philologikos Syllogos ‘Chrysostomos’, 2010*,* vol. 1: 281–307.

Wu, C. *et al*. 2011. Multicore bundle adjustment. In *Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference*: 3057–64.

Wu, C. 2011. VisualSFM: A Visual Structure from Motion System. [Online] Available at: http://ccwu.me/vsfm/.

Creating 3D Replicas of Medium- to Large-Scale Monuments for Web-Based Dissemination Within the Framework of the 3D-Icons Project

Anestis Koutsoudis(1)
akoutsou@ceti.gr

Athanasios Tsaouselis(1)
atsaouselis@ceti.gr

Fotios Arnaoutoglou(1)
fotarny@ceti.gr

George Ioannakis(3)
gioannak@ee.duth.gr

Vasilios Liakopoulos(2)
vasilis@aeroview.gr

Christodoulos Chamzas(3)
chamzas@ee.duth.gr

[1] Multimedia Research Group, Athena Research and Innovation Centre, Xanthi's Division, Xanthi, Greece
[2] Aeroview, Xanthi, Greece
[3] Faculty of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece

Abstract: Web-based dissemination of cultural heritage 3D content has clearly increased over the last decade. EU-funded research and development projects have established affordable pipelines allowing efficient 3D documentation and dissemination. Such an example is the 3D-ICONS project which has focused on the 3D digitization of European monuments of outstanding cultural importance and their dissemination through Europeana (an Internet portal). In this paper, we present the methodologies applied by the Athena Research Centre digitization team in order to provide high-resolution 3D digital replicas of six medium- to large-scale monuments listed as UNESCO world heritage. The selected monuments are all located in the regions of Macedonia and Thrace, Greece, and their time span ranges from the Roman era up to the Late Byzantine era. We present a hybrid 3D digitization pipeline along with data quality evaluation procedures and a 3D content web-based dissemination approach that is based on the use of the WebGL/X3DOM framework, as well as the support of novel low-cost interactive virtual reality approaches such as the Google cardboard.

Keywords: Structure from Motion/Multiple View Stereovision, 3D digitization, Large-scale monuments, Web visualization, X3dom

Introduction

Currently 3D digitization is applied in entertainment, industrial design, prototyping, and medicine. High accuracy 3D digitization is considered a common practice in the cultural heritage domain (Koutsoudis 2012). The data produced are used to provide answers to divergent questions related to the preservation, study, and dissemination of our cultural thesaurus.

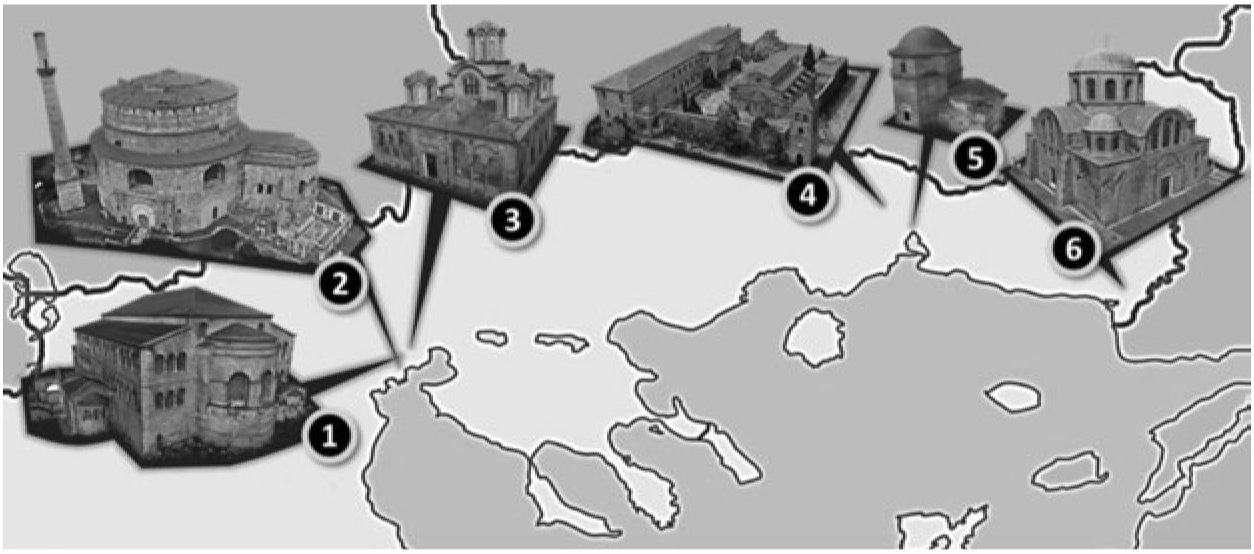
Numerous digitization projects and initiatives that have focused on the cultural heritage domain have produced high-quality, accurate 3D digital replicas of artefacts, monuments, and architectural and archaeological sites (3D-Coform 2008; Beraldin 2002, 2006; Carare 2009; Carrozzino 2009; El-Hakim 2008; Ioannidis 2005; Remondino 2008). As there is a significant variety of 3D acquisition methodologies, the selection of the most appropriate approach is defined by the requirements of a project and its financial plan. It is a fact that the available budget is one of the primary aspects that affect the breadth and scope of any project. Additionally, the nature of the subject to be digitized, the purpose of its digitization and subsequent 3D data usage, comprise the four primary aspects that are integrated into the design process and thus drive the project. As the financial aspect of a project should make sense for both the contractor and the client, the first should select the optimum data collection approach while the latter should be ensured that the end product meets its initial requirements specification.

The 3D-ICONS (2012) was a pilot project funded under the European Commission's ICT policy support project, the consortium of which had to made decisions while building on the results produced by previous projects such as the CARARE (2009) and 3D-COFORM (2008) projects. The main scope of the 3D-ICONS project was to digitize 3D architectural and archaeological monuments and buildings identified by UNESCO as being of outstanding cultural importance and to increase the critical mass of 3D content available in Europeana (2008).

This paper summarizes the important aspects and challenges of the digitization pipeline followed by the Athena Research Centre digitization team in order to deliver 3D content that not only meets the project's requirements but also quantifies the data quality in terms of accuracy. In Section 2, we give a brief overview of the monuments digitized, while in Section 3 we discuss the digitization pipeline. In Section 4, we present the data processing pipeline and web-based dissemination technologies used in order to deliver the 3D content to both desktop and mobile devices, as well as the support of the Google cardboard (2014).

1 Selected Medium- to Large-Scale Monuments

The selection of monuments was based not only on their obvious archaeological, architectural, and historical importance but also on properties such as their spatial distribution,



No.	Appellation	Time Period	Location	WGS84 (lng, lat)
1	Church of Panagia Acheiropiitos	Early Byzantine Era 450-475 AD	Thessaloniki	40.634,22.947
2	Rotunda	Roman Era 27 BC – 393 AD	Thessaloniki	40.633,22.952
3	Church of the Holy Apostles	Late Byzantine Era 1204 – 1430 AD	Thessaloniki	40.642,22.937
4	Monastery of Panagia Kalamou	Middle Byzantine Era 1001-1100 AD	Xanthi	41.156,24.885
5	Kutuklu Baba Tekkesi	Byzantine – Ottoman era (15th – 16th)	Sidini, Xanthi	41.075 25.058
6	Monastery of Panagia Kosmosotira	Late Byzantine Era 1204 – 1430 AD	Feres, Evros	40.893,26.170

Fig. 1. Spatial distribution of the digitized monuments (Macedonia and Thrace, Greece).

accessibility, surrounding environment, and the ability to acquire the required permissions from the related ephorates and the Greek Orthodox Church within the time limits introduced by the project. It is a fact that such properties are reflected on the financial and time limitations introduced by the project's work plan and deliverables. Figure 1 depicts the locations of each of the monuments. The time span of the selected monuments ranges from the Roman era up to Late Byzantine era. It should be noted that only the first three monuments (Fig. 1) are currently identified by UNESCO as being of outstanding cultural importance.

1.1 Church of Panagia Acheiropiitos

The Church of Panagia Acheiropiitos was built over a large complex of Roman baths, probably one of the most important public buildings of Thessaloniki. The church's name and patron saint is the subject of an ongoing scientific debate. Most scholars, however, believe that the church was dedicated to the Virgin Mary. Indeed from the 12th up to the 15th century it was referred to as the Great Church of Theotokos. The name Acheiropiitos was linked to the church in a document of 1320 and means 'not made by hand'. It refers to a devotional icon of the Virgin that was worshipped in the church. Written sources attest that the icon depicted Theotokos holding the child Jesus at her side (Hodegetria iconographic type), while it miraculously changed to depict Theotokos standing in a frontal and prayer pose, with her arms raised (Orant iconographic type) (Raptis 2010). The church occupies a building block and thus it is possible to access all its sides. This is of great importance when attempting to digitize a monument and it is one of the primary reasons for selecting this and all the monuments mentioned below. In terms of effort, a complete and efficient digitization of the exterior can be achieved if, and only if, there is enough available surrounding space to perform the different data-collection phases while keeping the requirements for additional equipment such as scaffolding to a minimum.

1.2 Rotunda

The Rotunda was built at the north-eastern part of Thessaloniki, close to the east city walls. Its location was previously an uninhabited, sparsely built area, which was added to the city during the 3rd-century fortification. The building is located on the axis of a road that led through the arch of Galerius to the royal palace to the south and was connected to this arch through a monumental colonnaded way leading to the palace. It was travellers in the 18th and 19th centuries that gave the monument its common name due to its circular plan. The monument has a rich history of more than fifteen centuries, during which its function and shape changed (Torp 1991). The Rotunda's surrounding yard offers adequate space allowing not only its complete exterior digitization but also a secure environment for flying the UAV and storing the rest of the digitization equipment. Furthermore, the monument is open to visitors and its staff keep them informed about our work, which reduces dramatically the chances of interruption of our data collection by the presence of passers-by.

1.3 Church of the Holy Apostles

The church is situated in the homonymous square in Thessaloniki. Originally it was the *katholikon* (main church) of a sizeable monastery. Except for the church, little evidence remains of the original complex. Moreover, it had probably ten to twenty monks living in it and derived its revenues mainly from estates, including scriptoria and workshops for minor art and other crafts. The *katholikon* was initially dedicated to the Virgin Mary (or jointly with Christ), as is evidenced by the painted decoration and the special place given to themes related to the Virgin. The designation of the church as Holy Apostles is of recent date and was said to be based on the existence of twelve vaults in the building (Bakirtzis 2008). It should be noted that one of the primary reasons for selecting this as well as the other the monuments was their high compatibility, in terms of surfaces, with the SFM/MVS digitization method; they exhibit strong features and high frequency colour changes that are of great importance when using targetless photogrammetric methods.

1.4 Monastery of Panagia Kalamou

The monastery is situated on the mountain lying north of Xanthi at an altitude of 170 m and is dedicated to the Virgin Mary (Panagia). It was probably founded during the 11th century AD, as is evidenced by parts of a marble iconostasis and a funerary stele with embossed decoration, now kept in Kavala. Local tradition dates the foundation back to the iconoclasm years (AD 726–843), when iconolaters fled Constantinople and came to this area, where they built the monastery. The name Kalamou or Kalamiotissa derives from the local tradition that states that a miraculous icon of the Virgin Mary was found in a reed bed near the Kossinthos River. Thus, the monastery, along with its *katholikon*, was dedicated to the Dormition of the Mother of God. The monastery can be considered as the most complex one in terms of morphological features as it is composed of a set of different buildings. At the same time, being one of the closest destinations from the digitization team's base played an important role in selecting it despite the digitization challenges introduced by its size. For many low-budget digitization projects, travelling expenses and requirements of in situ presence are the primary reasons for not avoiding to select large-scale monuments for digitization.

1.5 Kutuklu Baba Tekkesi

The monument is located in the middle of a cultivable area on the west coast of the Vistonida Lake in Xanthi, Greece. It is considered one of the most important Ottoman monuments in the area and may have been built in the late 15th century. It was possibly built on the ruins of an Orthodox Christian temple that was dedicated to Saint George Kalamitziotis. Several conjectures have been made about the person buried in the monument. Today, for Muslims it is the grave of a Whirling Dervish called Kioutouklou Baba, while for Christians it is a place where Saint George is worshipped (Health 2009). It is the smallest monument being digitized and was considered ideal to be initially digitized in order to test and evaluate our data-collection and processing pipeline (Koutsoudis 2014). Again, being located in the middle of a cultivable area was a great advantage for the aerial data collection phase.

1.6 Monastery of Panagia Kosmosotira

Currently only the *katholikon* and some ruins of a fortified precinct remain from the original larger complex. It was a homonymous monastery, dedicated to the Virgin Mary and founded by the Sebastokrator (crown prince) Isaakios Komnenos (born in 1093), son of the Byzantine emperor Alexios I Komnenos. This monastery became the foundation in the area of a larger settlement called Vera. In AD 1151–52 Isaakios Komnenos established his monastic complex and drew up its *Typikon*, the monastic charter regulating life in the monastery (Ševčenko 1984). Similar to the previously mentioned monuments, the monument's apparent friendliness towards the digitization method along with the ability to gain access from all its sides meant it was a good candidate to be included in our list of monuments to be digitized.

2 Digitization Pipeline

The digitization was completed using a two-stage pipeline. The first stage was focused on the data-collection procedures (DC) while the second focused on the data processing (DP), content generation, and web-based visualization.

2.1 Data Collection

The data-collection (DC) phase involved Structure-from-Motion/Multiview Stereovision (SFM/MVS) (Engels 2006; Robertson 2009), and was the primary method to produce the principal 3D replica of the monument, which was later used to produce lower-resolution models. Selecting the SFM/MVS as the primary digitization method instead of range scanning had to do with the size and the accessibility of the monuments, the project's deadlines, and the fact that all selected monuments were considered SFM/MVS-friendly due to their feature-rich surfaces. As SFM/MVS is a targetless photogrammetric method, it relies on detecting surface feature points in order to compute both intrinsic and extrinsic parameters of the digital camera, to determine the position and orientation of images in 3D space, and to perform the dense stereo point-cloud generation. Thus, the existence of strong features is positively associated with the ability to reconstruct the scene (image spatial alignment), as well as with the quality of the produced 3D data. All selected monuments carry surfaces that exploit strong morphological features coupled with high-frequency colour changes and low reflectance.

The SFM/MVS input data were captured through multiple terrestrial and aerial (UAV-based) photo shooting sessions. The terrestrial photo shooting sessions were performed at a height range between 1.5 and 9 m, using tripods and monopods (Fig. 2). Additionally, a set of complementary terrestrial 3D DC methods were used in order to provide 3D scaling information and SFM/MVS data quality quantification. These were: i) terrestrial TOF laser scanning which provided numerous partial scans of various parts of each monument that were aligned and compared with SFM/MVS data; ii) total station surveying providing highly accurate measurements and empirical measurements performed using tape measures that were used for scaling the SFM/MVS 3D model and also

FIG. 2. TERRESTRIAL DATA COLLECTION USING DIGITAL CAMERAS, TIME-OF-FLIGHT LASER SCANNER, AND TOTAL STATION.

to verify the absence of proportional errors or deformations. These procedures involved the positioning of photogrammetric targets and the identification of strong surface features.

Aerial DC was performed at a height range between 10 and 40 m (Fig. 3). A custom UAV was built for the needs of the project. As a no safety distance limit was introduced, the UAV was designed to ensure flying stability. The UAV used was a hexacopter that followed the X frame arrangement with an 80 cm diameter. It had a payload capability of 2 kg and a flying time of 15 minutes using five cell Li-Po batteries. For the DC phase, other important aspects of the UAV were the remote-controlled anti-shock three axis gimbal camera base, GPS-based altitude hold functionality, and telemetry functions such as first person view, altitude, and voltage monitor. For both aerial and terrestrial sessions a set of Samsung NX1000 (20MPs, 16mm fixed zoom and 22–55mm lenses) mirrorless DSLR cameras were used. Figure 3 illustrates the UAV in action as well as the multiple closed loops used to collect image sequences. The top two aerial image sequences (depicted in Fig. 3 as green circles) were always captured with the camera at a low angle oblique and in a vertical position. It should be noted that due to the high morphological complexity of specific areas of the monuments, the existence of strong occlusions due to concavities, and the need to capture fine details, additional image sequences were also captured. In some areas where terrestrial photo shooting was expected to be able to provide the required data but failed, additional aerial image sequences were captured and contributed to the completion of terrestrial images sequences.

One of the challenges encountered during the data-collection phase included the need to inform staff about our work and the safety procedures we were following, especially for the aerial phases. As some of the monuments are open to the public there were many occasions when DC procedures had to be interrupted not only to ensure visitors' safety but also to respect their visiting experience. Weather conditions were

FIG. 3. UAB-BASED AERIAL DATA COLLECTION AND ILLUSTRATION VISUALIZATION OF THE MULTIPLE CLOSED LOOP PHOTO SHOOTING APPROACH.

TAB. 1. TOTAL NUMBER OF IMAGES AND VERTICES PER DIGITIZATION PROJECT.

No.	Appellation	Number of images used for creating the primary 3D model	Number of Vertices of primary 3D models	3D Model Bounding Box Dimensions (width x depth x height in metres)
1	Church of Panagia Acheiropiitos	5872	405,211,706	23.4 x 45.1 x 56.9
2	Rotunda	12,133	525,652,072	68.3 x 58.7 x 52.2
3	Church of The Holy Apostles	4088	187,091,516	20.5 x 20 x 23
4	Monastery of Panagia Kalamou	10,005	235,062,280	60 x 51 x 52.2
5	Kutuklu Baba Tekkesi	938	79,149,149	10.6 x 8.4 x 13.4
6	Monastery of Panagia Kosmosotira	4119	62,383,781	17 x 21 x 23.5

another factor taken into consideration. In order to avoid capturing the monument's surfaces with strong shadows that would introduce problems when trying to simulate different lighting conditions, we tried to perform all DC on cloudy (overcast) days. Furthermore, wind gusts affected the aerial DC and reduced the total flying time as the UAV was trying to hold its position against them, thus causing faster battery drain. In some cases, the automatic hold position approach was not efficient due to slow GPS response and manual navigation was inevitable. In addition, the monument's morphology often blocked the pilot's line of sight to the UAV and the pilot, along with ground station (telemetry monitors), had to change ground position continuously. It is a fact that a monument's morphology is always depicted on the flight plan design time. Another challenge during the aerial DC was birds, particularly seagulls and crows, which attempted attacks on the UAV.

The following table (Table 1) details the total number of images that were used for the reconstruction of each of the six monuments. This number is not the total number of images captured but those used to create the primary 3D model of each monument.

The duration of the completion of a DC phase is related to the quality requirements of a digitization project. In cases where SFM/MVS is used the total number of images required may vary. More specifically, if a low-quality 3D model is required for web-based dissemination via mobile devices or for other similar uses (e.g. low-resolution distant visualization in a video sequence-rendering) then a small number of aerial images using a UAV and a large ground sample distance (GSD) may prove to be adequate. On the other hand, if the requirements specification demands a high-resolution and high geometrical accuracy for archiving, preservation, restoration, or other scientific purposes, the DC phase becomes demanding in terms of time and the amount of data required. More specifically, the demand for a small ground sample distance results in a dramatic increase in the total number of images collected at various heights and viewpoints around the monument using both close-range terrestrial and aerial approaches. It also becomes more complex, because in order to acquire the high-quality data defined by the requirements specifications, all the usual concavities and small details of a monument must be captured from multiple viewpoints.

For the 3D-ICONS project, we implemented both approaches mentioned above, in order to produce quickly and with a minimum set of data (image set and processing times) a primary SFM/MVS-based low-quality model. This model was then used by the digitization team to identify in more detail the overall morphology of the monument, and to design the aerial (flight plans) and terrestrial (walking areas — distances from monument) dense DC phases required for the creation of the high-quality primary 3D model.

2.2 Data processing

The data-processing phase (DP) was based on an arsenal of commercial and open source software tools. Agisoft Photoscan Professional (2014) was selected as our SFM/MVS implementation, due to its performance demonstrated in a number of experiments previously performed while digitizing both small- and large-scale objects (Koutsoudis 2013, 2014). For further processing of the primary 3D models produced by Photoscan and all derivatives such as video sequences, orthophotographs, etc. we have used Meshlab (2012), xNormal (2005), Blender (1995), CloudCompare (2003), and Arius 3D Pointstream (2006) editor. In addition, a total of six desktop computer systems were used. Some of their main specifications were *64-96GB* RAM, Intel i7 6-cores 3.4Ghz processors, ATI Radeon R9 280X, and GeForce GTX580 graphics cards. These six systems enabled us to complete the generation of the project deliverables within the given deadlines but proved to be insufficient in delivering and handling the highest possible (based on our input 20MPs image sequences) 3D reconstruction datasets. Given the specific software and hardware, in some cases the processing times for completing an image set spatial alignment exceeded 200 hours, when using a maximum of 10,000 matching points per image for a set of around 9000 images. On the other hand, the dense stereo 3D reconstruction phase is the most memory-demanding phase, hence long processing times (in some cases more than a week) were inevitable in order to produce the primary dense 3D point cloud. SFM/MVS is a much lower cost approach when compared with 3D range scanning, but its processing demands delay the generation of the primary dense point cloud and inspecting even partial data is not as immediate as viewing a point-cloud file produced by a range scanner. On the other hand, an efficient image set along with a powerful computer

Tab. 2. Fixed 3D model resolution level approach.

Resolution Level	Number of facets	Texture Map Resolution	Target
Lowest	< 30K	512^2	Use as 3D thumbnail image
Low	< 100K	1024^2	Mobile devices over low bandwidth connections
Medium	< 300K	4096^2	Average desktop/laptop personal computer over cable connection
High	< 1M	8192^2 (multiple images)	High end desktop/laptop personal computer over cable connection
Raw	> 20M	Vertex colour	Research purpose data – Available after licensing

system unburden the digitization team from procedures such as the partial scan alignments that are not only inevitable when using range scanning but also introduce errors. In order to overcome the challenge of large memory requirements when producing the dense point clouds of such large image sets, we exploited the Python scripting functionality offered by Agisoft Photoscan. The script offered the ability to divide the 3D space automatically into a predefined number of smaller volumes and perform dense stereo 3D reconstruction on each of the volumes, and hence acquire high-density point clouds while keeping memory requirements to a minimum. Nonetheless, the amount of data produced by applying dense stereo 3D reconstruction to large image networks is a challenging issue that involves special algorithmic approaches in order to handle such big data that are currently missing from the software tool being used.

Furthermore, once the primary 3D model was produced, it was scaled to its real world dimensions using data produced by the range scanner, the total station, and empirical measurements. In order to compare the quality of the data produced and the existence of any deformations, we performed surface deviation comparisons between the range scanner data (partial scans) and the data produced by the SFM/MVS pipeline. This was achieved using Meshlab to align single view range scanner partial scans with the primary 3D model; through CloudCompare we calculated the cloud-to-mesh distances between the two data types. The high density of the image networks allowed the production of 3D models that produced low mean and standard surface deviation distances when compared with the scanner's data. The average standard deviation in many cases was found to be around 2 cm while the average distance between two consecutive points on the primary 3D model was around 3 cm. It should be noted that the iterative closest point (ICP) algorithm was used to align the partial scans and the primary 3D models. This builds up the surface deviation error as ICP minimizes (by distribution) the alignment error between overlapping areas. Again, the distance between two consecutive points can be reduced and the resolution of the primary 3D model can be increased using the same image sets. This is true if computer systems of higher specifications capable of handling the increased data size are used.

On the other hand, video sequences were one of the primary data derivatives and were used to depict a virtual camera flying around each monument. In order to enhance the photorealism of the video sequences, post-processing effects such as depth of field, camera lens barrel distortion, colour aberration, and vignette were introduced. In some cases, secondary video sequences were produced in order to provide detailed views of specific parts of the monuments. All video sequences were produced at 1080p resolution using Blender.

2.3 Web-based dissemination

One of the primary concerns of web-based 3D data dissemination is the ability to handle the different types of devices (e.g. smartphone, tablet, desktop/laptop, etc.) and provide the most efficient approach that takes into consideration aspects such as user interaction and visualization, as well as 3D graphics and network bandwidth capabilities. A number of 3D-ICONS partners decided to use the X3DOM (2010) framework to deliver their 3D content as it is a solution that is compatible with all major web browsers over a wide range of operating systems. It is a Javascript implementation that requires no plug-in installation as it works on top of WebGL (2011). Currently, the framework does not support *true* progressive 3D data streaming and its current version offers a staged-progressiveness approach that is based on the generation of various meshes depicting the same model with different mesh complexities. Thus, a decision was made that each monument will be offered with a set of different *scope-usage* resolution levels. Each level defines a maximum possible number of vertices (mesh complexity) and a maximum texture map resolution. Table 2 depicts the different resolution levels along with their targets in terms of device and purpose of use. All 3D models are delivered online using the X3D file format while in the RAW level the 3D data are offered as downloadable PLY file formats. The binary X3D file format has been used for the high-resolution level as it offers data compression and reduces the downloading times.

Additionally, as the development of a user-friendly website was a prerequisite, we have addressed the following aspects. An altered version of the X3DOM Javascript has been created in order to provide a downloading progress bar along with the required multilingual messages. The website offers different visualization schemes for the 3D content based on the device used (e.g. mobile or desktop). This is true also for the 3D-model interaction that changes depending on whether a touch screen or a pointer-based device is used. The X3DOM framework offers all the standard navigation modes (walkthrough, fly, rotation) and also offers the turntable navigation mode that prevents the user accessing unwanted viewpoints (e.g. the bottom side of a monument that cannot be captured). Additionally, a tabbed document graphical user interface is used to display below the 3D model the metadata and all derivatives such as video

FIG. 4. SCREENSHOTS OF THE LANDING PAGE AS VIEWED ON DIFFERENT DESKTOP AND MOBILE DEVICES.

sequences, orthographic photographs, and references (Fig. 4). Furthermore, the versatility of the X3DOM framework in combination with the HTML5 standard allowed us to deliver the produced 3D content in a format compatible with Google cardboard. Hence, mobile device users that have a Google cardboard or an equivalent VR headset are able to explore the 3D models in a true VR stereoscopic mode using only their pre-installed web browser without the need to download and install additional applications. JavaScript is responsible for reading the orientation sensors of the mobile device and allows the user to move around in order to view the model from different viewpoints. Accessing the Google cardboard mode is done simply by following a link on the website. The low-resolution level 3D model is currently used for the Google cardboard VR mode. This was a simple way to achieve a balance between visualisation quality, downloading times, and 3D graphics performance requirements.

3 Conclusions

For more than a decade now 3D digitization has been applied in the cultural heritage domain. In this paper we outlined the procedures and the technologies used for data collection, 3D model generation, web-based dissemination, and VR exploration of monuments located in northern Greece. The procedures described compose a versatile pipeline that delivers high-quality 3D models that are not only efficient for dissemination but also applicable in numerous scientific applications such as archiving, documentation, monitoring, and curating. The data-collection phase produced large image sets with small ground sample distance that in some cases can be characterized as 'oversampling' and exceed the requirements of the 3D-ICONS project. Nevertheless, as acquiring digitization licenses for a monument is a complex procedure, the digitization team always attempted to collect the greatest amount of data possible given the predefined time limitations. Additionally, a digitization plan that allowed a period of three months for the completion of the primary 3D model of each of the six monuments has successfully been followed using the software and hardware described above. Additionally, the quality of the data produced by the current SFM/MVS software solutions is a strong indication that digitization projects on a tight budget with low hardware requirements can be successful. In conclusion, the software solutions used in our pipeline comprise a powerful arsenal capable to provide — apart from different versions of the primary 3D models in terms of geometric quality — numerous data derivatives by exploiting modern computer graphics technologies such as non-realistic visualisation shaders for exaggerated visualization of surface morphological features, as well as normal and displacement mapping usually found in modern computer games for, in terms of processing and memory requirements, the efficient visualization of high-complexity 3D models.

Bibliography

3D-COFORM 2008. [Online] http://3dcoform.eu. [Accessed: 10th June 2015].

Carare Best Practise Network 2009. [Online] http://www.carare.eu. [Accessed: 10th June 2015].

3d-Icons 2012. [Online] http://3dicons-project.eu. [Accessed: 10th June 2015].

Agisoft Photoscan Professional 2014. [Online] http://www.agisoft.ru. [Accessed: 10th June 2015].

Arius 3D pointstream 2006. [Online] http://en.souvr.com/product/200712/334.html.[Accessed: 10th June 2015].

Bakirtzis, C., Mastora, P., Vassiliadou, S., Pitsalidis, N. 2008. *Lessons Learned in Theory and Practice of Mosaic Treatments: The Case of the Wall Mosaics in the Church of the Holy Apostles, Thessaloniki, Greece, The Getty Conservation Institute, Los Angeles, 2008*.

Beraldin, J., Blais, F., Cournoyer, L., Picard, M., Gamache, D., Valzano, V., Bandiera, A. and Gorgoglione, M. 2006. Multiresolution digital 3D imaging system applied to the recording of grotto sites: The case of the Grotta dei Cervi. In *7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST)*.

Beraldin, J., Picard, M., El-Hakim, S.F., Godin, G., Valzano, V., Bandiera, A., Latouche, C. 2002. Virtualizing a Byzantine crypt by combining high-resolution textures with laser scanner 3D data. *In Proceedings of VSMM 2002*: 3-14.

BLENDER 1995. [Online] https://www.blender.org. [Accessed: 10 June 2015].

Carrozzino, M., Evangelista, C., Bergamasco, M. 2009. The immersive time-machine: a virtual exploration of the history of Livorno, *International Archives of the Photogrammetry. Remote Sensing Spatial Info.Sci., 38(5 W1)*: 1682-777.

Cloudcompare 2003. [Online] http://www.danielgm.net/cc. [Accessed: 10 June 2015].

El-Hakim, S., Beraldin, J. A., Picard, M., Cournoyer, L. 2008. Surface reconstruction of large complex structures from mixed range data - The erechtheion experience. In *Proceedings of XXI Congress of the International Society for Photogrammetry and Remote Sensing (ISPRS), 37*: 1077-82.

Engels, C., Stewénius, H., Nistér, D. 2006. Bundle adjustment rules, In *The photogrammetric computer vision conference, ISPRS, Bonn, Germany, September 20–22 (2006)*.

Health, W. L. 2009. *In the Footsteps of the Ottomans: A Search for Sacred Spaces and Architectural Monuments in Northern Greece, Mary Martin Booksellers, Bahcesehir University Publications, Istanbul, 2009*.

EUROPEANA 2008. [Online] http://www.europeana.eu.[Accessed: 10 June 2015].

Google Cardboard 2014. [Online] http://www.google.com/get/cardboard.[Accessed: 10 June 2015].

Ioannidis, C., Demir, N., Soile, S., Tsakiri, M. 2005. Combination of laser scanner data and simple photogrammetric procedures for surface reconstruction of monuments. In *Proceedings of CIPA XX International Symposium, Turin, ITALY - 26 September - 1 October 2005*.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., Chamzas, C. 2014. Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*. 15(1): 73-79.

Koutsoudis, A., Vidmar, B., Arnaoutoglou, F. 2013. Performance evaluation of a multi-iamge 3D reconstruction software on a low-feature artefact. *Journal of Archaeological Science*. 40, 12: 4450-6.

Koutsoudis, A., Stavroglou, K., Pavlidis, G., Chamzas, C. 2012. 3DSSE – A 3D scene search engine: exploring 3D scenes using keywords. *Journal of Cultural Heritage* 13, 2: 187-94.

MESHLAB 2012. [Online] http://meshlab.sourceforge.net. [Accessed: 10 June 2015].

Raptis, K., Zombou-Asimi, A. 2010. The consolidation and restoration project of Acheiropoietos basilica in Thessaloniki. In *8th International Symposium on the Conservation of Monuments in the Mediterranean Basin, Patra, 31 May – 2 June 2010*: 411-28.

Remondino, F., Girardi, S., Gonzo, L., Rizzi, A. 2008. Multi-resolution modeling of complex and detailed cultural heritage. In: *Proceedings of 9th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST 2008)*: 1-8.

Robertson, D. P., Cipolla, R. 2009. Structure from motion, *Practical image processing and computer vision, John Willey and Sons Ltd* 2009.

Ševčenko, N. 1984. The Tomb of Isaac Komnenos at Pherrai, *Greek Orthodox Theological Revue* 29: 135-40.

Torp, H. 1991. The Date of the Conversion of the Rotunda at Thessaloniki into a Church, O. Andersen & H. Whittaker (eds.) (1991) *The Norwegian Institute at Athens, The First Five Lectures*: 13-28. Athens.

WEBGL 2011. [Online] https://www.khronos.org/webgl. [Accessed: 10 June 2015].

X3DOM 2010. [Online] http://www.x3dom.org.[Accessed: 10 June 2015].

XNORMAL 2005. [Online] http://www.xnormal.net.[Accessed: 10 June 2015].

The Lidoriki Project: Low Altitude, Aerial Photography, GIS, and Traditional Survey in Rural Greece

Todd Brenningmeyer
tbrenningmeyer@maryvilll.edu
Maryville University, Saint Louis, USA

Kostis Kourelis
kkoureli@fandm.edu
Franklin and Marshall College, Lancaster, USA

Miltiadis Katsaros
m.katsaros@m2k.gr
National Technical University of Athens, School of Architecture, Athens, Greece

Abstract: Initiated in 2010, the Lidoriki project brings together an international team of scholars focused on an examination of the cultural and physical landscapes of the region surrounding the village of Lidoriki in the Province of Phocis, Greece. Since the 1960s, a series of modern interventions have radically altered the ancient topography of this region. The various topographic changes of the modern age fragmented the cultural landscape.

Within this landscape exists a cultural topography and regional architectural history whose documentation is the focus of this project. In the summer of 2010, a team of scholars began compiling drawings, maps, photographs, and oral histories of the region, which supplement and inform ongoing surveys of vernacular architecture. Current research involves the melding of traditional architectural practices with aerial photographic collection and photogrammetric documentation of landscapes and villages. This paper discusses the project, focusing specifically on the application of aerial survey techniques and technologies.

Keywords: Architecture, UAV, SfM, GIS

Introduction

The village of Lidoriki is located in the modern region of Phocis, Greece, 20 km inland from the Gulf of Corinth (Fig. 1). It once commanded the confluence of three rivers whose waters were collected in 1979 to form a large reservoir to deliver Athens with drinking water. The Mornos Reservoir radically altered the natural topography of this region, cutting off traditional routes of transportation and communication. Bauxite mining on the slopes of Mount Giona has further eroded the region's idyllic landscape. The cultural geography of Lidoriki represents the typical changes in the Greek countryside from antiquity to the present with enough regional variation to make it an excellent case study for archaeological, architectural, art historical, and anthropological research. An international team of scholars, practitioners, and local community members from the United States and Greece has been studying Lidoriki since 2010. The Lidoriki Project has mapped settlements, individual buildings, infrastructure, and other types of material culture that will aid in reconstructing the history of the region, as well as assess its cultural heritage.

The Lidoriki region has been occupied continuously since prehistory. Its mountainous terrain, the abundance of water, and varied topography has sustained human occupation for centuries with particular prominence in pastoralism. The Lidoriki Project has surveyed sites from different periods, such as the ancient city walls of Fyskos (modern Malandrino), the medieval citadel of Velouchovo (ancient Kallion), an early modern mill, and two bridges. The most extensive of Lidoriki's architectural heritage are villages that date to the 19th and early 20th centuries. The Project has investigated the modern villages of Lidoriki, Aigition, Leukaditi, Skaloula, and Karoutes. Like most other regions of Greece, Lidoriki experienced a demographic boom in the 19th century with numerous villages founded across the fertile valley (Asdrachas 1979). A paved road linking Lidoriki to Eratini further connected Lidoriki to the coast and national markets. This economic and demographic growth is marked by the foundation of new villages and the construction of new churches. Greece's financial collapse in 1893 began a phase of slow economic decline. In response, a quarter of a million Greeks immigrated to the United States between 1906 and 1914. Emigration from Lidoriki tended to concentrate in Wisconsin, where native livestock skills could be used in the industrial slaughterhouses of the American Midwest. The Balkan Wars (1912–1913), World War I (1914–1918), World War II (1940–1945), and the Greek Civil War (1945–1949) further decimated the Lidoriki region. Many villages were burned by the German Army in the last year of World War II or were involved in the destructions of the Civil War. During the 1960s large numbers of villagers migrated to the Athens, leaving behind a visibly deserted landscape. The region has never fully recovered from the mid-20th-century migrations to Athens and abroad.

The large village of Lidoriki weathered the economic and political upheavals and was never fully abandoned in spite of being burned by the Germans. Other sites present a history similar to the village of Aigition, which was destroyed in 1943, partially repopulated, but ultimately deserted. An interviewer who grew up in the village during the 1940s enumerated 100

Fig. 1. Satellite view of the Mornos Lake with the village of Lidoriki to the south-east of this feature.

families living there before it was burned. When we visited the village in 2010 there was a single elderly occupant remaining in the village. By 2014, the village was entirely deserted. The village extends over 5 ha and contains over 50 residential structures, baking ovens, animal pens, storage areas, threshing floors, a mill, and two wells. A few houses are seasonally used as storage spaces but the village has been turned over into cow pasture. The centre of the village contains a piazza (*plateia*) shaded by a large plane tree. A large basilica church constructed in 1852 marks the western edge of the piazza and the village cemetery. The church burned down in the 1940s but has been restored. A village school — whose construction was privately financed in 1908 — extends the limits of the piazza to the north. The houses are typically two stories tall, with the lower storey used for animals and storage (*apotheke*) and the upper storey used by the family. The collapsed stone houses preserve intricate details of local construction practices in which wooden beams are integrated with masonry. Second floor fireplaces, well-hewn quoin blocks, and internal carpentry represent the best craft traditions in Greece (Kouremenos 1989). Two house dedication stones from 1914 and 1915 illustrate the village's last moment of prosperity, financed by remittances from the United States. In its ruined state Aigition offers unique glimpses into a century-long horizon of occupation (1850–1950) that is being reconstructed through the combination of digital and traditional survey techniques used in the Lidoriki project.

1 Previous approaches

The study of the Greek countryside has greatly advanced with the application of computer technologies. Archaeological regional surveys in the Peloponnese and Central Greece have used GIS platforms to model settlement patterns along large regions. The Southern Argolid Survey, the Methana Survey, and the Nemea Valley Archaeological Survey have most intensely studied early modern villages and the processes of desertion (Jameson *et al.* 1994; Sutton 2000; Forbes 2007). The regional surveys, however, have predominantly modelled scatters of pottery sherds rather than architectural walls. With large numeric data, GIS applications allow the creation of statistical models and spatial analysis. Although noted as 'sites', the early modern villages cannot easily fit in the horizontal modelling of object scatters. Their three-dimensional complexity leaves them outside the purview of traditional spatial analysis. With many villages occupied, it becomes difficult to sweep them for pottery. Fieldworkers tend to walk around them. Another methodological problem is that early modern villages tend to be located on steep slopes. The declination of the land means that even when existing, the pottery scatters wash into lower levels. Village architecture has, thus, become a black hole in the strategies of GIS site analysis by archaeologists.

During the 1980s, a Dutch team of archaeologists surveyed the area of Lidoriki and published a foundational study of sites across time (Bommeljé *et al.* 1987). Joanita Vroom, the project's post-classical pottery specialist, observed that, unlike other regions surveyed by archaeologists, the Lidoriki region is surprisingly free of surface scatters. Its 'sherdless sites' represent an interesting counterpoint to 'artefact-rich sites' in other regions of Greece (Vroom 1998). In the absence of surface scatters to enumerate in GIS, architectural survey becomes increasingly important. The early modern villages of Greece represent vernacular architecture, a field of study that blossomed during the 1970s after Bernard Rudofsky's exhibition at the Museum of Modern Art entitled 'Architecture without Architects' (Rudofsky 1964). The ideal Greek village, especially in the islands, proliferated the western imagination and architects sought to document it, concluding with the multi-volume publications of *Vernacular Architecture in Greece* (Philippides 1983). The survey of Greek villages by Greek architects focused on structures that represented the clearest aesthetic ideals. Privileging the beautiful and the best-preserved houses skewed research away from complete sampling of houses. The art-historical focus on best specimens also ignored houses and villages that had advanced into deterioration. In the 1990s, the Minnesota Archaeological Researches in the western Peloponnese initiated a methodology of full architectural coverage in the Morea Project. Making early use of GPS mapping and remote sensing, the Morea Project produced the first comprehensive survey of vernacular architecture in one region (the north-western Peloponnese) with a sample of 3000 houses and 150 villages (Cooper *et al.* 2002). The authors of this paper all participated in this innovative project and produced some early technical literature on the computer applications (Brenningmeyer *et al.* 1998).

Building on the experiences of the Morea Project, Brenningmeyer experimented with kite and balloon photography in 2010, the first season of the Lidoriki Project. Kourelis contributed his expertise on the archaeology of medieval and post-medieval Greece, and Katsaros introduced the perspective of an architect. They were aided by topographer Nikos Lakafosis and ethnographer Sofia Klosa who live in the village and collect data year-round. Klosa spearheaded the establishment of a folk museum, collecting hundreds of artefacts that have been assembled in a dedicated folklore museum building. The Lidoriki Project has not been highly structured but has gathered scholars and students with different concentrations of each of the five years of the project. During some seasons the project included a field-school populated by the students that Brenningmeyer, Kourelis, and Katsaros brought from Maryville University, Franklin and Marshall College, and the National Technical University of Athens respectively. The region of Lidoriki has undergone rapid changes during the five years of the project's operation. Bauxite mining, the termination of agricultural subsidies, and most notably Greece's severe economic crisis have visibly affected the economy of the region. Thus, in addition to collecting important scientific data, the Lidoriki Project has sought to assist the local population in its cultural heritage management. Katsaros has presented the project's research to numerous community gatherings in Lidoriki and Delphi. The project has operated under the auspices of the Ephorate of Antiquities based in Delphi. With Greece's limited archaeological resources devoted to ancient and Byzantine sites, the Lidoriki Project has brought necessary attention to the later monuments.

Research involves multiple levels of data collection and analysis. At the regional level, we examine how environmental and economic forces affect broad trends of population movement and village growth and abandonment. At the village level, the documentation of architectural details and building and village organization provide insight into the development of the village and the social organization of the individuals that occupied these locations. Finally, the creation of a catalogue with 3-dimensional reconstructions of artefacts from the folklore museum in the village of Lidoriki provides an opportunity to further examine specific examples of material culture from this region.

2 Project methodology

In 2010 the project began preliminary surveys of the villages in the project area. Oral histories describing the establishment of villages within the project survey and the memories of the families that occupied these locations were collected. Measured plans of mills, bridges, and buildings produced by architects from the Technical University of Athens provided detailed information about the decorative and structural components of a handful of buildings (Fig. 2). This form of data collection allowed the architects to develop a personal understanding of each structure through the act of physically measuring and drawing the buildings. Traditional architectural plans are slow to produce, however, and our ability quickly to document large villages with numerous structures spread across a diverse and uneven terrain was limited by time and the availability of trained draftsmen. The regional scope of the project called for a broad view of sites to situate the various buildings under examination within their topographic and spatial contexts.

During our initial field season in 2010, we experimented with the collection of aerial information using techniques that the field crew had applied in projects elsewhere in Greece. As part of this process, local Greek surveyors collaborated with students from Maryville University and Franklin and Mashall College to establish coordinate grids for the locations under examination. Ringed Automatically Detected (RAD) targets were laid throughout the sites and their positions were documented using Trimble GPS rovers. These control points provided geographic references for the photos that would be captured from the air using Kite Aerial Photography (KAP), Balloon Aerial Photography (BAP), and Pole Aerial Photography (PAP). KAP/BAP pilots walked transects spaced approximately 15–20 m apart with the camera typically suspended 20–30 m above the site surface. The camera's operating system was manipulated using an Open Source development kit known as CHDK, enabling us to program the camera to take photographs at specific intervals and at a range of exposures during the survey. The kite/balloon pilot viewed the camera's position and objects contained in the camera's frame using a video downlink displayed on a small LCD screen.

While we were able to collect overlapping views of some of the sites using this technique, we realized that transferring methods used elsewhere to the remote villages of Lidoriki was not a simple or straightforward task. Our field seasons tend to be very brief and wind and weather patterns can be unpredictable in the mountain villages. Many of the villages under investigation are in remote locations and the journey to and from the site involves an investment of time and resources. Waiting for ideal environmental conditions to fly a kite or balloon can be both a frustrating and resource intensive act. Surveying within villages often has its own unique difficulties with power lines that crisscross village streets and topography and vegetation that can cut tethers or rupture helium filled aerostats. Likewise, transects cutting across the site following the direction of the wind often required the pilot to walk up and down the mountain multiple times while navigating through dense brush. The effectiveness of tethered aerial collection certainly depended on the specific characteristics of the site under examination.

In 2014, the project added an Unmanned Aerial Vehicle (UAV) to improve the efficiency of the data collection process. The UAV is a small DJI Phantom 2 that provides a first-person view using a video downlink attached to a GoPro 3+ camera. Flight times range between 15 and 20 minutes per battery allowing most villages to be captured with 3–4 batteries. Given our familiarity with KAP and BAP photography, our approach to the use of the UAV followed that described above. The flight lines mimicked transects used in KAP/BAP collection. These were visually determined by the pilot and a 'spotter' that followed the UAV, staying just out of the view of the camera. The pilot was typically positioned at a high point to enable a visual confirmation of the position and orientation of the aircraft. Photographs were taken using an intervallometer set at a 2-second interval. This allowed the pilot briefly to view the frame before each photo was acquired. The pilot could reposition the UAV between shots to acquire additional images

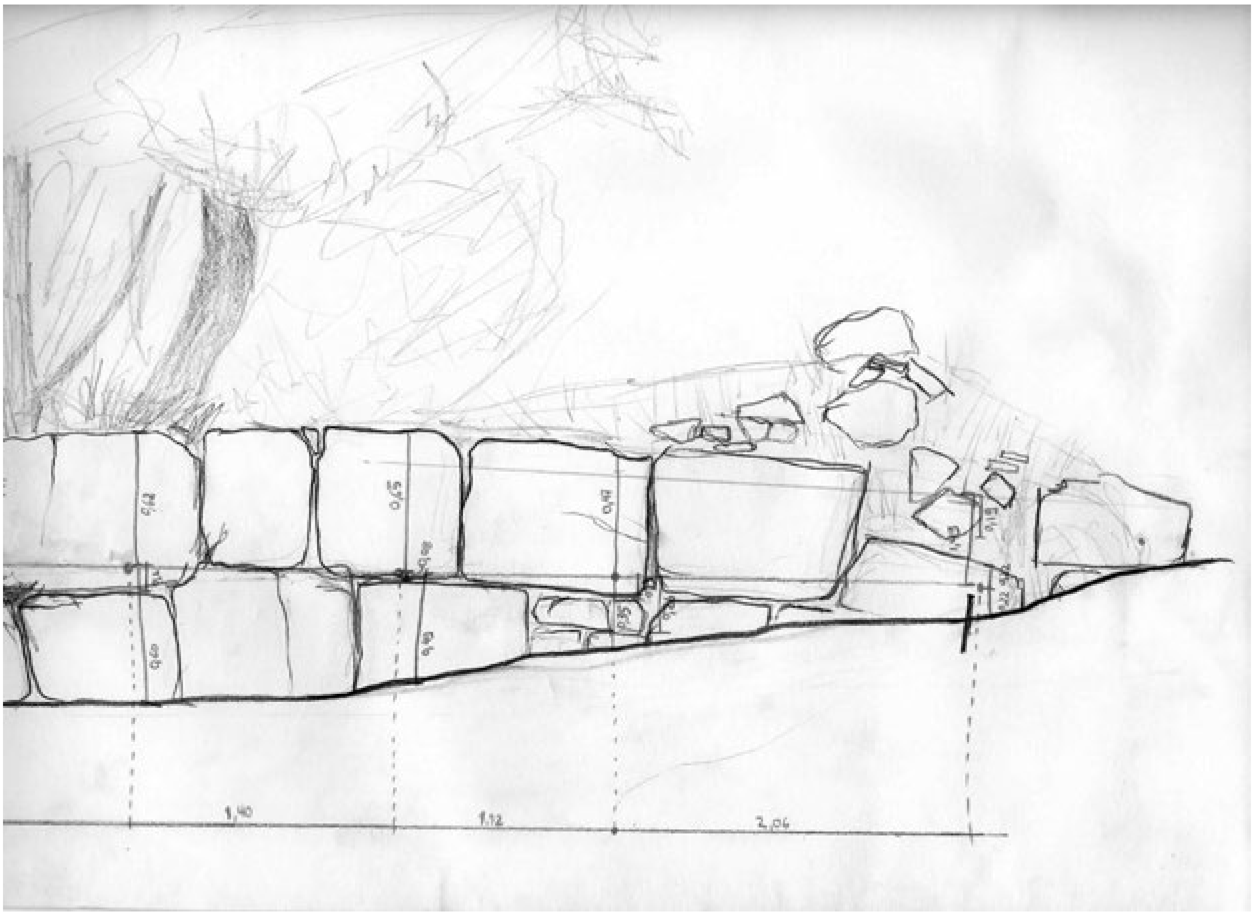


Fig. 2. Sample of architectural sketches created by architects in the field.

of the architecture if needed. As with KAP/BAP photography, the photos were sorted and reviewed manually at the end of the field day. The UAV was ideally suited for a particular collection environment that was distinct from the conditions that suited KAP/BAP collection. Strong or gusting winds and pronounced updrafts along the ridge of steep slopes adversely affected the UAV's performance. Sites bounded on all sides by steep slopes prevented the UAV from acquiring a GPS lock, increasing the difficulty of flying the drone and raising the likelihood that the drone would not respond to the pilot's control (which happened on at least two occasions). In these instances KAP photography could capture what was difficult with the UAV. We found the UAV a complement rather than replacement for other forms of aerial collection.

3 Camera and processing

While the UAV offered increased options for data collection in low or no wind, we were sceptical about the performance and effectiveness of the GoPro 3+ camera. Our kite and balloon platforms allow a range of cameras to be used: from small Canon S series to cameras approaching a DSLR. The payload limits of the Phantom 2 were not sufficient to effectively carry cameras larger than the GoPro 3+ and the gimbal used on our UAV was specifically designed to work with this camera. The benefits and limitations of this action camera are well documented. Unlike frame cameras, the GoPro uses a rolling shutter that can produce a 'ghosting' or 'smeared' effect in photos captured when the camera or object in the field of view is in rapid motion. The camera lens has a barrel distortion that is particularly pronounced along the right and left edges of the photos. Adjustments of camera collection parameters are also limited in comparison to what is available on frame cameras. From a traditional photogrammetric perspective, the GoPro and similar action cameras seemed to be a less than ideal option.

We began testing the effectiveness of using the GoPro data with structure from motion (SfM) software in the fall of 2014. Processing our aerial data using SfM software has been part of our workflow since the beginning of the project and we were interested in examining the effectiveness of using the GoPro 3+ imagery for the generation of dense point clouds and orthophotos of buildings and sites. While we understood that the GoPro and similar cameras with barrel or fisheye distortion are not ideal for photogrammetric collection, it was important to keep in mind that SfM is different than traditional photogrammetry. SfM developed from computer vision research and uses a method for extracting 3D data that deviates from traditional photogrammetric practices (see James *et al.* 2012 for a brief overview of SfM). In traditional photogrammetry, aerial photographs are collected using a calibrated metric camera with flight lines carefully selected to ensure typically a 60% forelap and 30% sidelap in every image. By contrast, SfM software was designed to work with unordered photographs taken with cameras that may vary in terms of their lens characteristics (see for example Snavely *et al.* 2006, 2007).

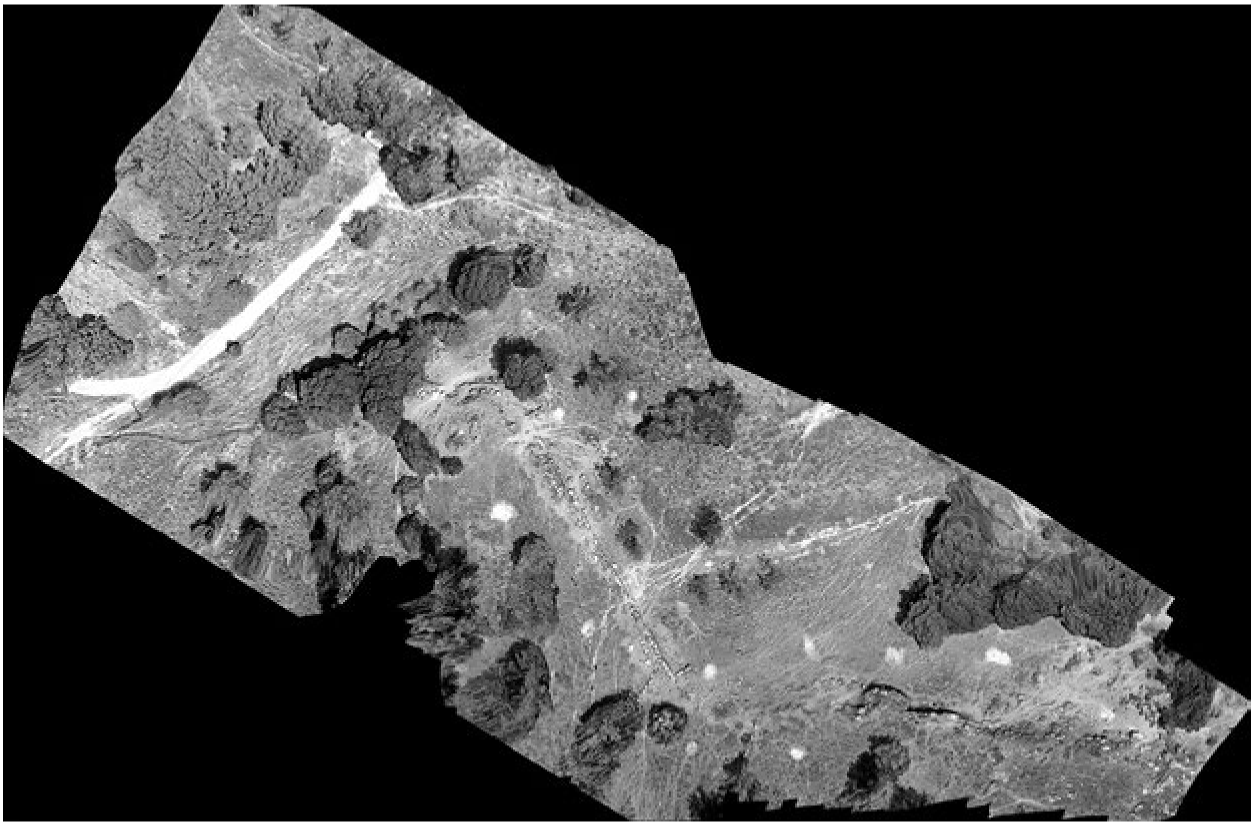


FIG. 3. ORTHOPHOTO OF THE SITE OF FYSKOS USING PRE-PROCESSED IMAGERY. NOTE JAGGED EDGE ALONG SOUTHERN BORDER OF THE PHOTO WHERE CLIPPED PHOTOS PROVIDED INSUFFICIENT OVERLAP FOR MODEL.

SfM software develops estimates for the interior and exterior orientations of the camera while identifying matching features across photographs selected for processing. While a DTM may be generated from two overlapping stereo pairs in traditional practices, SfM will often use many more photographs with overlap that exceeds 60%. Cameras that would be unusable in traditional photogrammetry have some utility in SfM software.

We explored three different techniques to remove the barrel distortion in the GoPro photos. The first technique simply clipped out those areas of the photo that were most affected by the barrel distortion. The edge of each photograph was clipped in Photoshop where the distortion appeared most pronounced. These photos were then opened in Adobe Raw where they were flattened using the GoPro 3+ lens profile correction option. The resulting images were then processed in Photoscan. The second technique created a circular mask that was applied to all of the photographs within Photoscan prior to camera alignment. The intent was that the areas most affected by the barrel distortion (along the right and left edges) would be removed from processing. The masked images were then processed in Photoscan. The final technique was to establish a quality camera calibration using Photoscan's Lens camera calibration software and then process all images using this calibration file. The previous two techniques used the calibration automatically generated by Photoscan.

The results of these three pre-processing methods can be seen in Figures 3, 4, and 5. The first method (Fig. 3) produced a mosaic with minimal visible offsets. The clipping removed some data along the edges of the photographs, which reduced the overlapping coverage slightly, diminishing coverage along the southern edge of the site where image overlap was less consistent. The second method produced some particularly problematic distortions and effects in the image mosaic. As can be seen in Figure 4 circular distortions that replicated the pattern of the mask carried into the mosaic. Holes in the data, produced from the removal of data along the photo edge, further diminished the utility of this approach. The third method, which used the full image with a quality calibration file, produced the best results of the three (Fig. 5). The effect of the calibration on the lens distortion can be seen clearly during the process of calibration. Figure 6 presents the raw uncalibrated photograph used during the calibration process. The effect of the lens distortion on the calibration grid is clearly visible. Figure 7 presents the image after calibration. The lens distortion is removed following calibration of the camera. The removal of the edge distortion provided a full image for the SfM software to use during image alignment, allowing a stronger tie with adjacent photographs and reducing holes in the data that appeared when portions of the photograph were clipped or removed during pre-processing.

We tested additional methods for enhancing the mosaics created using this approach. In traditional photogrammetry a bare earth surface is often used to generate orthophotographs. We replicated this with our data by classifying bare earth, vegetation, and buildings in our generated point clouds. A test mosaic was generated from the resulting bare earth surface. The results were not as beneficial as we hoped. As can be seen

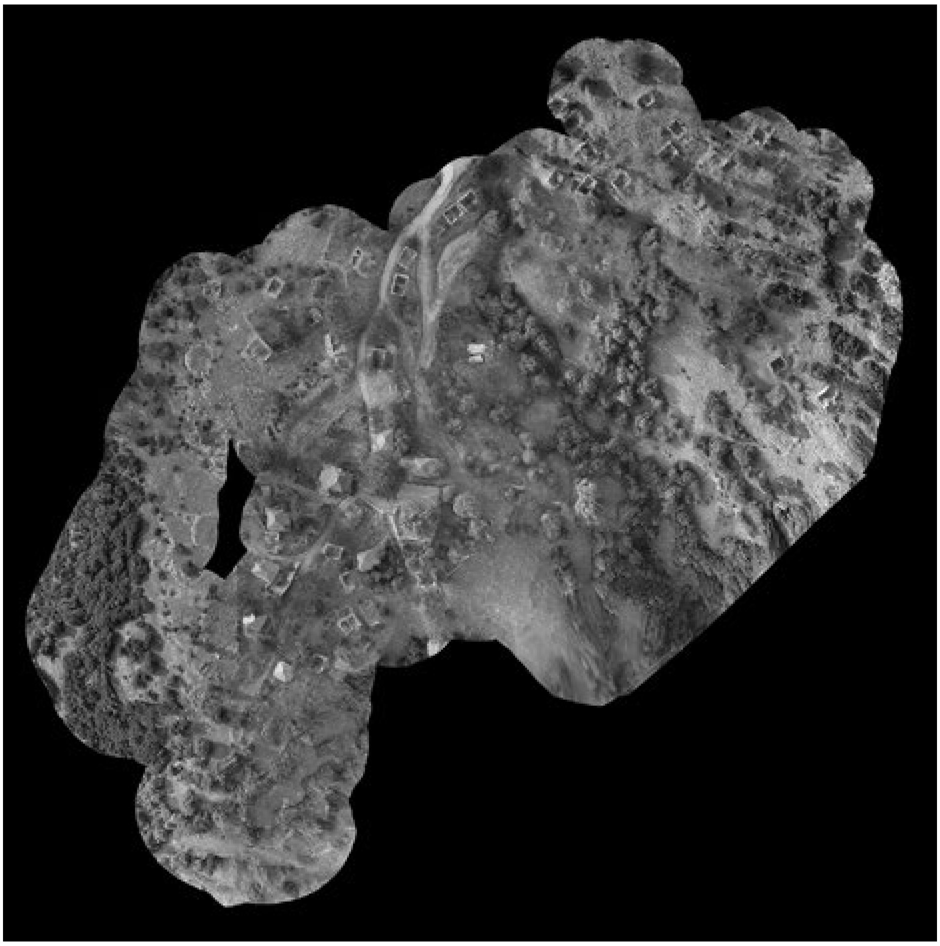


Fig. 4. Orthophoto of the site of Aigition using circular mask. Note gaps in the mosaic at the south-west and circular pattern of the mask that persisted in the processed images.

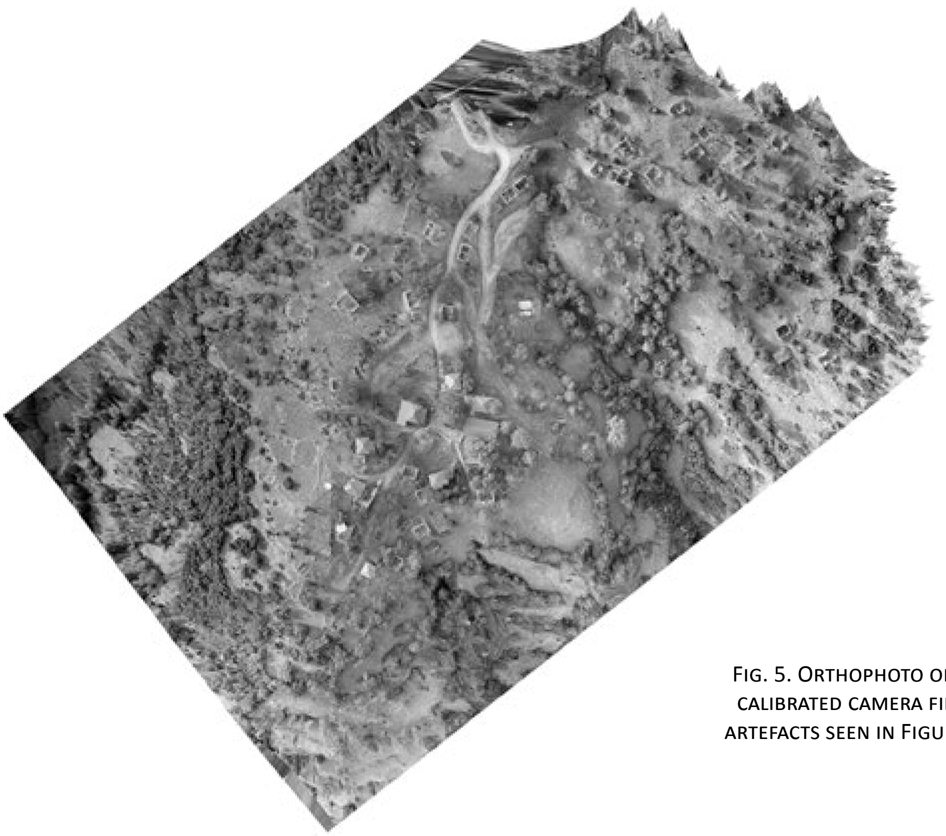


Fig. 5. Orthophoto of the site of Aigition using calibrated camera file. Note that the gaps and artefacts seen in Figure 4 are no longer present.

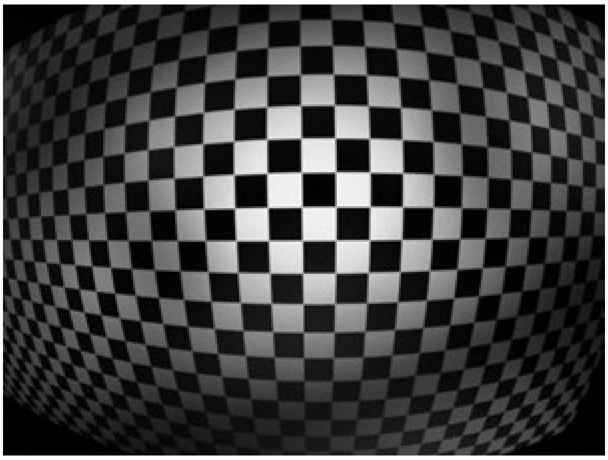


Fig. 6. Photograph used for calibration that shows the lens distortion inherent in the GoPro.

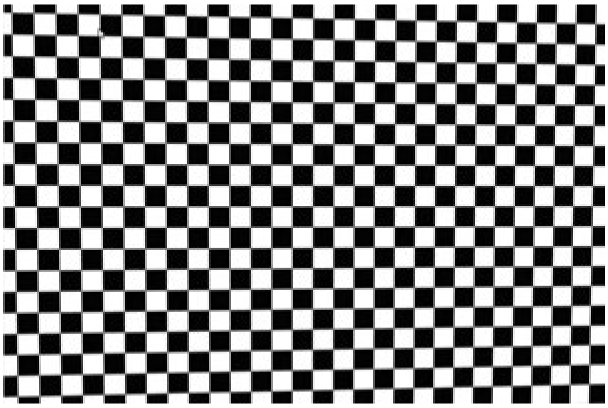


Fig. 7. Image produced after calibration with distortion seen in Figure 6 removed.

Fig. 8. Section from orthophoto produced using bare earth surface in Agisoft. Note the 'ghosting' around several buildings where the surface was insufficient to hold all features to the same surface location.

in Figure 8, the bare earth surface did not provide sufficient information to model vegetation and building features. As noted above, SfM generated data is different from that produced by traditional photogrammetric survey. The software uses multiple views of locations and needs surface information for all features in the photographs to correctly map these to their corresponding position on the earth's surface. The 'ghosting' shown in Figure 8 is the result of a lack of positional information to correctly tie features to their locations. We found that including all features in the elevation model was most effective for generating quality orthophotographs.

4 Conclusions and future directions

The results of the UAV and GoPro camera collection were generally very good. The control that the pilot had over the flight path and the untethered characteristic of the UAV allowed the team to rapidly survey areas that were difficult to access with KAP and BAP techniques. While the camera worked well for our needs, we found that the GoPro had certain limitations. The quality of the images, while sufficient for building and village level analysis, is not as defined as what can be produced using larger sensors and better lenses typically found on DSLR cameras. Our methodology was also somewhat inefficient. The techniques that work for KAP photography are not always best suited for UAV work. Visually determined flight lines did not always fully maintain the position of the UAV. During periods of strong wind, the UAV would gradually shift off course causing holes or areas of minimal coverage over certain parts of the site. The 'spotter' was not always visible to the pilot and was not always able to effectively relay details about direction and orientation. Our work also suggested that a combined approach to data collection is beneficial for understanding and interpreting village and building level features. While the UAV survey provided a good base map for our study, the manual documentation of buildings and architecture was invaluable for interpreting and understanding these features. The act of physically viewing and drawing architecture forces the mind to interpret and analyse structural details in a manner that cannot yet be replicated through SfM mapping.

The data acquired using the UAV and the architectural survey will be added to our project GIS. Additional work is ongoing. Terrestrial photographs of buildings will be taken during the 2015 field season further to document the buildings captured using the UAV (a preliminary building model of a structure from Aigition can be seen in Figure 9). High-resolution DSLR photographs of objects from the folklore museum will be used to generate 3D images of materials from the sites under examination. The project data will be disseminated through a project web interface similar to that developed for work conducted in the western Peloponnese (Brenningmeyer and Cooper 2009; Brenningmeyer and Franck 2010).

The data collected by the Lidoriki Project spans the regional, urban, architectural, and artefact scales. Features and objects photographed and reproduced in 3-dimensional format allow for virtual analysis and reconstruction. The project hopes to answer a number of historical questions on the life of Greek villages during the century of their economic and demographic heyday, 1850–1950. At the same time, it creates an objective record of sites that can be used for documenting future deterioration and processes of entropy. Given the increasingly limited resources in archaeological research both in Greece and the United States, our method of documentation will present a streamlined set of operations that can be easily applied by other researchers. The authors are collaborating with two additional surveys of deserted Greek villages, the deserted mud-brick village of Penteskouphi (Corinth Excavations, American School of Classical Studies at Athens) and the seasonal hamlet of Schinochori (Western Argolid Archaeological Project). A gathering of American scholars working on similar deserted Greek villages will compare data during two organized panels at the 2016 annual meetings of the Archaeological Institute of America. Our work in Lidoriki hopes to set some methodological standards and encourage the compilation of similar village data by other researchers.

The scholarly questions that the Lidoriki Project will address begin at the scale of the settlement. The efficient mapping of the entire village of Aigition highlights the urban organization of the site. Radiating from the village centre, the housing is concentrated along two ridges divided by a brook. Two large threshing floors and associated storage spaces are concentrated on the western slopes of the settlement, to capitalize on the direction of the winds during harvest. At the urban scale, the mapping of the village will, thus, clarify the seasonal and productive logic of the village particularly in its mixture of grain agriculture and animal husbandry. The placement of the church, the cemetery, and the school around the central piazza clarifies the civic dimension of rural society.

During the survey of Aigition, we discovered spatial relationships between clusters of houses. This will allow us to reconstruct relationships between primary and secondary structures, or between human and animal usage. The spatial relationship between individual houses will further help us understand some relative chronologies. Does a cluster of houses, for example, represent intergenerational growth within a family unit? Are retaining walls, storage spaces, or animal pens shared by a cluster of houses to suggest some shared familial organization? At the outer limits of the village, terrace walls give evidence for the maintenance of agricultural plots. Although the land holdings of Aigition would extend over great distances, we can relate the most adjacent terraced plots with the village.

Moving into the architectural scale of the individual house, a detailed 3D survey of the ruined walls provides new information about house construction as a system of orchestrated craft expertise and material. The houses in the region of Lidoriki are all built of masonry stone, but there are variations in the treatment of that stone that reflect stylistic aspirations. Most notable is the special treatment given to corner blocks that are critical to the structural integrity of the rectangular building. In addition to being finally dressed ashlar blocks, with at least four of the six block sides flat, the blocks often contain surface treatment — most notably rustication — derived from the monumental architecture of the urban centres. The corner quoin blocks are also where all inscriptions are placed, typically at the highest course. Beyond stone masonry, the houses incorporate wooden beams along the length of the stone walls. These beams are used to anchor structural timber, as well as the wooden casings for doors and windows. The inclusion of so much wood in the masonry walls is very different from masonry practices in other regions in Greece, such as the Peloponnese. The availability of wood from the nearby forests explains this practice. Although stone is ample, there is a shortage of good limestone to be used

Fig. 9. Preliminary model of house from Aigition using terrestrial photographs.

for lintels and other structural details. Beyond the structural elements of stone and wood, the 3D survey of architectural houses provides information on even finer details, such as the use of metal hardware in the attachment of wood with wood or wood with stone. In some parts of the structural frame, such as in the roof trusses, mortise and tenon joints are used. The houses of Lidoriki are beautifully crafted with pre-modern techniques. In their ruined state, the walls are dissected and offer clear evidence of their construction. Built entirely of local material, the houses provide lessons on ecological design and the creation of an architectural system based on environmental availabilities.

Ruined and abandoned for two generations, Aigition's houses contain no furnishings or domestic assemblages from their last time of usage in the 1950s and 1960s. Luckily, the Lidoriki Folklore museum has been assembling domestic artefacts from family heirlooms throughout the area. Objects such as pottery, textiles, agricultural implements, looms, tools, machines, and furniture give a representative glimpse of domestic life in the 19th and early 20th century. In 2015, we photographed 137 such artefacts. Using the same 3D modelling software (Agisoft) as in the urban survey, we have produced 3D models of numerous objects. Having 3D-modelled the houses and the objects separately, we hope to bring the two models together and repopulate the empty houses with their respective artefacts. Through a digital exhibition and house reconstruction, we hope to recreate the original spaces of Lidoriki. The Folklore Museum has no staff or budget and serves more like a repository for posterity. Our digital modelling of its objects will be disseminated through our website and made available for the first time to both scholars and the general public.

In short, the Lidorik Project has provided a new methodological format of cheaply and efficiently recording deserted Greek villages across three scales: landscape, architecture, and objects. At the same time, it has created a scientific record of material culture as it exists now to be used as a benchmark for further documentation or as a vehicle for drafting a cultural heritage policy. As a digital project in cultural heritage management it simultaneously builds a scholarly base and offers resources to users outside the scholarly community, such as students, national and local organizations, planners, and citizens.

Bibliography

Asdrachas, S. 1979. *E oikonomike dome ton valkanikon choron (15os-19os aionas)*, Athens, Melissa.

Bommeljé, S., Doorn, K. P. M. Deylius, J., Vroom, Y., Bommeljé, Y., Fagel, R., Van Wijngaarden, H. 1987. Aetolia and the Aetolians: Towards the Interdisciplinary Study of a Greek Region. *Studia Aetolica I*, Utrecht, Parnassus Press.

Brenningmeyer, T., Cooper, F. 2009. Remote Inventory of Greek Vernacular Architecture: Online Capture of Spatial Information, *CAA07*: British Archaeological Reports International Series: 243-5.

Brenningmeyer, T., Cooper, F., Downey, C. 1998. Satellites, Silicon, and Stone: Spatial Information and Greek Archaeology. *Geo Info Systems*: 20-8. January 1998.

Brenningmeyer, T. and Franck, S. 2010. Developing an Intuitive GIS Interface for Archaeological Data at the Pyrgos Museum, Greece. *CAA 2009 Making History Interactive, 22-26 March 2009, Williamsburg VA*. Electronic Document.

Cooper, F., Kourelis, K., Foster, H. D., Coulton, M., Alchermes, J. D. 2002. *Houses of the Morea: Vernacular Architecture in the Northwestern Peloponnese (1205-1955).* Athens, Melissa.

James, M. R., Robson, S. 2012. Straightforward Reconstruction of 3D Surfaces and Topography with a Camera: Accuracy and Geoscience Application. *Journal of Geophysical Research* 117(F3). [Online] Available from: http://onlinelibrary.wiley.com/doi/10.1029/2011JF002289/full.

Jameson, M. H., Runnels, C. N., Van Andel T. H. 1994. *A Greek Countryside: The Southern Argolid from Prehistory to the Present Day*. Stanford, Stanford University Press.

Kim, J. H., Pyeon, M. W., Eo, Y., Jang, I. 2014. An Experiment of Three-Dimensional Point Clouds Using GoPro. *International Journal of Civil, Architectural Science and Engineering.* 8, 1: 82-5.

Kouremenos, K. E. 1989. *Phokida*, trans. P. Ramp, Athens, Melissa.

Rudofsky, B. 1964. *Architecture without Architects. A Short Introduction to Non-Pedigreed Architecture,* Garden City, N.Y., Doubleday.

Snavely, N., Seitz, S., Szeliski, R. 2006. Photo Tourism: Exploring Image Collections in 3D. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2006)*. [Online] Available from: http://phototour.cs.washington.edu/Photo_Tourism.pdf.

Snavely, N. Seirz, S., Szeliski, R. 2007. Modeling the World from Internet Photo Collections. *International Journal of Computer Vision*. [Online] Available from: http://phototour.cs.washington.edu/ModelingTheWorld_ijcv07.pdf.

Sutton, S. B. 2000. *Contingent Countryside: Settlement, Economy, and Land Use in the Southern Argolid Since 1700*. Stanford, Stanford University Press.

Vroom, J. 1998. Early Modern Archaeology in Central Greece: The Contrast of Artefact-Rich and Sherdless Sites. *Journal of Mediterranean Archaeology* 11: 131-64.

A Fully Integrated UAV System for Semi-automated Archaeological Prospection

Matthias Lang[(1)]
matthias.lang@uni-tuebingen.de

Thorsten Behrens[(2)]
thorsten.behrens@bitmapping.de

Karsten Schmidt[(3)]
karsten.schmidt@uni-tuebingen.de

Dieta Svoboda[(1)]
dieta.frauke.svoboda@uni-tuebingen.de

Conrad Schmidt[(4)]
conrad.schmidt@uni-tuebingen.de

[1] eScience-Center, University of Tübingen
[2] BitMapping GmbH
[3] Collaborative Research Center 1070, RessourceCultures, University of Tübingen
[4] Institute for Ancient Near Eastern Studies (IANES), University of Tübingen

Abstract: In this paper we will discuss the use of semi-automated UAV mapping and image processing for large-scale aerial surveys in contrast to widely used low-cost systems. We will also compare a fully integrated software package to the workflow based on well-known structure-from-motion solutions. Moreover, we will show the first results gathered by the system from two large-scale archaeological surveys on the Heidengraben in south-west Germany and in Al Khashabah in the Sultanate of Oman. We will show that semi-automated UAVs offer the possibility of a precise, efficient, and fast documentation of extensive archaeological sites. Thereby such systems are valuable tools for preserving and managing these monuments. In a last step we will compare the Digital Surface Model (DSM) obtained by the UAV with a common high-resolution Lidar scan.

Keywords: UAV, Aerial survey, SFM, Lidar, Photogrammetry

Introduction

In the last few years unmanned aerial vehicles (UAV) have become one of the emerging new technologies in archaeological fieldwork (Eisenbeiss 2009; Lambers *et al.* 2007). In combination with powerful software packages, orthophotos and digital surface models can be obtained in a short time. While conventional aerial archaeology is very cost-intensive and limited to large-scale sites, a UAV can be used to obtain very high-resolution images of small excavations. The biggest benefits of the technology are relatively low costs and the fact that operating UAVs is easy after appropriate training.

The results obtained by these systems can easily be imported into a GIS without a time-consuming rectification process. Another advantage beside conventional aerial or satellite archaeology is the possibility to repeat the survey after a certain time to document ongoing archaeological fieldwork or for time-series analysis — to monitor the state of preservation or to detect new features by differences in vegetation patterns in the course of the seasons. Furthermore, a Digital Surface Model (DSM) and an orthophoto can be obtained simultaneously based on the same image dataset.

1 Objectives

In summer 2014 we decided to evaluate a low-cost UAV system to support a wide range of archaeological projects at the University of Tübingen. We chose a DJI Phantom 2 Vision + and Agisoft Photoscan Pro in combination with a handheld GPS for measuring ground control points. This set-up is currently used by a wide range of archaeological projects all over the world.

First, we used the system within a survey in Iraqi Kurdistan (Sconzo 2014) to document settlement structures — mainly tells — in the investigation area. In this case the method was much faster and more efficient than conventional surveying technologies using Differential-GPS (DGPS) or a total station.

In addition we tested the set-up on the so-called Heidengraben (Stegmeier 2009) in south-west Germany. The aim was the generation of an orthomosaic of 1600 ha. After first tests it became clear that the workflow was much too slow and complicated to cover an area of that size. It was almost impossible for the pilot precisely to operate the UAV manually at the right speed, on the right path, and at the same altitude to cover the required area fully and to guarantee enough overlap of the images to generate a DSM and an orthomosaic. Moreover, it was very difficult to determine which area was already covered and which was not. Due to the relatively long processing time using Agisoft Photoscan it was not possible to control the results within a reasonable time in the field and thus to plan subsequent missions easily. Furthermore, the flight time was limited to less than 20 minutes. Another downside of the set-up is the imprecise GPS unit of the UAV, by which it was necessary to lay out and measure up to 15 Ground Control Points to allow a precise allocation of the obtained result.

As a result of that evaluation we concluded that such systems are appropriate for small-scale aerial surveys such as excavations or limited prospection areas. For large sites, however, such set-ups are not suitable because of the lack of control and the time-consuming data processing.

Hence, we were looking for an optimized system, in other words:

- the ability to program auto-missions allowing for precise mission planning
- long endurance
- precise onboard GPS-based georeferencing
- fast on-site image control (image quality and image location)
- ease of operation by one person
- simple and automated image processing workflow
- cost-efficient

Based on these technical preliminaries we developed and tested a new UAV hardware and software solution to overcome the shortcomings described above. Subsequently, we tested the suitability of the proposed methodological framework in two different study areas, on the above-mentioned Heidengraben and in Al Khashabah in the Sultanate of Oman.

3 Technologies

3.1 Hardware

Endurance is crucial for many surveying applications. Most commercial systems, however, are designed for cinematography or aerial photography and require carrying heavy payloads; thus these systems often provide flight times of less than 20 min. Field surveying, however, requires long-endurance systems with relatively small payloads, but also systems that can be easily transported — again resulting in some trade-off. On-site image geo-referencing control, as well as optimal orthomosaics, require nadir images. This necessitates a stabilized camera gimbal, which again adds weight. To allow the application without specific permits the entire set-up must be below 5 kg.

To fulfil these requirements we developed a UAV specifically designed for mapping requirements (Fig. 1). The UAV is a hexacopter, which, compared to a quadrocopter, gives some degree of redundancy and thus security as well. It has easily detachable arms and legs and can carry a payload of 400 g for up to 45 min (depending on battery and weather conditions). The 400 g payload comprises a brushless stabilized gimbal and a Canon S110 camera. The total weight including camera, gimbal, and battery is 3.1 kg.

The advantages of a copter compared to a plane for archaeological surveys are:

- a copter can take off and land on one spot
- the copter can be forced to keep yaw which helps to analyse the images and provides additional security, since the orientation of a copter is sometimes hard to see at the end of the line-of-sight
- a copter can fly at lower speeds and with smaller radii, which is important for many archaeological projects
- a copter can hold position, which is important for documentation as well as for security reasons
- in case of emergency a copter can immediately change direction

The UAV is based on the APM autopilot, which is an open source and open hardware project supported by 3D Robotics (3D Robotics 2015a) and the Computer Vision and Geometry Group of the ETH Zurich (Computer Vision and Geometry Group 2015).

The APM autopilot can be programmed to fly auto missions for surveys and to trigger the camera according to GPS positional information. This allows for a precise control of the image overlap.

2.2 Software

2.2.1 Mission planning

A major aim was a system that can be operated by one person. Moreover, fieldwork has shown that mission planning is best done on site and not in the office for various reasons (security, access, etc.). We decided to use the open source Tower (3D Robotics 2015b) application. Tower runs on android systems and allows the planning of survey missions by simply drawing paths or polygons on a Google Map on a tablet and by the selection of flight altitude and image overlap and sidelap (Fig. 2). This allows the surveyor to plan the flight within minutes directly in the field. Maps can be pre-loaded. Hence, an Internet connection in the field is not necessary.

2.2.2 CHDK

Using the Canon Hack Development Kit (CHDK 2015a) it is possible to trigger Canon cameras via USB from the autopilot. Moreover, the optimized settings for shooting a photo can be evaluated and controlled by a script running on the camera. Therefore, we use a special version of the KAP UAV Exposure Control Script (CHDK 2015b). This also offers us the possibility of determining the shooting delay and thus to use this information for precise georeferencing.

Fig. 1. The UAV with its remote control.

Fig. 2. On-site mission planning.

2.2.3 Mapping and visualization

To allow image evaluation and controlling directly after finishing the UAV survey in the field, Mavis was developed (Fig. 3). It allows the georeferencing of the images, to analyse image focus/blurriness, and to generate stitched mosaics within minutes. This helps to save time in case some camera settings were not appropriate. Beside this Mavis provides a complete and seamless workflow from precise and automatic image geo-tagging, to generating digital surface models and orthomosaics, as well as to analyse and post-process the data to derive vegetation indices to manipulate colours and generate reports.

The 3D mapping section, which generates DSMs and orthomosaics, is based on MicMac (Public Lab 2015). MicMac (Multi-Images Correspondances, Méthodes Automatiques de Corrélation) is an open source photogrammetry software package developed at the French National Geographic Institute (IGN).

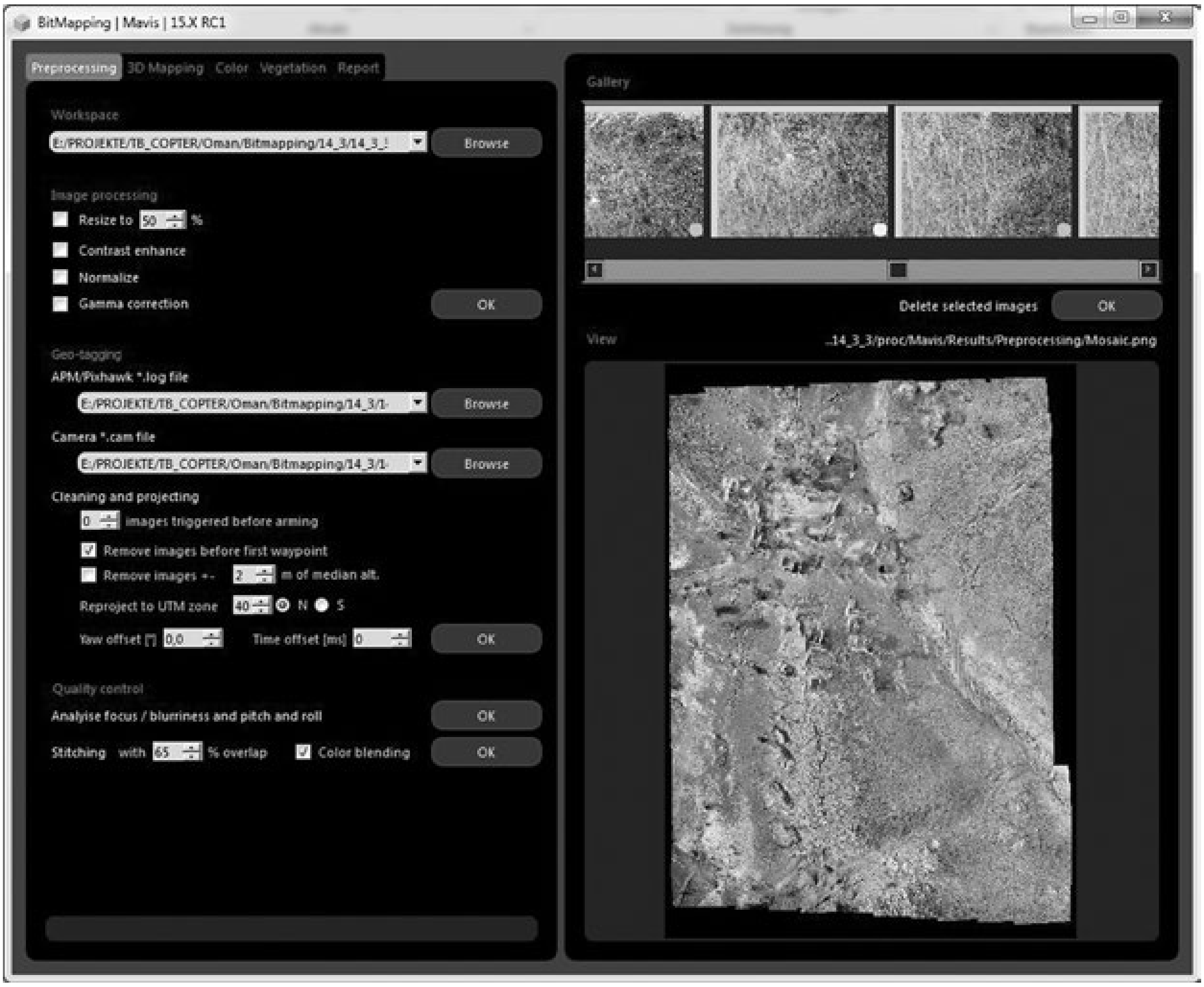


Fig. 3. Interface of Mavis.

MICMAC comprises a set of photogrammetric tools (Pierrot-Deseilligny and Clery 2011; Lisein *et al.* 2013).

The basic workflow is based on:

- the generation of tie-points based on automated feature extraction
- camera calibration and image triangulation: based on computer vision and photogrammetry
- dense matching for generating the DSM and the single ortho-images where a multi-image, multi-resolution, matching approach based the Cox and Roy optimal flow image matching algorithm (Roy and Cox 1998) is applied
- generation of the orthomosaic

Normally, MicMac uses the scale-invariant feature transform (SIFT) to extract and match features (Lowe 2004). In Mavis a new unique combination of the AKAZE feature extraction algorithm (Alcantarilla *et al.* 2013) with the CLAHE contrast enhancement technique (Zuiderveld 1994) is used to provide a powerful and license-free alternative.

The generation of the final orthomosaic in Mavis is also based on an alternative approach to provide optimized results.

All processing results are provided either in georeferenced *.png format or in SAGA GIS binary grid format, which can be imported or loaded in most GIS packages for further processing.

2.3 Operation

Easy on-site operation is crucial. It helps to avoid errors as well as to speed up mapping. A key point is automated missions including automated take-off and landing. Even though for security reasons the first flight should be conducted in manual/stabilize mode to check the system, subsequent flights can be run in full autonomous mode.

The UAV is operational in less than 10 min. Mission planning using Tower is accomplished in about 5 min. Depending on the normal mission length of 20 to 40 min and the subsequent image analysis in Mavis, which generally takes about 5 to 25 min, the entire process including packing takes 45 to 100 min. Depending on the weather conditions, altitude, and battery type up to 0.5 km can be covered in one flight. Final image

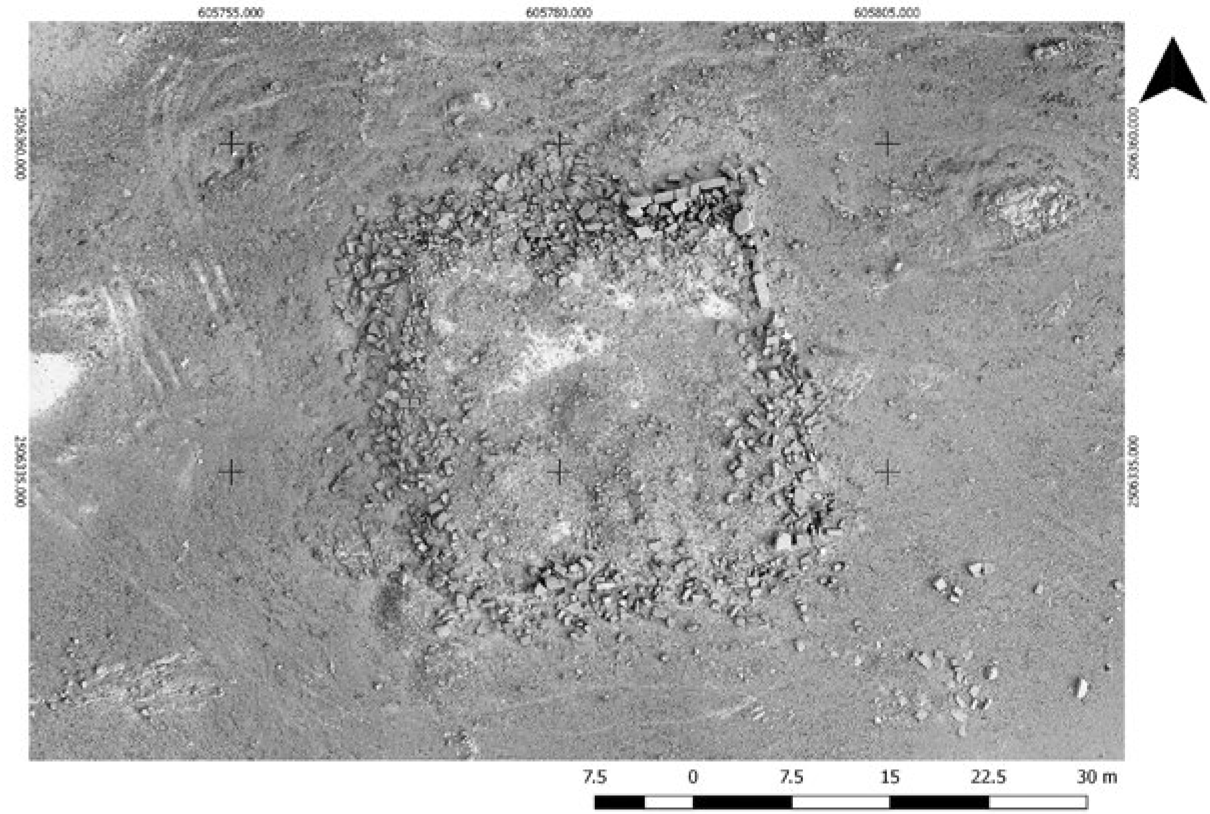


FIG. 4. ORTHOFOTO OF AN EARLY BRONZE AGE SQUARE BUILDING.

processing times in the office strongly depend on the desired final resolution as well as the processing power available, since most stages take advantage of multi-core computing environments.

3 Results and experiences

In this paragraph we discuss our experiences with the system, its advantages, and downsides on the examples of the two different project sites in the Sultanate of Oman and in south-west Germany.

3.1 Al Khashabah, Sultanate of Oman

The aim of the aerial survey in Al Khashabah in the Sultanate of Oman was to generate a high-resolution DEM and an orthomosaic of the whole area to document the site and to detect so far unknown archaeological features. Since the geodata provided by Google Maps or Bing Maps were the best information available for this area so far, a further aim was to generate a detailed site map.

The archaeological features visible on the surface of the site were numerous cairn tombs, three monumental round stone buildings, so-called towers, and three monumental square buildings, all Early Bronze Age (3rd millennium BC). The square buildings have a side length of up to 30 m (Fig. 4). The diameter of the towers is up to 25 m. The function of the latter, which in most cases feature several ring walls, is still disputed. They are mainly seen as communal structures connected to defending and controlling the land, to irrigation, or as meeting place for the community. The orthomosaic provides detailed plans of each of these building, highlighting their different layouts and settings within the landscape. In addition to the Early Bronze Age features, a few tombs from the Middle and Late Bronze Age (2nd millennium BC) as well as from the Iron Age (1st millennium BC) and the Islamic period (2nd millennium AD) were also detected. The very well preserved late Islamic mud-brick village of Safrat Al Khashbah is of special interest (Fig. 5). In this case, with the orthomosaic detailed plans of every single building within the settlement, the surrounding fields, and the irrigation channel — which runs several kilometres from the mountains to the village — can be obtained. The DSM helps to understand diachronic changes in land use at the site and thus helps to gain a better understanding of the different archaeological features found in Al-Khashbah and hence the changes in social organization in each period. The orthomosaic provides an excellent basis for mapping all structures and finds from the archaeological field survey that was carried out at the site in 2015. Through this, concentrations of finds can be correlated with archaeological features and features in the landscape that are sometimes hard to see on the ground but which are clearly visible from the air. For example, clusters of a specific type of late Islamic pottery can be linked to shallow circular elevations in the landscape that might represent historic wells.

Because of the lack of vegetation and the limited size of settlements and cultivations the area was well suited for an aerial survey. As a result the DSMs shows the surface of the

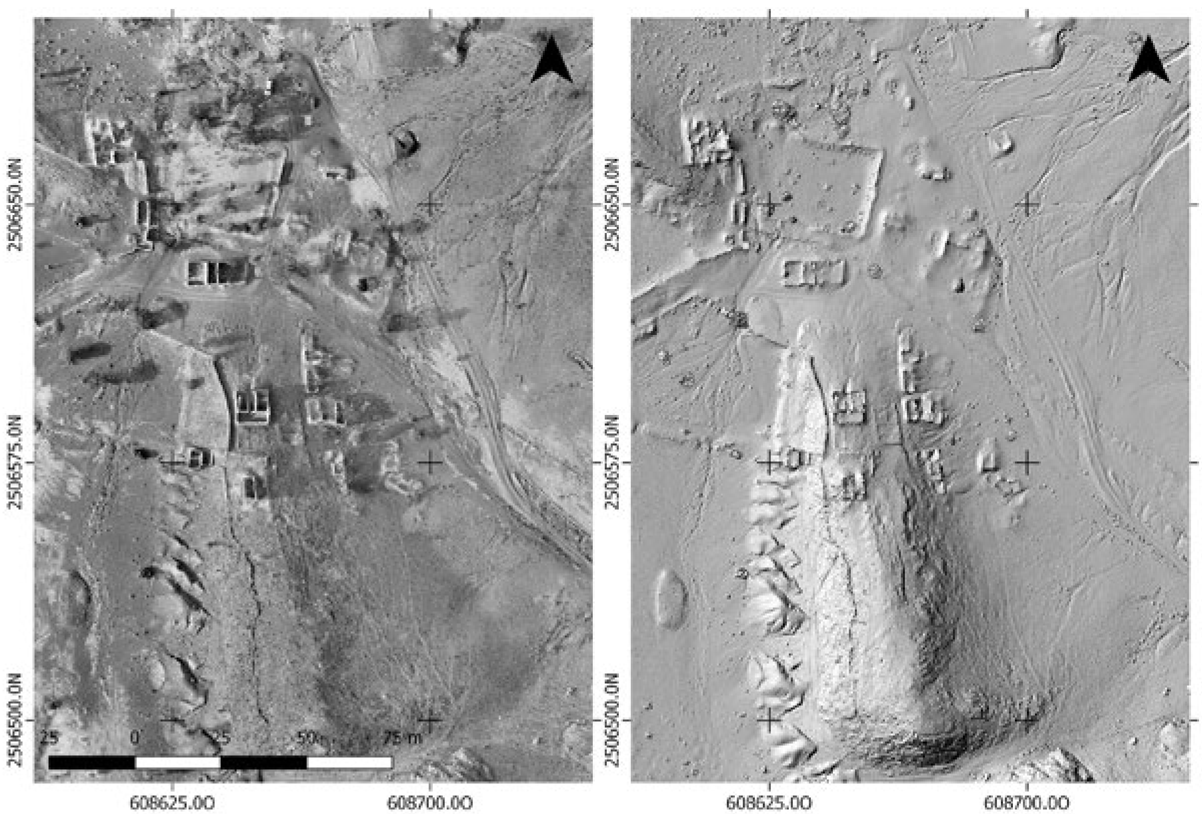


Fig. 5. Orthofoto and DSM generated by the UAV.

terrain without much interference and the relevant features are clearly visible in the orthomosaic. By choosing an operating altitude of 60 m, a ground resolution of about 2 cm could be obtained. For some areas with a more complex topography an altitude of 80 m was chosen for safety reasons, which is still good enough for most archaeologically relevant structures. For those areas where a very detailed resolution was necessary we decided to use the flight altitude of 30 m with an achieved resolution of 1 cm. From those pictures it is quite possible to map every single stone of an architectural structure.

For precise georeferencing we measured three Ground Control Points using a DGPS. The mean difference between the coordinates determined by the hexacopter's onboard GSP-unit and the ground control points was less than 2 m in most locations. The error within one orthophoto is nearly linear, showing that the obtained results are nearly distortion-free. As a result the detection of one control point is sufficient to georeference the orthophotos and DEMs accurately.

3.2 Heidengraben

With an area of 1600 ha the Heidengraben is the largest Celtic settlement (1st millennium BC) in central Europe and many features are still visible in the relief (Stegmeier 2009). In particular, the fortifications from the La Tène period (1st millennium BC) are extremely well preserved (Ade 2013) (Fig. 6). As almost the whole site is still subject to extensive agriculture, settlements, traffic-infrastructure, and contains two stone pits, it is highly endangered. The main aim of the aerial survey is therefore the documentation of the current status of the site to prevent the ongoing destruction of the archaeological features. Furthermore, high-resolution mapping of the area will help to detect and preserve so far unknown archaeological structures.

In general this survey was much more difficult compared to the project in Al Khashabah. One of the biggest problems is the intensive usage of the area; two nearby sports airports prohibit the use of UAV for safety reasons without the agreement of the airport authorities. Furthermore, large parts of the site are covered with forest and shrub and the terrain surface therefore cannot be surveyed using structure-from-motion techniques.

Despite all these problems, the UAV is a very helpful tool to support the ongoing documentation process.

3.2.1 Comparison of the UAV-generated DSM with a Lidar scan

Airborne Lidar data is a valuable source of information for archaeologists on the landscape scale. For this reason we decided to compare the existing Lidar scan of the Heidengraben area with DSMs generated by the UAV in the order to evaluate whether an aerial survey is significant when a Lidar generated DEM is already available.

It soon became obvious that the UAV-generated DEM offers a much higher level of detail than the Lidar scan (Fig. 6).

The typical resolution of Lidar is less than 50 cm whereas the typical resolution of UAV/SfM data is better than 5 cm.

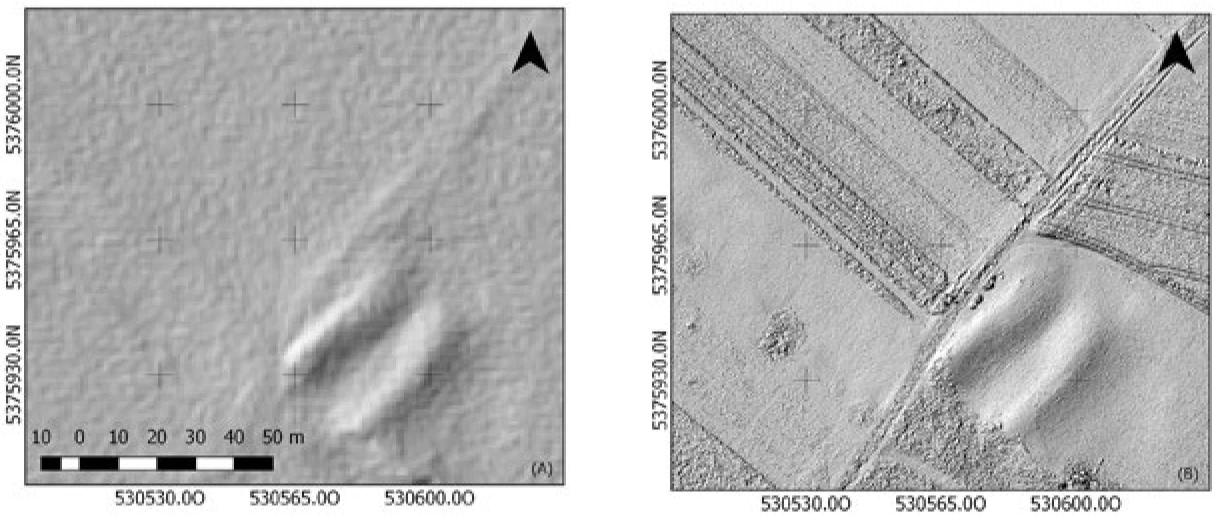


Fig. 6. Comparison between a Lidar (left) and a UAV-generated DSM (right).

Depending on the flight altitude above ground and the focal length as well as the resolution of the camera, resolutions better than 1 cm are easily possible allowing the mapping of the finest details and structure. Furthermore only the UAV will generate a precise orthophoto while the Lidar scan will be limited to the DSM.

Hence, UAV systems are much more appropriate when an extremely high resolution is needed and the site is not covered by dense vegetation. Under forest, however, Lidar is the better solution.

4 Summary

It became clear that a semi-automated UAV system is well suited to document even very large archaeological sites in an efficient and precise way. In comparison to a Lidar scan it offers a much higher level of detail and even small changes in the relief are clearly visible. Moreover, the documentation process is repeatable in any necessary time interval at low cost. Such systems are also appropriate to document an ongoing excavation or changes in the condition of an archaeological monument. Another benefit compared to a Lidar scan is that every flight provides an orthomosaic and a DSM at the same time with the same sensor.

One of the downsides is the impossibility of removing the vegetation from the resulting elevation models. In this case the connection of the UAV-based aerial survey and a Lidar scan seems to be a more productive strategy.

5 Outlook

The system is operational and has been used for about 100 archaeological mapping missions so far. the next step is to integrate RTK (real-time kinematics) GPS solutions for precise georeferencing. Colour calibration is also relevant when analysing time-series data. Hence, the focus is primarily on the software/processing side.

Lidar systems which can be carried using a UAV are available. Endurance is limited, however, and the costs are much higher than the system used in this study, but a lightweight long endurance system is one goal of our working group.

Bibliography

Ade, D. *et al.* 2013. *Der Heidengraben - Ein keltisches Oppidum auf der Schwäbischen Alb. Führer zu archäologischen Denkmälern in Baden-Württemberg 27*. Stuttgart, Theis.

COMPUTER VISION AND GEOMETRY GROUP (2015) [Online] http://cvg.ethz.ch/ [Accessed: 29 June 2015].

Eisenbeiss, H. 2009. UAV Photogrammetry. IGP Mitteilungen 105. Zürich, Institut für Geodäsie und Photogrammetrie Eidgenössische Technische Hochschule.

Lambers, K. *et al.* 2007. Combining photogrammetry and laser scanning for the recording and modelling of the late intermediate period site of Pinchango Alto, Palpa, Peru. *Journal of Archaeological Science* 34: 1702-10.

Lisein, J., Pierrot-Deseilligny, M., Bonnet, S., Lejeune, P. 2013. A Photogrammetric Workflow for the Creation of a Forest Canopy Height Model from Small Unmanned Aerial System Imagery. Forests, Volume 4, Issue 4: 922-44. Available at: dx.doi.org/10.3390/f4040922, December 2013.

Lowe, D. 2004. Distinctive image features from scale-invariant keypoints. Int. J. Comput. Vis. 2004, 60: 91–110.

Pablo F., Alcantarilla, J. N. and Bartoli, A. 2013. In British Machine Vision Conference (BMVC), Bristol, UK, September 2013.

Pierrot-Deseilligny, M. and Clery, I. 2011. Evolutions recentes en photogrammetrie et modelisation 3d par photo des milieux naturels. Collect. *EDYTEM* 12: 51–64.

PUBLIC LAB 2015. *MicMac, another OS photogrammetry program* [online] http://publiclab.org/notes/mathew/7-12-2012/micmac-another-os-photogrammetry-program [Accessed: 29 June 2015]

Roy, S. and Cox, I. J. 1998. A Maximum-Flow Formulation of the n-Camera Stereo Correspondence Problem. In *Proceedings of the Sixth International Conference on Computer Vision, Bombay, India, 4–7 January 1998*: 492–9.

Sconzo, P. 2014. *The Tübingen Eastern Habur Project Archaeological Survey in the Dohuk Region of Iraqi*

Kurdistan [Online] https://www.academia.edu/9547402/The_T%C3%BCbingen_Eastern_%E1%B8%AAabur_Project_Archaeological_Survey_in_the_Dohuk_Region_of_Iraqi_Kurdistan [Accessed: 22 July 2015].

Stegmeier, G. 2009. Stadt - Land - Fluss: Überlegungen zum Wirtschafts- und Besiedlungsgefüge des spätkeltischen Oppidums Heidengraben und seines weiteren Umlands. In Karl, R. and Leskovar, J. (eds.), *Interpretierte Eisenzeiten. Fallstudien, Methoden, Theorie. Tagungsbericht der 3. Linzer Gespräche zur interpretativen Eisenzeitarchäologie*. Studien zur Kulturgeschichte von Oberösterreich, 22: 253-64. Linz, Oberösterreichisches Landesmuseum.

WIKIA 2015a. *CHDK* [Online] http://chdk.wikia.com/wiki/CHDK [Accessed: 29 June 2015].

WIKIA 2015b. *CHDK* [online] http://chdk.wikia.com/wiki/KAP_UAV_Exposure_Control_Script#Release_History [Accessed: 29 June 2015].

Zuiderveld, K. 1994. *Graphic Gems IV*: 474–485. San Diego, Academic Press Professional.

3D ROBOTICS 2015a. *3D Robotics* [online] http://3drobotics.com [Accessed: 29 June 2015].

3D ROBOTICS 2015b. *3D Robotics* [online] http://3drobotics.com/software/ [Accessed: 29 June 2015].

Stereo Visualization of Historical Aerial Photos as a Valuable Tool for Archaeological Research

Anders Hast
aht@cb.uu.se
Department of Information Technology, Division of Visual Information and Interaction, Uppsala University, Sweden

Andrea Marchetti
andrea.marchetti@iit.cnr.it
Istituto di Informatica e Telematica, Consiglio Nazionale delle Ricerche, Pisa, Italy

Abstract: Stereo visualization of historical aerial photographs can be a valuable tool in the field of aerial archaeology. Visualizing in stereo gives a much better understanding of these photographs since the environment and buildings appear to be 3D. Moreover, they offer a way to go back in time, exploring things as they were, while at the same time allowing a comparison with a modern-day situation. An archive with several millions of such photographs is maintained by the AeroFototeca Nazionale (AFN) of the Italian Ministry of Cultural Heritage in Rome. Since the end of the 19th century this has constituted an important archive in Italy, before its transformation by post-war reconstruction. The archive is a valuable resource for aerial archaeologists and is made available through the GeoMemories application. Here, using several examples, we demonstrate how stereo is beneficial for obtaining an insight on what is actually seen and how this can be useful in archaeology.

Keywords: Historical aerial photographs, Stereo visualisation, Depth cue

Introduction

Historical aerial photographs can be a valuable tool in the field of digital heritage and aerial archaeology (Hanson and Oltean 2013). Visualizing such photographs in stereo gives a much better understanding as the environment and buildings appear to be 3D. We demonstrate in several examples how this is beneficial for obtaining an insight on what is actually seen and how it can be useful in aerial archaeological research. It is much harder, and often impossible, to estimate heights of objects, such as trees and bushes, from single photos. In fact they often tend to look the same, which is detrimental for understanding the environment. The depth cue (Hast 2010) is very important for distinguishing between objects and background. Therefore, by viewing these photos in stereo, a better understanding of the content can be obtained, such as the morphology of the site and the distribution of features around them, since the relative height of objects is discernible (Casana and Cothren 2008).

Aerial photography has been a rich source for understanding the historical development and changes in our world (Kirk 2005; Dunnage 2002) and these photos have predominantly been used with success in the field of aerial archaeology (Bourgeois and Meganck 2005; Brophy and Cowley 2005; Riley 1987; Wilson 2000).

As an example, in some photographs one can find crop marks etc. revealing ancient man-made constructions in places where no excavation can take place because of urban expansion, so that the photographs are the only practical way to study the past (Abrate *et al.* 2013).

1 Stereo as a valuable tool for finding artefacts

During the Second World War in the so-called Operation Crossbow (J. Kelly 2011), the Royal Air Force identified and destroyed many of the infamous V-weapons thanks to a secret weapon, the stereoscope. It allowed the RAF photographic interpreters at Medmenham in Buckinghamshire to study the landscape in 3D. This device made it possible to view a single three-dimensional image or stereogram, which consists of stereoscopic pairs of images, that is, both a left-eye and a right-eye view of the same scene. By meticulously photographing the landscape of occupied Europe, as one example shows in Figure 1, photographs with at least 60% overlap were obtained (T. Kelly 2011). The whole operation was a significant success for the RAF that most likely shortened the war. Several millions of these photos taken over Italy are now kept by the AeroFototeca Nazionale (AFN) of the Italian Ministry of Cultural Heritage in Rome, which is located at the office of the Istituto Centrale del Catalogo e della Documentazione (ICCD) (Tartara 2013). This extensive archive is used in this paper to illustrate the advantage of stereo visualization.

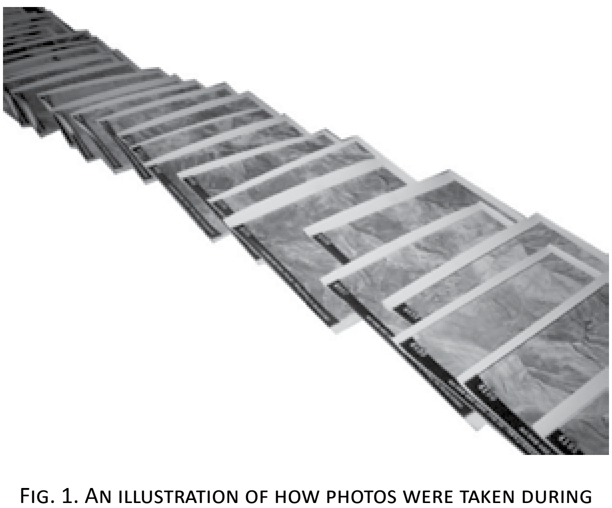


Fig. 1. An illustration of how photos were taken during an RAF flight over Italy. The individual photos are placed in their corresponding positions. (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

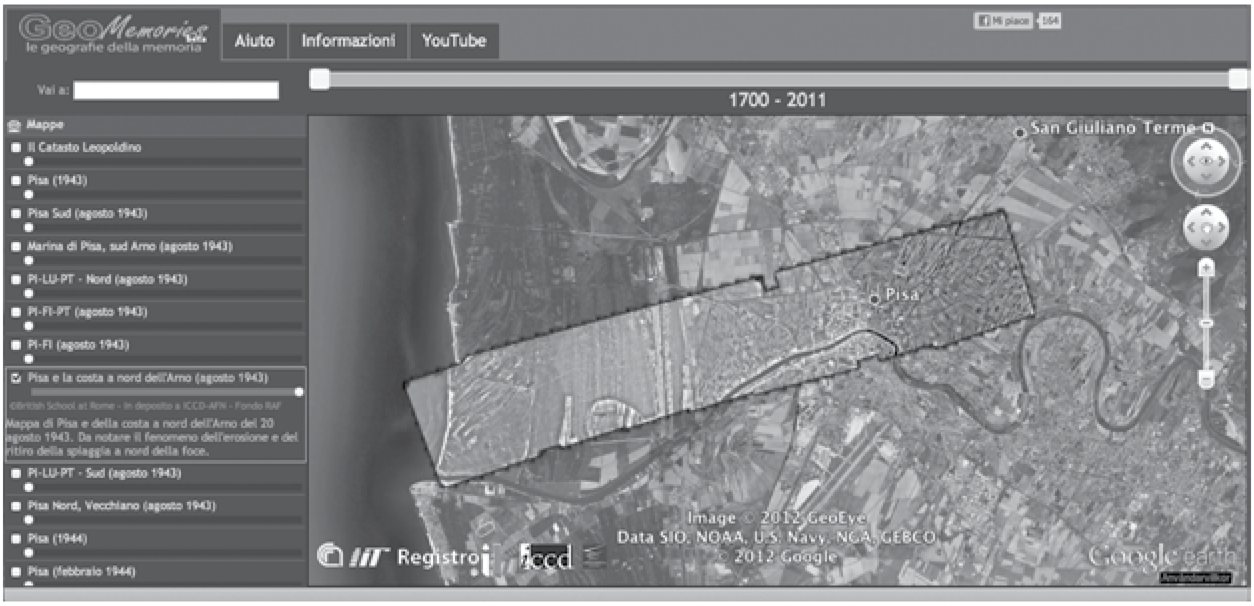


Fig. 2. The GeoMemories application. Note the GE navigation tools to the right and the historical map selector to the left. One historical map was chosen, which is composed of several photos taken by the RAF during a flight in August 1943 over the city of Pisa in Italy (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

2 GeoMemories

The Institute of Informatics and Telematics (IIT) of CNR in Pisa, launched the GeoMemories project in 2010, with the aim of making the AFN archive accessible via Internet through a web platform. The GeoMemories application (www.geomemories.org/) is a Google Earth (GE) based application, which allows the overlay of historical photos on GE maps and blending them together using a slider. Thanks to the images provided by AFN, researchers from fields such as archaeology, history, and also geology and geography, can revisit the 20th century and study the changes that occurred, whether due to human intervention or environmental changes. The GeoMemories application can therefore be used as a digital research tool, which has a great potential to become a valuable resource for all kinds of cultural heritage research and digital archaeology.

The original photographs in the AFN archive are digitized and processed before being inserted in the GeoMemories application. This process includes illumination correction (Hast and Marchetti 2011) and cropping borders so that information about the flight is removed and what remains is an evenly exposed image of the ground. To be able to stitch the photograph into a map (Szeliski 2006) at the right position with the right dimensions, the photograph is then orthorectified and georeferenced (Aguilar 2008; Hill 2006). A snapshot from the current version of the application is shown in Figure 2 where it can be seen that the navigation tool is the same as for GE. The user can choose which maps to overlay on the GE maps and blend by using the slider in the map selector to the left. In the snapshot, only one map is shown that is composed of photos taken from one flight (cf. Figure 1) in August 1943 by the British RAF during a flight over Pisa in Italy. The user can choose to show several maps that will be overlaid on each other or the application can also be used to explore individual photos from a specific flight or photos that covers a specific area that the user selects using the mouse.

3 Examples of Archaeological Value

The digital stereograms are a valuable resource for aerial archaeology research and some examples will be given here. They are especially valuable in cases where the actual artefact or building no longer exists and the photos are the only available source.

The first example is taken from the northern Italian city of Genoa, which underwent quite drastic changes when the new airport was built in the bay, as can be seen from the series of images in Figure 3. Large masses of rock and rubble were dumped in the sea to create the runway and just a part of it is visible in the bottom image. A more complete overview is given in Figure 4 and the impact on the environment is quite striking.

In Figure 3/a one can discern the Castello Raggio, once located on the popular beach of Genoa. The castle was damaged in the war and was eventually torn down in 1951 to make place for the airport. An anaglyph is seen in Figure 5 where the castle can be studied in 3D. Fortunately, there also exist a number of historical photos such as the one taken from a postcard in Figure 6.

Figure 7 shows the whole anaglyph obtained from a semi-automatic stereo pair extractor that was recently developed for the purpose of studying the AFN photos in stereo (Hast 2014). The original anaglyph is of size 4150 \times 4336, but this one is cropped and scaled down. Nevertheless, the original allows the study of fine details in the landscape that has been greatly transformed since the Second World War because of the rapid urban development of the city..

Figure 8 shows both the Palazzo Pretorio with its tower and the bridge Ponte di Mezzo, which both were destroyed during the Second World War. The destruction was total and both

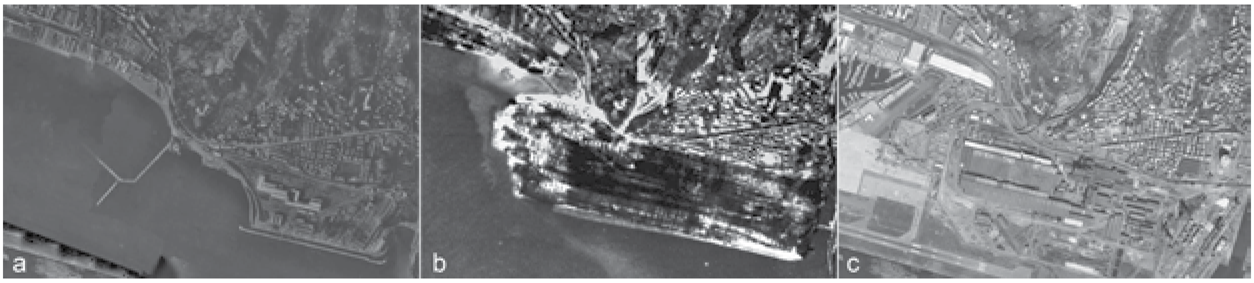


Fig. 3. Illustration of the change over time during the building of the Christopher Columbus airport in Genoa, Italy. The images are snapshots from the GeoMemories application. The overlaid photo a) was taken in 1943; photo b) was taken *c.*1954–56; c) a GE image from 2010 (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

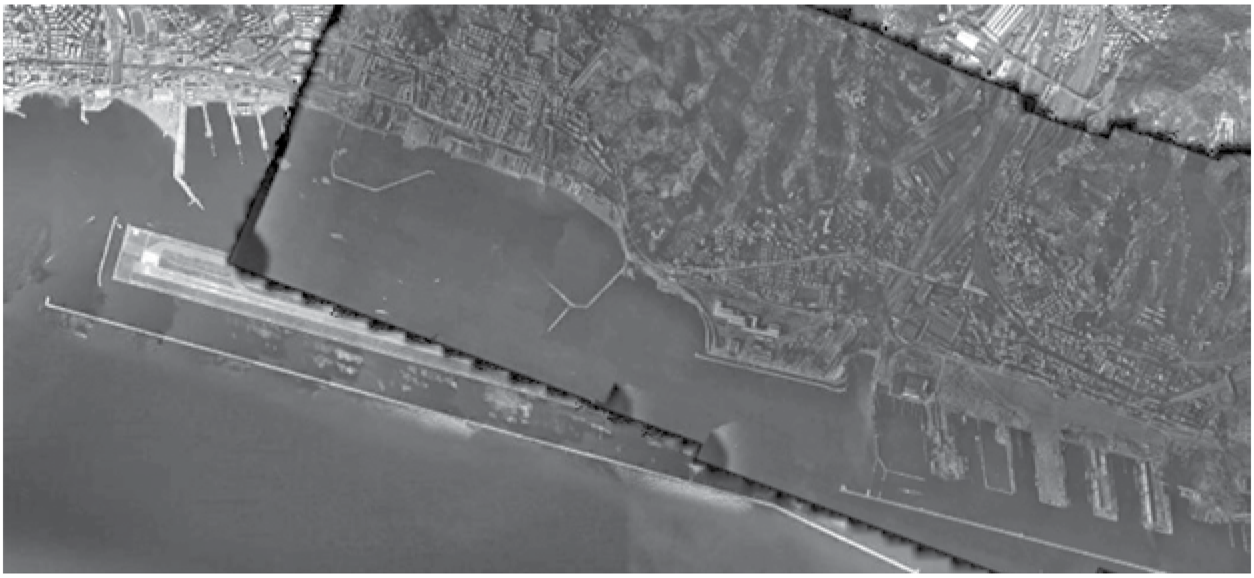


Fig. 4. Another snapshot from the GeoMemories application which shows the striking changes in the environment that were the result of building the Christopher Columbus airport in the bay of Genoa (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

Fig. 5. An anaglyph of the Castello Raggio in Genoa, Italy as it appeared in 1943 (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

Fig. 6. Castello Raggio as it appeared before being damaged in the Second World War and finally torn down in 1951 (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

Fig. 7. An anaglyph showing the beach of Genoa as it appeared in 1943. The airport was later built in the bottom part of the image. One can discern the Castello Raggio located at the beach in the centre of the bottom of the image (© MiBAC-ICCD, Aerofototeca Nazionale, fondo RAF).

were rebuilt after the war. The bridge is a modern bridge, while the palace with its tower was only partially based it on Gherardesca's design. According to the website (www.turismo.pisa.it/en/culture/detail/Palazzo-Pretorio/), 'the ground floor loggia was extended to the whole length of the building and the clock tower was built taller'.

4 Discussion

The main advantage with stereo visualization is that it gives a much better understanding of the photos, and hence a more accurate interpretation of the archaeological landscape can be made (Goossens *et al.* 2006). One example is shown in Figure 9, where the photos to the left do not reveal the height difference in the landscape very well. The only depth cue is the shadows that reveal that some parts are higher than others. In the anaglyph to the right, on the other hand, the height differences appear clearly. The 3D really helps to understand the content of an image (Hast 2010). The same goes for single objects such as houses, trees, bushes, etc. The height of such objects in the photos is clearly visible in stereo, while it is much harder, often quite impossible, to estimate heights from single photos.

There is no doubt that Operation Crossbow would not have been such a significant success without the use of stereo images. In particular, it would have been almost impossible for the photographic interpreters in Medmenham to locate the mobile V-2 mobile ramps without the use of stereo. In the same way, stereo literally offers an extra dimension to aerial archaeology researchers, which should not be underestimated. We therefore intend to publish the stereo content in the GeoMemories application in the future.

Stereo pairs or stereograms can be stored and viewed in many ways. Here it was chosen to show them as anaglyph images as they can be easily viewed using anaglyph glasses. For projector visualizations, however, it is usually better to store them digitally as a pair, which allows the use of both active shutter techniques and polarized filter glasses. There are already such archives available online today, but usually with very few stereo photos. This is because the process of creating stereograms still requires quite a lot of manual work and therefore the cost of producing them is rather high. Nevertheless, we claim that for aerial archaeology research they are worth the extra effort.

The results shown in this paper were obtained from work in progress and might have limited archaeological value per se. We claim that stereo is a valuable tool, however, which can be used to help archaeologists localize objects that would be difficult, if not impossible, to localize without stereo. Such objects might be man-made constructions that are now only found in historical aerial photographs due to changes in the landscape, either through natural causes or through human intervention such as submersion under water due to dam constructions and similar. We believe that the experiences obtained during Operation Crossbow clearly show that stereo visualization is very useful. When stereo images are inserted in GeoMemories, they will be publicly available for researchers all over the world.

5 Conclusions

Stereo images are important as they give a much better understanding of what is actually visible in the scene and the relative depth of landscape and objects. The perceived depth information provides clues that are not available in a single photo. Stereo adds a new dimension to 2D photos, both in terms of understanding but also for the ability to distinguish more clearly between objects and the ground. One particular advantage with historical aerial photographs is that they are important time documents. Because of rapid urban development as well as disasters, such as floods and earthquakes, these photos make it possible to study both buildings and environments that do no longer exist. The ability to view them in stereo helps to understand and see them as they once were. The GeoMemories application has the potential to become a valuable research tool for digital heritage research, especially when stereo content is being added.

Bibliography

AFN. *Aerofototeca nazionale, istituto centrale per il catalogo e la documentazione, Roma.* Available from: <http://www.iccd.beniculturali.it/>. [1 July 2015].

Aguilar, M. A., Aguera, F., Aguilar, F. J., Carvajal, F. 2008. Geometric accuracy assessment of the orthorectification process from very high resolution satellite imagery for Common Agricultural Policy purposes. *International Journal of Remote Sensing 29*: 7181–97.

Bourgeois, J. and Meganck, M. 2005. *Aerial photography and archaeology 2003: a century of information; papers presented during the conference held at the Ghent University, December 10th - 12th, 2003*, ser. Archaeological Reports. Academia Press.

Brophy, K. and Cowley, D. 2005. *From the Air: Understanding Aerial Archaeology*, Tempus Series. Tempus.

FIG. 8. A) AN ANAGLYPH IMAGE OF PALAZZO PRETORIO AND PONTE VECCHIO IN PISA, ITALY WHICH BOTH WERE DESTROYED DURING THE SECOND WORLD WAR. THE FIRST WAS RECONSTRUCTED IN 1956, WHILE THE SECOND WAS TOTALLY REBUILT; B) THE PALACE TO THE LEFT, WITH ITS TOWER, AND THE BRIDGE IN THE MIDDLE (© AUTHOR); C) AN IMAGE SHOWING THE TOTAL DESTRUCTION OF THE BUILDING AND BRIDGE (© WWW.TURISMO.PISA.IT).

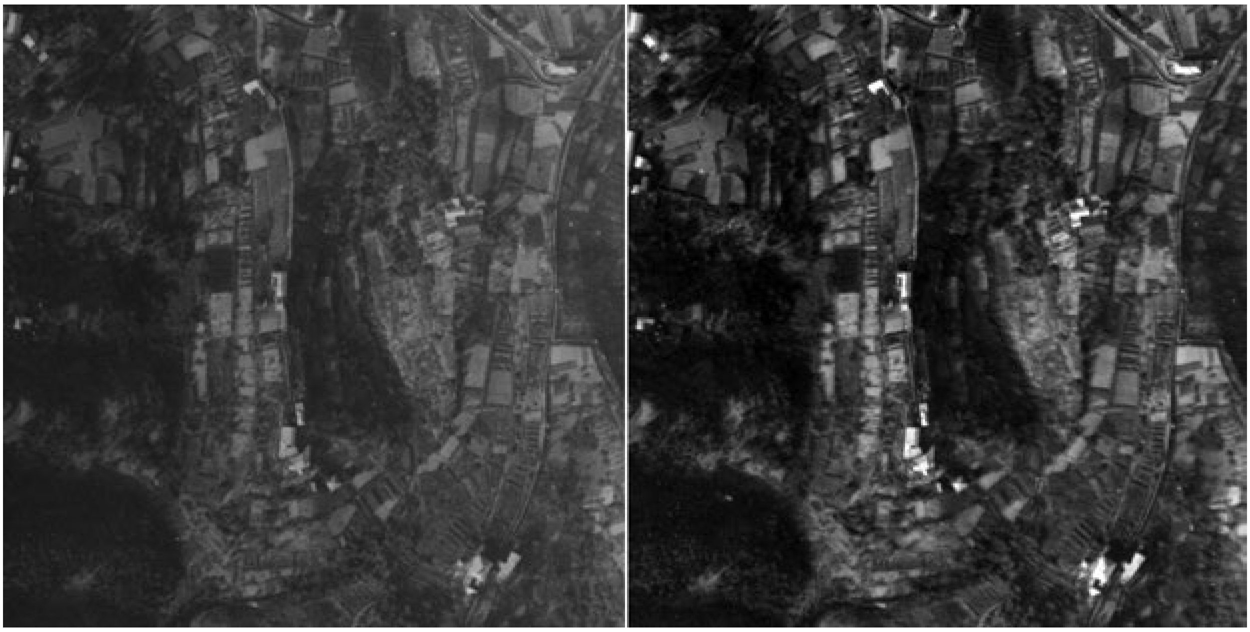


FIG. 9. BY LOOKING AT THE PHOTOGRAPH TO THE LEFT IT IS HARD TO TELL HOW THE LANDSCAPE IS SHAPED. THE ONLY CLUE TO THE DEPTH IS THE SHADOWS. THE ANAGLYPH STEREO IMAGE TO THE RIGHT, ON THE OTHER HAND, REVEALS THESE DETAILS CLEARLY.

Casana, J. and Cothren J. 2008. Stereo analysis, DEM extraction and orthorectification of CORONA satellite imagery: archaeological applications from the Near East. *Antiquity* 82: 732-49.

Dunnage, J. 2002. *Twentieth Century Italy: A Social History,* ser. Social History of Europe Series. Prentice Hall.

Goossens, R., De Wulf, A., Bourgeois, J., Gheyle, W. and Willems, T. 2006. Satellite imagery and archaeology: The example of corona in the Altai mountains. *Journal of Archaeological Science 33*: 745–55.

Hast, A. 2010. 3D Stereoscopic Rendering: An Overview of Implementation Issues. In E. Lengyel, Jones and Bartlett (eds.), *Game Engine Gems*: 123–38.

Hast, A. and Marchetti, A. 2014. 'Towards automatic stereo pair extraction for 3d visualisation of historical aerial photographs'. In *IC3D 2014, International Conference on 3D Imaging*: 1–8.

Hanson, W.S. and Oltean, I.A. 2013. 'A Spy in the Sky: The Potential of Historical Aerial and Satellite Photography for Archaeological Research'. In W. S. Hanson and I. A. Oltean (eds.), *Archaeology from historical aerial and satellitearchives*: 3-12. Springer.

Hill, L. L. 2006. *Georeferencing*. The MIT Press.

IIT. *Istituto di informatica e telematica, consiglio nazionale delle ricerche.* [Online] Available from: <http://www.iit.cnr.it/>. [Accessed: 1 July 2015].

Kelly, J. 2011. *Operation crossbow: How 3d glasses helped defeat hitler.* [Online] Available from: <http://www.bbc.co.uk/news/magazine-13359064>. [Accessed: 1 July 2015].

Kelly, T. 2011. *How 3D Glasses Helped Win World War II.* [Online] Available from: <http://newsfeed.time.com/2011/05/13/how-3d-glasses-helped-win-world-war-ii/>. [Accessed: 1 July 2015].

Kirk, T. 2005. *The Architecture of Modern Italy: Visions of Utopia, 1900-Present, ser. The Architecture of Modern Italy.* Princeton Architectural Press.

Riley, D. 1987. *Air photography and archaeology.* University of Pennsylvania Press.

Szeliski, R. 2010. *Computer Vision: Algorithms and Applications*. New York, NY, USA, Springer-Verlag.

Tartara, P. 2013. A Spy in the Sky: The Potential of Historical Aerial and Satellite Photography for Archaeological Research. In W. S. Hanson and I. A. Oltean (eds.), *Archaeology from historical aerial and satellite archives*: 123-45. Springer.

Wilson, D. R. 2000. *Air Photo Interpretation for Archaeologists.* The History Press Ltd.

CHAPTER 12
Open Source and Open Data

Strati5 - Open Mobile Software for Harris Matrix

Jerzy Sikora
gunthers1@wp.pl
Archaeology Institute, University of Lodz, Poland

Jacek Sroka
sroka@mimuw.edu.pl
Institute of Informatics, University of Warsaw

Jerzy Tyszkiewicz
jty@mimuw.edu.pl
Institute of Informatics, University of Warsaw

Abstract: There are a number of software tools whose aim is to create and maintain Harris matrix data during fieldwork. They tend to be complicated, and most of those we know of, don't work on mobile devices, especially off-line.

Filling this gap, we present a very simple open software tool for recording Harris matrix data. It has all fundamental functionalities and, in addition to desktop and laptop computers, runs on mobile devices, almost irrespectively of their operating system.

Our tool is indeed a formula-only spreadsheet (i.e. one without macros or user-defined functions), in the older .xls format of Microsoft Excel. Its user interface will be therefore familiar to almost everyone, and can be run of that person's preferred spreadsheet software system, mobile or desktop.

Keywords: Harris matrix, Data collection, Open license software, Mobile software, Spreadsheet, Android, iOS

Introduction

The destructive nature of archaeological field work implies the need of detailed documentation of the excavated structures. Once dug structures cannot be surveyed again, so the verification is extremely difficult in field archeology. The basic principles of archaeological stratigraphy, and the concept of Matrix (now called Harris matrix) was developed in 1974 by Edward C. Harris (Harris 1979).

Traditionally documentation of archaeological stratigraphy was based on so-called context sheets, in paper form. With the development of personal computers, information from context sheets were introduced to a computer at the stage of post-field elaboration of excavation results, with the use of standard text editors, spreadsheets or Database Management Systems, as well as special stratigraphic applications (e.g. *Stratify* (Herzog 2004), which also have the possibility of generating the Harris matrix. Development of mobile computers, tablets, and smartphones lead to paper-less archeology and recording in digital form, directly at the archaeological site. In order to reduce the costs of specialized field rugged computers or tables, it is possible to use Android or iOS based tablets, which are considerably cheaper and sufficiently resistant to destruction. They require application which not only allows for recording stratigraphic data, but also prevents against multiple assignment of the same code of context, or the emergence of cycles in which incorrectly described relationships will cause the stratigraphic unit as situated at the same time over and under another context, what sometimes happens on complex sites, or by a typing mistake.

Strati5, the tool we present in this paper, is aimed at recording data for Harris matrix on mobile devices. It runs on computers under Windows, Linux and MacOS, too, but, while there are other software choices for desktop and laptop computers, *Strati5* is to the best of our knowledge the only existing multi-platform mobile solution for that purpose.

1 List of basic functionalities

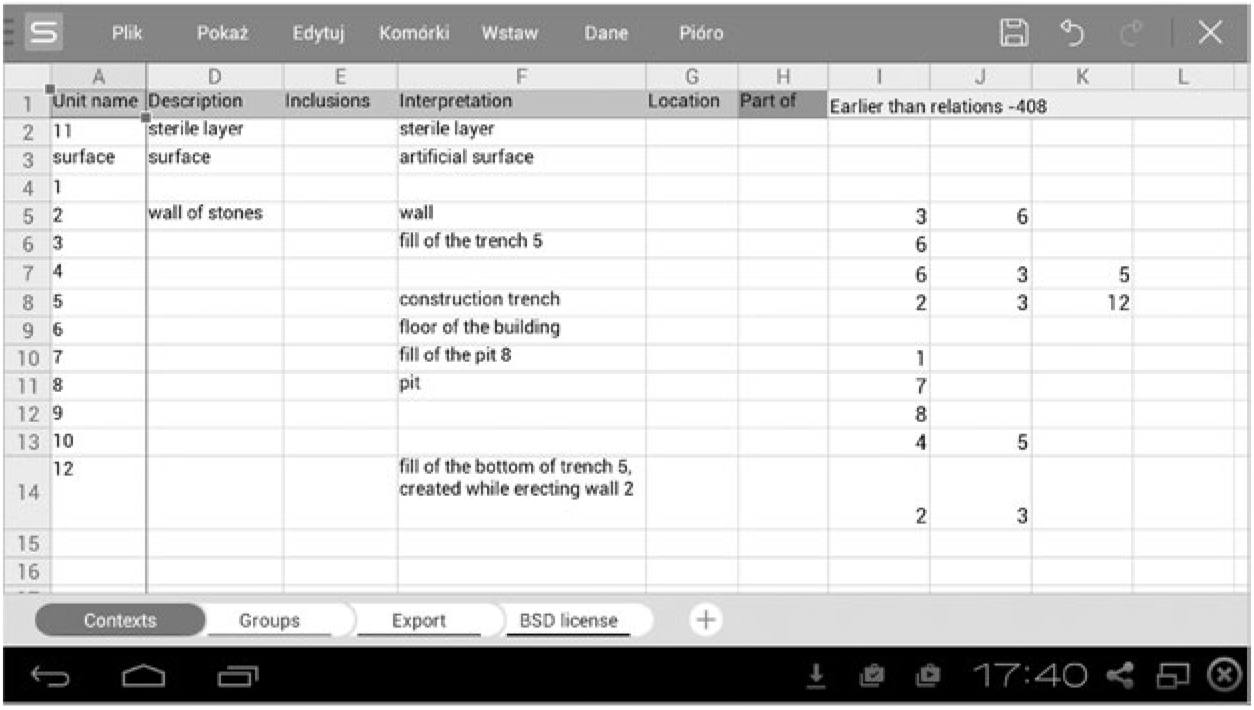
There are two variants of *Strati5*. The *offline* version is a simple spreadsheet – the adjective comes from the fact, that this version can run locally on mobile (and not only mobile) devices and does not need network access. The *online* version is the same spreadsheet, but uploaded to Google drive and enhanced by additional tools, made available by this environment.

1.1 Offline version

Strati5 offline satisfies the following functional requirements:

- Recording data about contexts, groups, and their relations
- Preventing duplicate context names
- Preventing duplicate group names
- Preventing assigning contexts to undefined groups
- Preventing creating relations involving undefined contexts
- Preventing cycles in relations
- Data exporting to *Stratify* format

The last item above means that the data recorded in our spreadsheet can be saved in a format, which in turn can be



	A	D	E	F	G	H	I	J	K	L
1	Unit name	Description	Inclusions	Interpretation	Location	Part of	Earlier than relations -408			
2	11	sterile layer		sterile layer						
3	surface	surface		artificial surface						
4	1									
5	2	wall of stones		wall			3	6		
6	3			fill of the trench 5			6			
7	4						6	3	5	
8	5			construction trench			2	3	12	
9	6			floor of the building						
10	7			fill of the pit 8			1			
11	8			pit			7			
12	9						8			
13	10						4	5		
14	12			fill of the bottom of trench 5, created while erecting wall 2			2	3		
15										
16										

Fig. 1. *Strati5 offline* in WPS Office on Android, the main working tab.

imported by the popular Irmela Herzog's *Stratify* software for Harris matrix (Herzog 2004).

The offline version has been tested and works on:

- Microsoft Windows (LibreOffice, OpenOffice, WPS Office, MS Office)
- Mac OS X (LibreOffice, OpenOffice, MS Office)
- Linux (LibreOffice, OpenOffice)
- iOS (WPS Office)
- Android (WPS Office)
- Windows phone (MS Office)

In general, an instance of offline *Strati5* filled with data can be saved on one device and opened on another one, under different operating system and spreadsheet software, and will work properly. This makes it extremely portable.

If a particular system-software combination is not listed above, it still might be fully operational.

1.2 Online version

The online version is available on any device with any operating system, as long as it has Internet access, web browser and the ability to edit Google spreadsheets. Additional functionalities of online version include:

- Accessing and editing by many users simultaneously
- Tracking changes history
- Access administration via Google accounts
- Rendering the Harris matrix
- Other online collaboration features as commenting changes and online chat

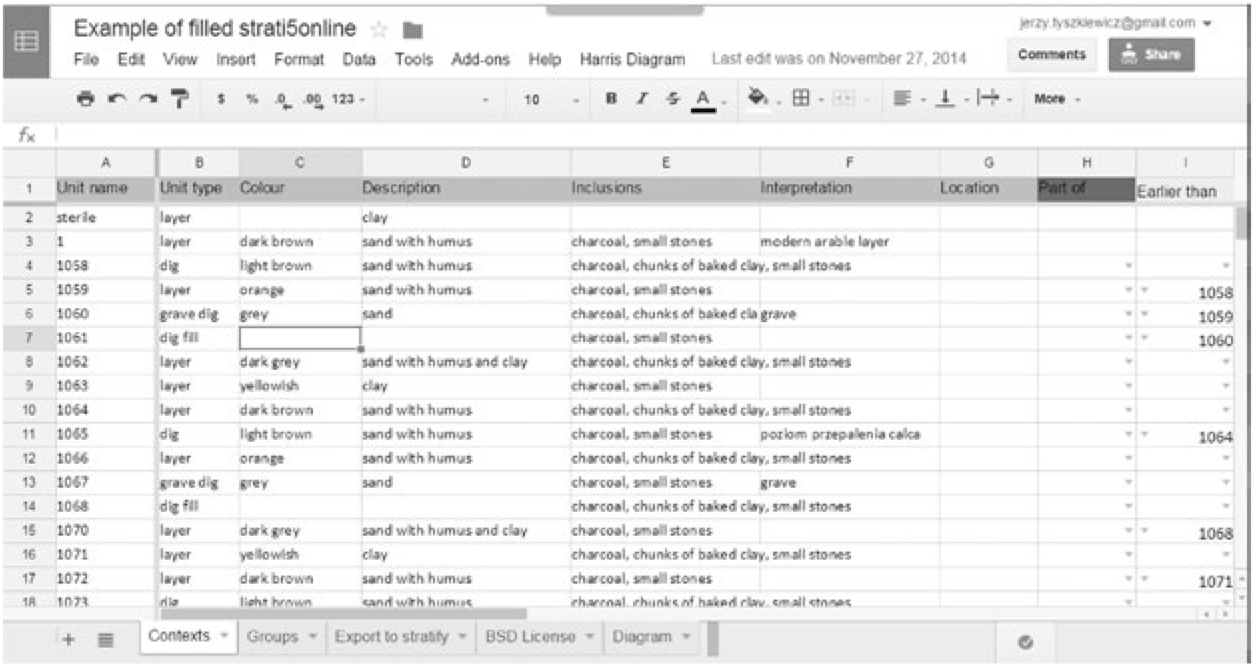
Microsoft Excel Online, part of Microsoft OneDrive, is also a potential host system for *Strati5 online*. It works properly with the offline version, but we do not know if its online capabilities can be exploited, e.g. for multi-user access, and to what extent. At the time of this writing, it is impossible to extend Excel Online spreadsheets by programmable features, which excludes the possibility of rendering Harris matrix.

2 Technical Matters

2.1 Technology

Strati5 offline is a spreadsheet consisting of formulas, conditional formatting, data validation and 'freeze panes' option, which makes certain columns and/or rows always visible on the screen. It is a conservative choice, which makes it compatible with most spreadsheet software systems.

On the other hand, it uses a spreadsheet implementation of a graph algorithm called Breadth First Search. It is used to determine if the already entered relations form a cycle. Its emergence manifests itself as a cyclic reference between cells in the spreadsheet. This specific implementation has been published in (Sroka, Stencel, Panasiuk, Tyszkiewicz 2015). It is relatively demanding in terms of the number of formulas and their complexity. Consequently, it can be a real challenge



	Unit name	Unit type	Colour	Description	Inclusions	Interpretation	Location	Part of	Earlier than
2	sterile	layer		clay					
3	1	layer	dark brown	sand with humus	charcoal, small stones	modern arable layer			
4	1058	dig	light brown	sand with humus	charcoal, chunks of baked clay, small stones				
5	1059	layer	orange	sand with humus	charcoal, small stones				1058
6	1060	grave dig	grey	sand	charcoal, chunks of baked cla	grave			1059
7	1061	dig fill			charcoal, small stones				1060
8	1062	layer	dark grey	sand with humus and clay	charcoal, chunks of baked clay, small stones				
9	1063	layer	yellowish	clay	charcoal, small stones				
10	1064	layer	dark brown	sand with humus	charcoal, chunks of baked clay, small stones				
11	1065	dig	light brown	sand with humus	charcoal, small stones	poziom przepalenia calca			1064
12	1066	layer	orange	sand with humus	charcoal, chunks of baked clay, small stones				
13	1067	grave dig	grey	sand	charcoal, small stones	grave			
14	1068	dig fill			charcoal, chunks of baked clay, small stones				
15	1070	layer	dark grey	sand with humus and clay	charcoal, small stones				1068
16	1071	layer	yellowish	clay	charcoal, chunks of baked clay, small stones				
17	1072	layer	dark brown	sand with humus	charcoal, small stones				1071
18	1073	dig	light brown	sand with humus	charcoal, chunks of baked clay, small stones				

FIG. 2. *STRATI5 ONLINE*, THE MAIN WORKING TAB.

for spreadsheet software of a small mobile device, and the computation will not be immediate. Next, unlike other features we rely on, reacting on cyclic references is accomplished in very diverse ways by different spreadsheet systems. It was quite a complex task to assure that a single spreadsheet will always report their emergence to the user, no matter what the underlying spreadsheet software is – although the actual form of warning will differ from system to system.

Strati5 online adds to that scripts written in Google App Script, a programming language based on JavaScript and used to program in Google Drive. The scripts produce a data payload, representing Harris matrix, which is sent to an external server, which renders the Harris matrix, using D3.js library by Mike Bostock (2015). The diagram is finally presented to the user as a Web page.

From the software engineering point of view, creating *Strati5* was a very interesting experiment in the area of mobile applications (Sikora, Sroka, Tyszkiewicz 2015). Indeed, we were able to produce a truly multi-platform mobile application, in a tiny fraction of the development time normally used to achieve a comparable functionality. The reason is that we used spreadsheets, an unusual technology in the field. In the development of mobile applications, the design and programming of the user interface is one of the most time- and resource-consuming tasks. In our case, we get the user interface for free, from the host spreadsheet software.

2.2 Tests

The offline version of the spreadsheet, scaled for 200 contexts and 500 relations, was tested in the field. One of the authors (J.Si) used it on SAMSUNG Galaxy Note 10.1 with Android and WPS Office. During several excavations in seasons 2014 and 2015 (including excavations in Ostrowite and Obrowo, Pomerania, Poland and in Rozprza, Central Poland), during which initial bugs were eliminated. A fully charged battery was more than sufficient for the whole day of operation. Mistakes in the data were caught and prevented: duplicates in context names, cyclic relations and references to undefined contexts.

Strati5 online was subject to a laboratory test with help of archeology students from Lodz, with 7 people editing it concurrently. No problems were detected.

2.3 Data security concerns

Strati5 is a multi-level application. It consists of a spreadsheet, spreadsheet software on which it is executed, and the operating system of the actual device. We have developed the spreadsheet with great care, did extensive tests and believe that it works correctly. However, the spreadsheet is quite large and consists of thousands of complicated formulas. Therefore, it is a serious challenge to the spreadsheet software on which it runs, and might expose its unexpected weak points.

We performed basic tests of all platforms reported in this document.

However, so far only the Android+WPS Office version passed field test of several weeks of operation. In case of this platform we did not encounter any significant failure combined with data loss.

2.4 Open standards

Both forms of *Strati5* are open software, distributed under BSD 2-Clause license. Due to the specific structure of spreadsheets, they do not exist in compiled, binary form, and the only form which is distributed is the source code. Depending on the actual system, some of the tabs can appear as hidden, but this status can always be changed by the user. (We do not recommend this, as the hidden tabs perform auxiliary computations and are not supposed to be edited by the user.)

The user can easily modify the appearance and organization of the spreadsheet, remove unnecessary parts of it, or add new ones, using all possibilities offered by the spreadsheet software he/she uses.

The additional software parts of *Strati5 online* residing in *Google drive* are also open and can be viewed and copied from the download page. The fragments which are located on our own server are not accessible for the public, but we distribute their source code and binaries to everyone interested. Rendering the Harris matrix is done by the D3.js library written by Mike Bostock (2015), which is also open software, under BSD license.

3 Description of the offline version

The description we provide here is not intended as a user manual. *Strati5* itself, as well as spreadsheet systems on which it runs can change over time and result in modification to the appearance and technical details of accessing various functionalities. An up-to-date manual is available from the download page.

3.1 'Contexts' tab

This tab is used to collect the data about stratigraphic contexts. This is the main working tab of the spreadsheet. See Fig. 1 above.

The description of each context contains the same fields as *Stratify software*:

1. Unit name
2. Unit type
3. Colour
4. Description
5. Inclusions
6. Interpretation
7. Location
8. Part of
9. Earlier than relations

The first row and first column of this tab are always visible on the screen. The first column is the area where context names are entered, while the first row contains the names of fields, which should be filled in for each recorded context. Their visibility helps to identify where to enter particular pieces of information. The first row is also the place where certain error messages are displayed.

The data in this tab can be processed using normal tools of spreadsheets: filtering, sorting, etc. If the user wants to export the data to *Stratify,* it is important that sorting leaves sterile layer and surface on their original positions (although renaming them and adding descriptions is harmless). Otherwise the data can be sorted in every desired way. Filtering affects only the visibility of data, so it is never a problem.

'Unit name' is the first column with context names. The context name can be any alphanumeric sequence, except number 0.

The first two contexts, representing the sterile layer and the surface, are always presented and should not be removed or moved to a different position. Their names and descriptions can be freely edited.

The warning in case of entering a duplicate context name appears in the heading of the column. On some systems, the duplicate(s) are highlighted in red. This does not block the entry and the user must remove the incorrect name manually.

In the column with 'Part of' heading one may enter the name of the group to which the context belongs. It is possible to enter only group names, which have already been defined in the 'Groups' tab (described below). On most of the systems, one gets a drop-down menu with the names of the already defined groups, from which the right one can be chosen. On a few systems there is no drop-down menu, and in case of a wrongly entered value, the only warning is a window with an error message. If the spreadsheet does not block the entry, the user must remove the incorrect value manually.

Further to the right, there are several columns, with a common heading 'Earlier than', for names of contexts which are later than the present one.

The surface layer is not supposed to be entered there.

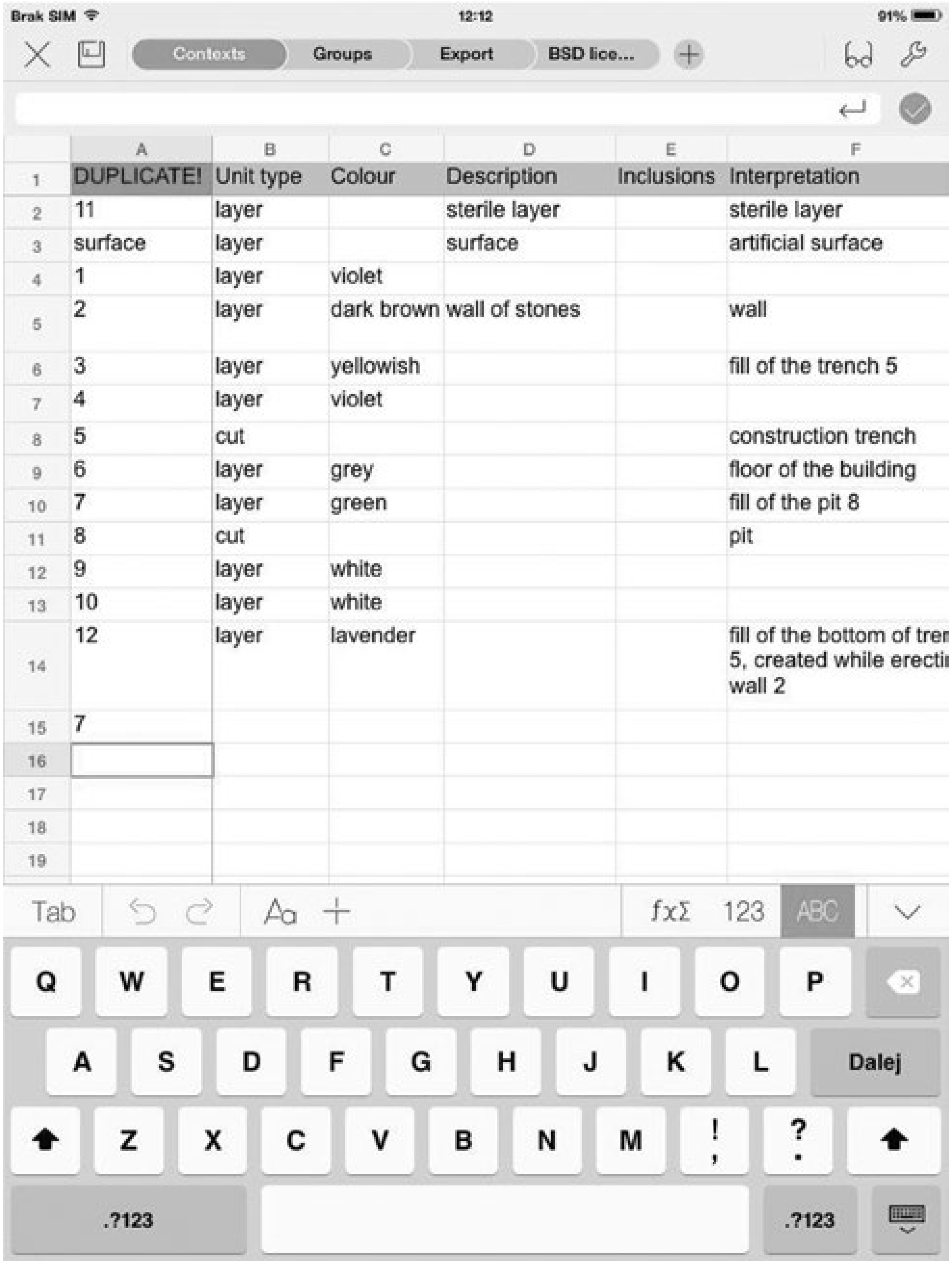
One should not leave empty slots, but enter the contexts in the consecutive columns

The system does not allow entering names of layers which have not been defined. On most of the systems, one gets a drop-down menu with the names of the already defined contexts, from which the right one can be chosen. On a few systems there is no drop-down menu, and in case of a wrongly entered value, the only warning is a window with an error message. On some systems, if they do not reject the entry and only warn the user, the heading of the columns becomes additionally red.

In a case when the defined relations form a cycle, the spreadsheet issues a warning. Depending on the operating system and spreadsheet software used, it is either a window with a warning of circular dependencies, or the heading of the column with relations becomes red and possibly displays a warning message, or both.

There is no possibility of entering earlier contexts. If one wishes to enter in a row of context A an earlier context B, the same information can be recorded by entering A among the contexts later than B.

At the end of the group of columns holding relations, there is a copy of the groups list – it should not be edited by the user.



	A	B	C	D	E	F
1	DUPLICATE!	Unit type	Colour	Description	Inclusions	Interpretation
2	11	layer		sterile layer		sterile layer
3	surface	layer		surface		artificial surface
4	1	layer	violet			
5	2	layer	dark brown	wall of stones		wall
6	3	layer	yellowish			fill of the trench 5
7	4	layer	violet			
8	5	cut				construction trench
9	6	layer	grey			floor of the building
10	7	layer	green			fill of the pit 8
11	8	cut				pit
12	9	layer	white			
13	10	layer	white			
14	12	layer	lavender			fill of the bottom of tre[...] 5, created while erecti[...] wall 2
15	7					
16						
17						
18						
19						

FIG. 3. A MESSAGE IN THE HEADER OF THE FIRST COLUMN, WARNING ABOUT A DUPLICATE CONTEXT NAME, *STRATI5 OFFLINE* IN WPS OFFICE ON IPAD.

3.2 'Groups' tab

The description of a group also contains the same fields as *Stratify*:

1. Unit name
2. Unit type
3. Colour
4. Description
5. Inclusions
6. Interpretation
7. Location
8. Part of

The 'Group name' can be any non-empty alphanumeric sequence, except number 0.

The warning in case of entering a duplicate group name appears in the heading of the column. On some systems, the duplicate(s) are highlighted in red.

In the column with 'Part of' heading one may enter the name of the group to which the group belongs. It is possible to enter only group names, which have already been defined in the 'Groups' tab. No other integrity check for this relation is performed.

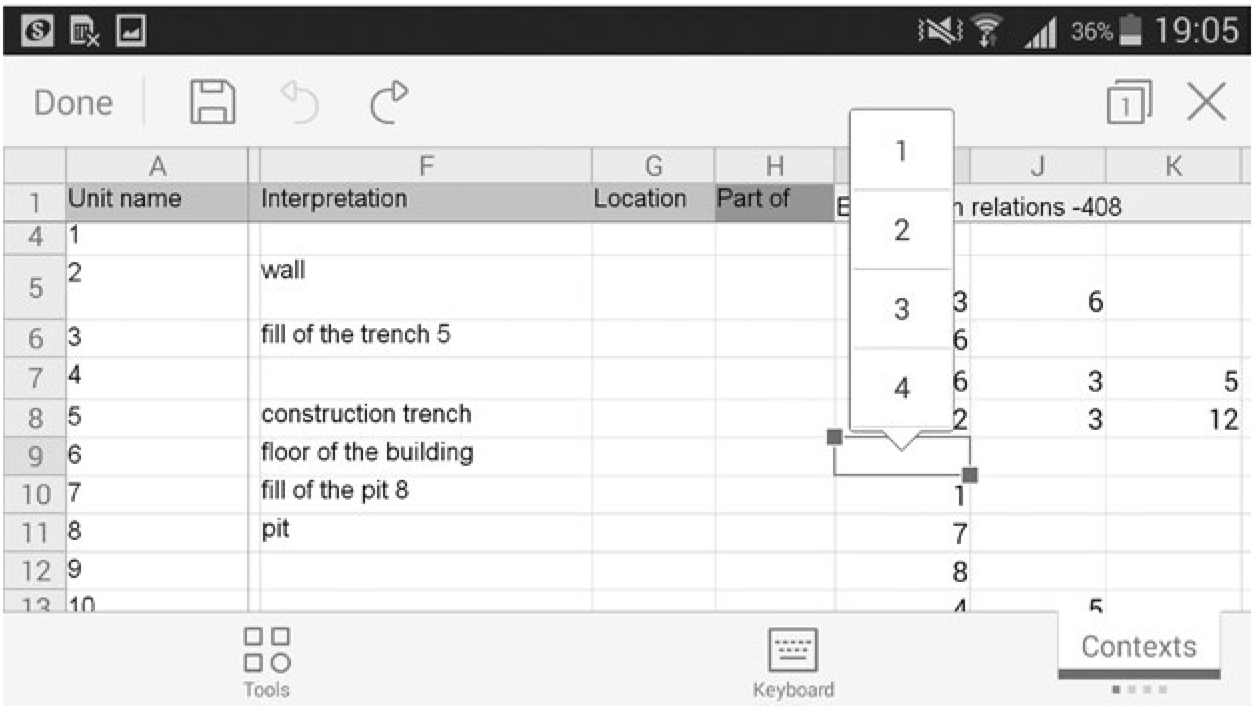


FIG. 4. CHOOSING A CONTEXT FROM A DROP-DOWN MENU, *STRATI5 OFFLINE* IN WPS OFFICE ON ANDROID

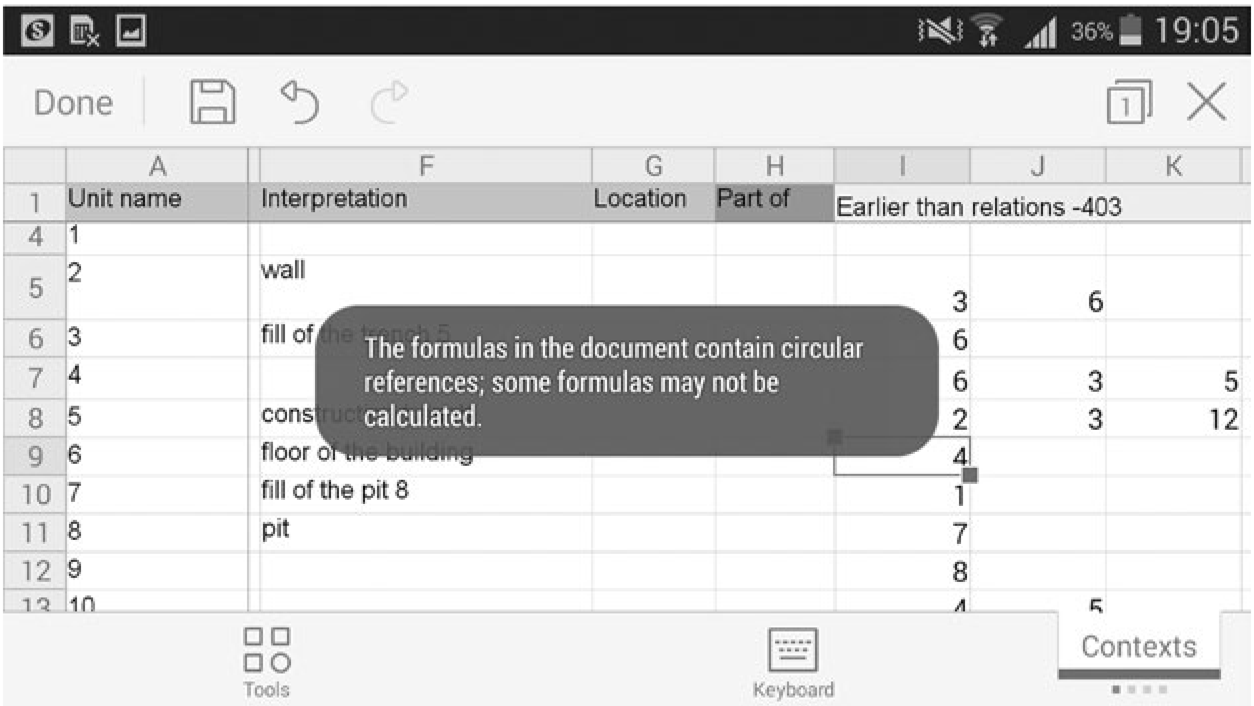


FIG. 5. A POP-UP WINDOW WITH A WARNING ABOUT A CYCLE IN RELATIONS, *STRATI5 OFFLINE* IN WPS OFFICE ON ANDROID.

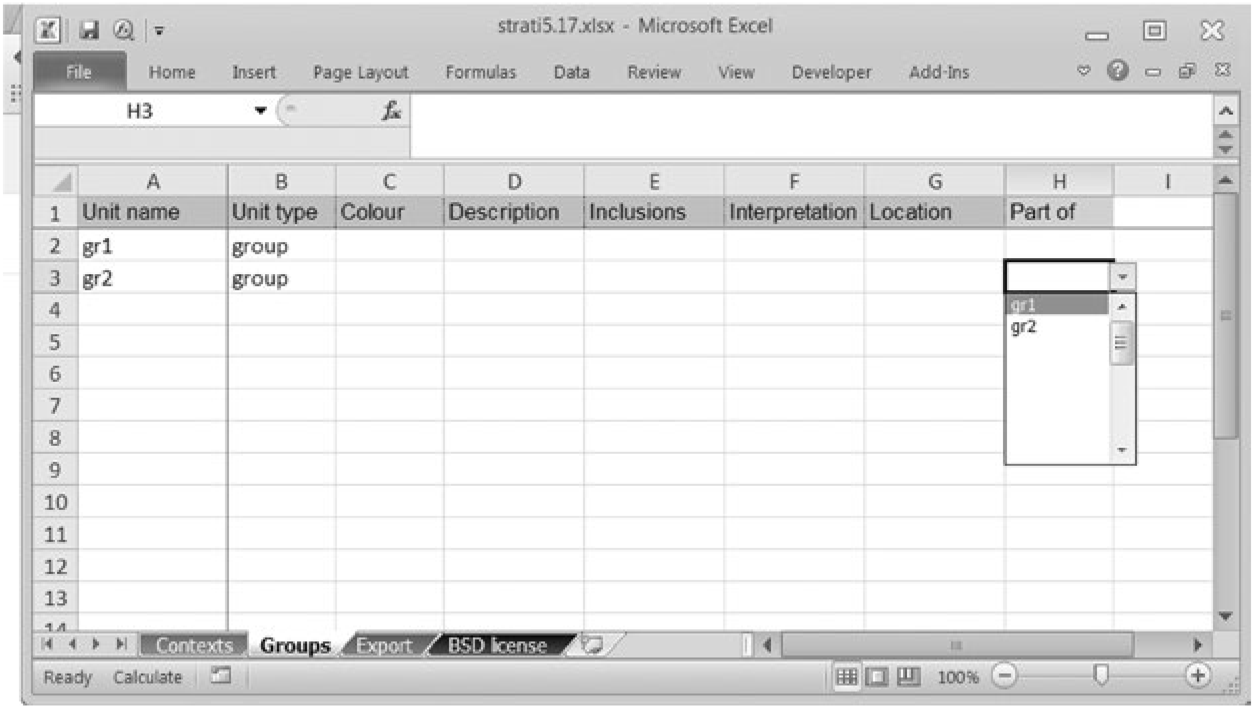


Fig. 6. Editing relations among groups, 'Group' tab, *Strati5 offline* in Microsoft Excel on Windows 7.

3.3 'Cycle test' tab

This tab contains formulas which check the existence of a cycle among relations. It is a computation area and is not intended for editing, even if the tab is visible (it is hidden on some systems).

If the user does not need this integrity check, the tab can be safely removed from the spreadsheet. As a consequence, the heading of 'Earlier than' columns in the 'Contexts' tab can start displaying an error message. It does not affect the operation of this tab and can be left there, or the offending formula can be removed manually.

3.4 'Auxiliary' tab

This tab contains formulas which prepare the data for export to *Stratify*. It is not supposed to be edited by the user, and it can appear hidden. This tab can be safely removed if the user does not need the functionality of exporting data to *Stratify* on this particular copy of *Strati5*.

3.5 'Export' tab

This tab contains formulas which produce the data for export to *Stratify*. They are not supposed to be edited by the user. This tab can be safely removed if the user does not need the functionality of exporting data to *Stratify*.

***3.6 Procedure of data export to* Stratify**

The process of exporting data is performed as follows (details are provided in the manual, available from the download page):

Mark and copy (Ctrl-C or equivalent) the area of 'Export' tab with visible data.

Paste the data (Ctrl-V or equivalent) into any text editor (not word processor!).

Remove empty rows at the bottom, if there are any.

Save the text in a file with extension .csv in the chosen directory.

Import the file into *Stratify*, following the steps described in the manual.

4 Description of the online version

In order to use the online version, it is recommended to create a Google account.

The online spreadsheet differs from the offline spreadsheet, because it contains more functions.

However, the offline version can be uploaded to Google docs and will be fully operational.

The offline and online versions are also fully compatible in the terms of data they hold: one can transfer the contents of tabs 'Groups' and 'Contexts' (in this order) by simple copy-and-paste operation, in both directions.

4.1 Multi-user operation

Any owner of a Google account can open the master version of the online spreadsheet from the download page, and then choose 'Make a copy' from the 'File' menu. Making a copy is also possible from the level of the directory. The newly created copy will be located in the Google drive of the user, who will become its owner. Then the spreadsheet can be renamed and shared with the people, with whom the owner wants to

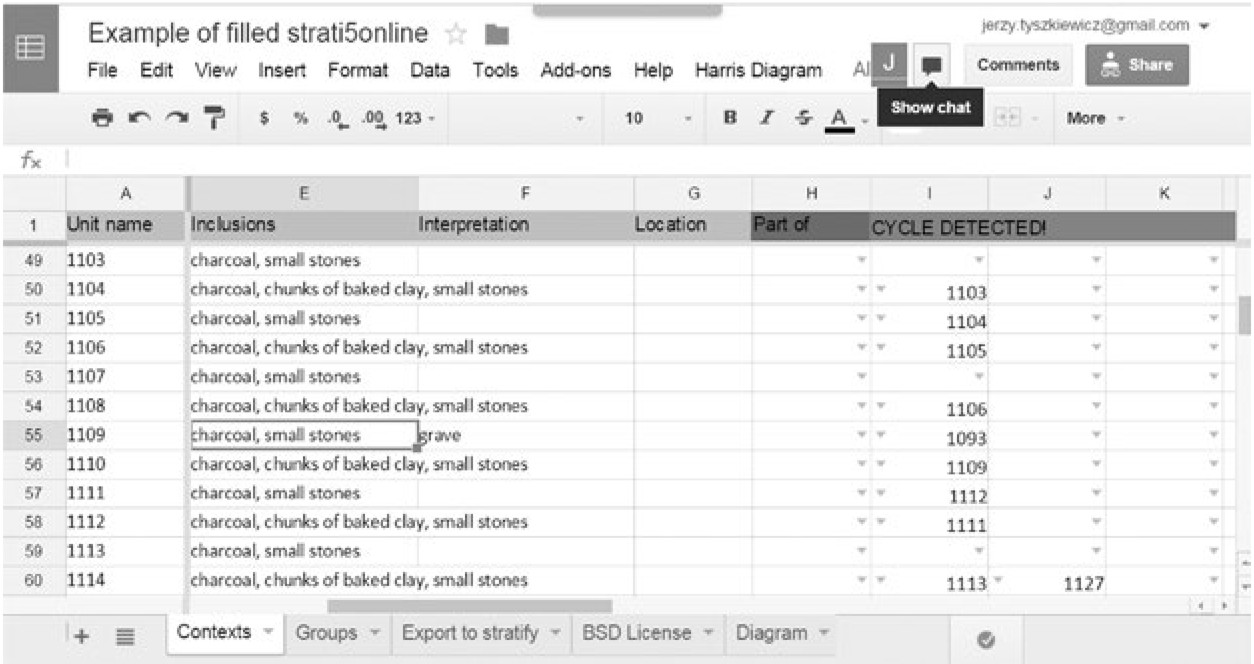


Fig. 7. *Strati5 online*, the following elements are visible: indication of another online user, chat, menu for rendering Harris diagram and a warning about cyclic relations.

collaborate. The extent of this collaboration can be decided by the owner: each user can be granted the right to edit, comment only, or view only.

During collaboration, many users can edit the spreadsheet simultaneously, and each of them can see the edits of the others in real time. The spreadsheet also records and displays the information about edits, identifying their authors (access to this feature may depend on the system and Web browser used).

A chat associated with the spreadsheet can be used for communication of the collaborators (access to this feature may depend on the system and Web browser used).

Refreshing the spreadsheet requires a considerable amount of data transfer, hence warnings about data integrity violations can be delayed. In particular, the warning about cyclic relations or duplicates can appear quite a while after the edit which actually caused them. These problems are due to the mechanisms of the Google platform.

4.2 Tabs

There are two additional tabs in the online version: 'List of relations' and 'Diagram'. They are hidden by default and are not supposed to be edited by the user. They can be removed if the user does not need the functionality of rendering the Harris matrix.

The remaining tabs are identical as in the offline version. In particular, the data export to *Stratify* is performed in the same way.

4.3 Harris matrix rendering

The Harris matrix can be presented in a form of a diagram, which we call below Harris diagram. *Strati5 online* is able to render the Harris diagram.

The top menu (visible on desktop Web browsers, for Android one can use Dolphin Web browser and set it to 'PC mode' in the options) there is a menu 'Harris diagram'. In order to get the diagram, one must first choose 'Harris diagram data' and close the window displayed on the screen (this indicates to *Google docs* that the user is aware that the data will be exported to an external service and accepts this operation).

The data is then used to generate the diagram on an external server, common for all users of *Strati5 online*. Each particular diagram is identified by a hash number, computed from its content. This hash becomes part of the URL under which the diagram is stored.

Next, one should choose the 'Harris diagram link' in the next window causing the diagram to be displayed in the Web browser.

The graphics are animated by JavaScript (contexts can be moved around, the links follow them; descriptions are displayed when the pointer hovers over nodes and links).

Groups are indicated by coloured nodes and links.

All normal functions of the browser work on this page, including search.

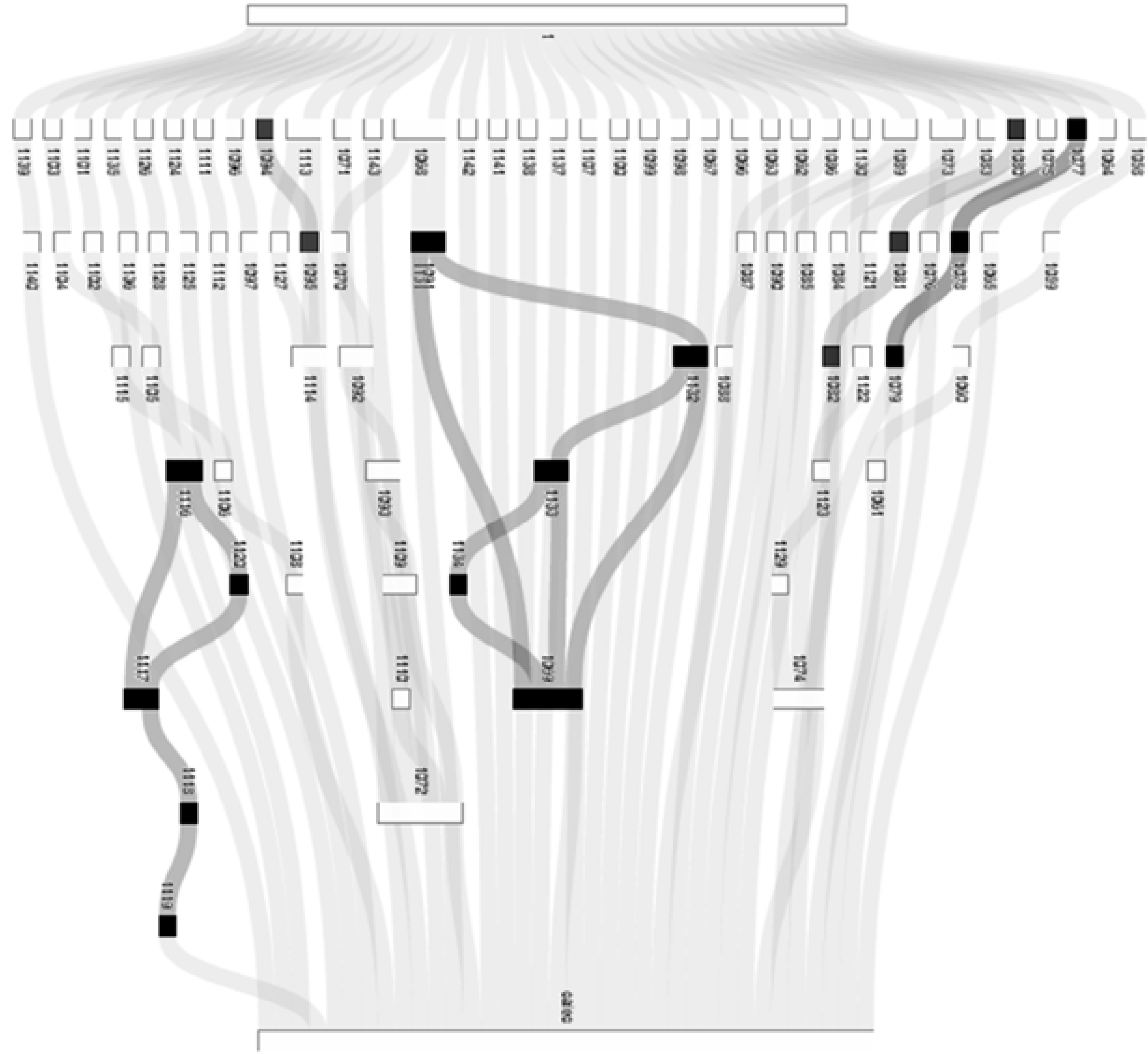


Fig. 8. Harris diagram, as rendered by *Strati5 online*.

The diagram can be saved as html page and retains its full functionality, including animations. It can also be saved as pdf file, which is then editable with graphics editors.

The link to the diagram can be shared with others and will remain valid until it is not overwritten due to generation of a new picture with the same hash. The capacity of the server is 10000 pictures, so the probability that one picture accidentally destroys another one is low, but not zero.[1]

The diagrams are not protected by the Google authentication system and are accessible for anyone.

The following method can be used to remove the diagram and the data from the server after it has been rendered: append '&delete=t' at the end of the diagram's URL in the Web browser (leave no space in between) and press Enter. Due to the identification of diagrams by hash, after the local data has changed, it is very difficult to recreate the same URL for destroying the diagram, unless it is recorded by the user. Probably the easiest way of proceeding is to render the picture, save it to the local disc and remove from the server immediately after that.

[1] It is possible to create and maintain a specific instance of the diagram server. Please contact the authors for more information.

5 Known bugs

Data import into *Stratify* requires that at least one of the contexts has a name which is not a number. Strictly speaking, it is a bug of *Stratify*, which however affects the operation of *Strati5*. If data export to *Stratify* is not planned, it is possible to use only numbers.

6 Exporting data to ArchEd

Prompted by one of the anonymous reviewers of the present paper, we have created a variant of *Strati5*, named *ArchEd5*, capable of exporting the collected data into the .lst text file format used by another stratigraphic software: *ArchEd*

(Hundack *et al.* 2002), reviewed in (Rains 2000). Specific properties of the target program cause *ArchEd5* to be very similar to, but incompatible with *Strati5*. In particular, the stratigraphic relations must be recorded in a form dual to what *Strati5* uses: instead of a list of later contexts, in this case the user must create the list of immediately earlier contexts in each row. Therefore the data collected in our two spreadsheets cannot be exchanged between them. Otherwise they share almost all formulas used to verify the data integrity. Of course, the formulas used for data export are completely different. The mode of operation of the two spreadsheets is almost identical.[2] The experience of adapting our spreadsheet to export to a different text format makes us believe that it can be further modified to export almost any reasonable text format of stratigraphic data.

Download

Fig. 9. QR Code for accessing the download page of *Strati5* and *ArchEd5*.

[2] We invite the users of ArchEd to contact us and help in testing the new tool. We thank the reviewer for the suggestion to create it.

[3] All versions of Strati5 and ArchEd5 can be downloaded from the Google drive of the user strati.five@gmail.com: https://drive.google.com/open?id=0B-miB5pAbyRuSlg4RzhMRHdwWjg&authuser=0
Email strati.five@gmail.com can be used for communication with the authors. The first mail sent to this address causes an automatic response, which sends back the above link to the directory with both spreadsheets. If you wish to contact the authors, please enter [HELP] or [CONTACT] in the Subject: line of your message.

Bibliography

Sroka, J., Panasiuk, A., Stencel K., Tyszkiewicz, J. 2015. Translating relational queries into spreadsheets. *IEEE Transactions on Knowledge and Data Engineering* 27, 8: 2291-303.

Sikora, J. Sroka, J., Tyszkiewicz, J. 2015. Spreadsheet as a Multi-platform Mobile Application. In *2nd ACM International Conference on Mobile Software Engineering and Systems (MOBILESoft)*: 140-1.

Harris, E. C. 1979. *Principles of Archaeological Stratigraphy*. London, Academic Press.

Herzog, I. 2004. Group and conquer - a method for displaying large stratigraphic data sets. *British Archaeological Reports International Series* 1227: 423-6. Oxford, Archaeopress. [Online]. Available from: http://www.stratify.org [accessed: 4 July 2015].

Bostock, M. 2015. *Data-Driven Documents*. [Online] Available from: https://d3js.org [accessed: 4 July 2015].

Hundack, Ch., Mutzel, P., Pouchkarev, I., Reitgruber, B., Schuhmacher, B., Thome, S. 2002. *ArchEd. A program for drawing Harris Matrices*. [Online] Available from https://www.ac.tuwien.ac.at/files/archive/ArchEd/ArchEd_UsersGuide.pdf [accessed: 11 November 2015].

Rains, M. 2000. Review of ArchEd and Stratigraph - Excavation recording and analysis software [Software], *Internet Archaeology* 8. [Online] Available from http://intarch.ac.uk/journal/issue8/reviews/rains.html [accessed: 11 November 2015].

Archaeology as Community Enterprise

Néhémie Strupler
nehemie.strupler@etu.unistra.fr

« Archéologie et Histoire ancienne : Méditerranée-Europe », ARCHIMÈDE (UMR 7044), Université de Strasbourg
Institut für Altorientalische Philologie und Vorderasiatische Altertumskunde, Westfälische Wilhelms-Universität Münster
Deutsches Archäologisches Institut, Abteilung Istanbul

Abstract: Computers are commonly used to address practical, methodological, and theoretical issues in archaeology. However little discourse is devoted to the software that is used to perform the analysis, manipulate data, or to how the software workflow should be available. This paper addresses the pressing need to adopt Free Software and transparent research pipeline now when data is becoming easily available online, and tools to make reproducible research are becoming widespread. This configuration challenges current ways to disseminate and evaluate archaeological research.

Keywords: Free Software, Collaborative Authoring, Reproducibility, Computational Archaeology

Introduction[1]

The Open Access movement generates plenty of sympathy among archaeologists. Academia.edu has grown to one of the biggest repositories for 'freely' available archaeological papers, cross-cutting the boundaries of traditional reading circles.[2] Everyone can understand the benefits of this ready availability of papers. On the other hand, the Free Software movement, where the origin of the Open Access movement is to be situated, is mostly ignored since it is not considered as relevant. However, on-going and growing debates about benefits of data release available through new information technologies challenge this position. Why, though, should archaeologists become more aware of the philosophy of Free Software?

Even if Free Software is well established inside and outside academia, the advantages of Free Software (that is the 'free' as in 'free speech', and not the 'free' as in 'free beer') are rarely acknowledged.[3] Free software is in many cases (in the imaginary) assumed to be complicated, untrustworthy or not as effective as 'industry-standard' software. More generally software is treated as a neutral tool to answer research questions, and emphasis is placed on the results with little time devoted to the reuse of either work-flows or of the collected data.

The aim of this paper is to give a brief overview of the intersection of Free Software with Archaeology. This closer look draws our attention to changes in information technologies that question orthodox models of knowledge dissemination. Open Access is important not only to enable access for a much wider audience to research outcomes, but it falls on us to make the access to the data and the analysis in both transparent and reproducible ways, ideals which are closer to the ethics of scientific research. This will create a stronger research environment into the future.

1 Earlier Work

Papers discussing Free Software in archaeology have been published from the end of the 1990s onwards, presenting showcases, new software, or dedicated environments.[4] Benjamin Ducke recently published articles discussing the relation of Free (and Open Source) Software and archaeological software (Ducke 2012; 2013). He focusses attention on the problem of 'black boxes' (Morin *et al.* 2012) and of sustainability for the development of archaeological software. Proprietary software restricts the review of methods and control over the processes, it and hinders the dissemination of the analysis. All those without a license to use specific proprietary software are *de facto* excluded from the understanding and reproduction of the analysis. In this sense, proprietary software acts like 'black boxes', where, at best, only inputs and outputs are (partially) released. As he acknowledges, Ducke does not examine the philosophical or social aspects of Free Software. In the analysis here, I would like to focus more narrowly on these aspects and how these paradigms question methods established in archaeological research without narrowing the questioning of software.

1 This paper is a revised version of a talk given during the session 10A 'ArcheoFOSS: free/open source software and archaeological research, ten years later' at the CAA 2015 conference 'Keep the Revolution Going'. I am grateful to the organisers and to the participants for the comments in a nice and motivating atmosphere. The original paper, the slide-show and extra material are accessible online. DOI: 10.5281/zenodo.16596. A video of that lecture was recorded by Doug Rocks-Macqueen and has been published under his project 'Recording Archaeology'. I would like to thank Mathias Strupler, Vera Egbers, Toby C. Wilkinson and Joseph Lehner for discussions, contributions, useful comments and suggestions on the language and structure of the manuscript. I also am grateful to two anonymous reviewers for their close reading and perceptive comments.

2 academia.edu is 'free to use' but it is not free. There is no API, which would have enabled a query of the growth of papers tagged with #Archaeology during the last years and consequently asserts the affirmation from the main text. For now, it is just a guess.

3 See the definition of the Free Software Foundation [accessed: 30 June 2015].

4 It is not the purpose to review earlier literature in this paper but the proceedings of ArcheoFOSS (Serlorenzi 2013 for the latest published) and papers published in the proceedings of the CAA are a good starting point to gain an overview about Free Software and archaeology.

2 Scientific community

Science is cumulative even though it is often obscure how exactly knowledge accumulates. In any case it is a community endeavour. In this process, members of the scientific community contribute different points of views, different questions, and different methods to resolve same problems. The community is a pool of inspiration: interactions encourage innovation and spark ideas about new lines of evidence, new applications, new questions, and alternate explanations. Lively interactions of the community allow knowledge to accumulate and become 'stable' faster.[5]

The scientific community also creates a motivating force for recognition, respect from peers or academic prestige, and institutes controls over the quality of research by scrutinising the work of others (e.g. peer-review in journals or books review). Both represent a system of checks and balances that assures that claims are not fraudulent. The communication and the open process inside the community make claims more robust, or, contrarily, it allows the rejection of weak claims. Indeed it is not the work of a lone researcher that makes science strong and reliable, it is rather the true scrutiny and critics of peers (Fanelli 2013).

3 Free Software and Science

Free Software shares a lot of characteristics with science. Both have scrutiny and cumulative knowledge, which can be seen in process like peer review, where open data is subject to validation and replication. There is a strong culture of credit, civility, reputation, and communication.

The motivations to do science or develop Free Software are in many aspects similar: it's based on the reputation earned with published work, and there is in both cases an ethic to attribute the work (Kelty 2001). Researchers make their work available to others and citations accredit reuse of ideas, concepts, or code. In Free Software or in science, differences are made according to the status of the contribution (author, contributor, maintainer, etc.). Contributions are based on same principles of cumulative knowledge, its reuse, mixing, and modulation.

But similarities between Free Software and science should not hide differences. Dissimilarities, specifically Free Software's assets, challenge what is taken for granted in the process of accumulating knowledge.

4 Modifiability

Modifiability is without any doubt the most fascinating concept among the dissimilarities between science and Free Software (Kelty 2008: 12). Books and articles have bolstered science by making stable knowledge. Yet the impression often given by books or articles is that of a final or definitive version of expertise. Free Software questions this concept with practices like forking, new versioning, cloning, and the constant evolution of source code. Every 'newly available' operating system, even proprietary, contains older pieces of software.

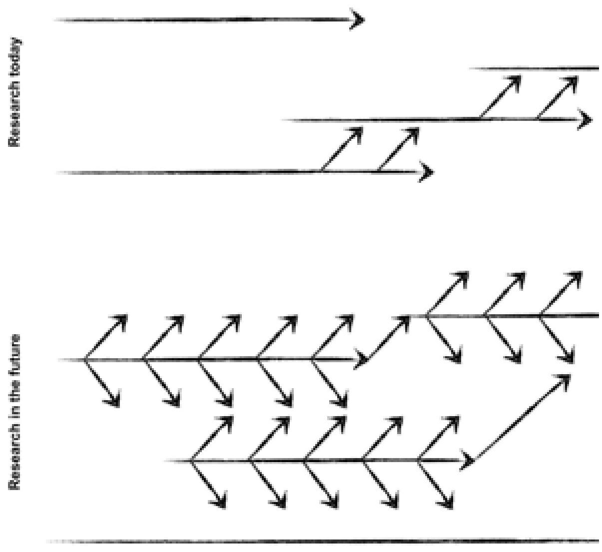


Fig. 1. Open and wide communication of negative as well as positive findings (Bartling *et al.* 2014: Fig. 3, 10) (http://dx.doi.org/10.1007/978-3-319-00026-8_1) | CC BY-NC 3.0

The top of this diagram [Fig.1] shows a representation of the current way of doing research with stable knowledge: results are only used when they are stable. The bottom part represents how software development works and how science could be made to work. The process of sharing and reusing readily available knowledge becomes more dynamic. However this poses a question. If the content does not need any more to be stable and it is used like Free Software, 'how should the authority, stability and reliability of knowledge be assessed?' (Kelty 2008: 300). In this sense Free Software can be said to challenge the 'Power of Knowledge'.[6]

5 Free Software challenges the Power of Knowledge

New practices of publication associated with the appearance of new information technologies render knowledge more dynamic (Vinck *et al*. 2014). Wikipedia is the most famous example: its content can be updated, changed, deleted, copied, or forked at any time by anyone. The last 10 years have seen a complete revaluation of Wikipedia across the academy. Ten years ago, as I saw it in France, it was mostly rejected as 'untrustworthy source'. Now academics explain to their students how to use it in scholarly context (Garrison 2015).

Even if there is a growing discussion on publication of dynamic content there are still few examples of work-flows in academia. The model proposed by Kansa and others – *Push and Publish* – will certainly have a bright future (Kansa *et al*. 2014). In this model, data are published on-line and may be updated, completed, corrected, cloned after the first online release. Repositories and digital archiving enable new dissemination methods.

By looking at the practice of Free Software, it is easier to ask how authority is established and question the finality of

[5] 'Stable knowledge' refers to the process of establishing a fact, among others Latour *et al*. (1979).

[6] I refer to the expression of C. Kelty in his book *Two bits* (2008).

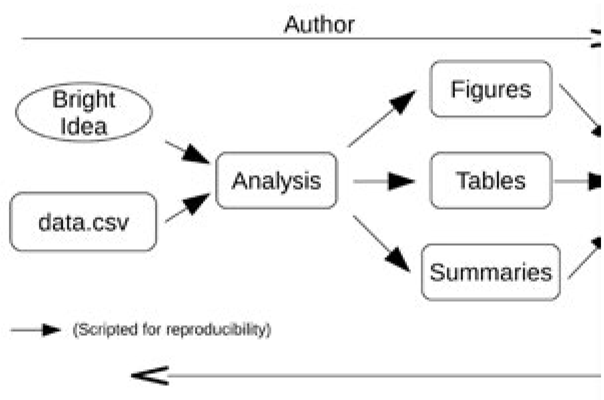


Fig. 2. Research Pipeline (after ideas from Roger Peng and Kieran Healy) | N. Strupler CC BY-NC 4.0

publication. Free Software focuses not only on the results (the software) but unifies operations and the possibility of control, improvement, and reuse. Free Software allows computational archaeology not only to concentrate on the results but broaden the attention consequently on how results are reached. This is the only way to reconcile the ethic of science and the establishment of (computational) facts. It is with this sense in mind that I will turn to the problem of reproducibility for computational archaeology.

6 Reproducibility

Reproducibility allows anyone to start from the same data and check all the processes undertaken, in order to verify the results. The complete process, from ideas and data to the publication has been termed as a 'research pipeline' [Fig. 2]. In archaeology there has been no culture of creating code for reproducibility until very recently.[7] If we turn back to the definition of science, however, reproducibility and sharing of code are even *sine qua non* for scholarly communication, permitting the community to scrutinise the work. It is the only way to stick with a robust exposition of facts. 'We often forget that scientific knowledge is reliable not because scientists are more clever, objective or honest than other people, but because their claims are exposed to criticism and replication.' (Fanelli 2013)

It is unrealistic to describe all the steps of an archaeological project by means of programming language. But several sub-steps – where computer plays a central role – can be made more explicit with scripts. A script is a plain text file of code composed in programming languages that instruct a computer to accomplish a set of tasks. Scripts may be augmented by comments that work like annotations. They help readers to understand the logic of the tasks. Scripts are firstly meaningful for creators to remember themselves how they obtained the results, and they record workflows that can be inspected, reused, or modified by others. Making scripts public allows reader to fully understand how results have been obtained.

For archaeological analysis, best practices permit the combination of data, code, and results through scripting and shared computational environments (Marwick 2015, forthcoming). This chain must be attained to adhere to the ethic of science. Moreover reproducibility has a huge potential for empirical research, like archaeology. Reproducibility is important to reuse and maintain data up to date. If, as shown in the *Published and Push* model, data are updated, then the analysis can be quickly updated, and therefore results do not need to remain fossilised in the (out-dated) state they were published.

Reproducibility helps to cast research into modules. Bits of research based on code can be transformed and reused for similar projects or built upon for new projects. The modularity of code impacts on two levels. Firstly, open and reproducible archaeology makes resources easy available as paradigmatic pedagogical object. Hands-on workshops, modulations of research, testing of new hypothesis can be done in teaching environments with a direct, *do it yourself* approach. Secondly, the modularity of Free Software eases the blurring of academic borders in unpredictable ways. By providing a common language, Free Software creates new transversal communities that make science stronger.

7 Discussion

There are undoubtedly barriers inhibiting the spreading of this paradigm. Modern archaeology is largely a low-tech field and archaeologists acquire minimal computer training at the university which is not refreshed. Analysis methods and presentation of data did not dramatically improve for over a century. This situation, where computers are mainly used as a 'writing machine', does not favour debates about the limitations and advantages of software or strategies to develop a research program that uses Free Software and open format as standard.

Debates about licensing, black boxes, and reproducibility have emerged and are primarily questioned in the computational sciences before occurring in archaeology. Furthermore, an intense advocacy for data publication and reproducibility emerged from multiple scandals about the falsification of results and after the retraction of publications. As far as I know, there is no such (known) case in archaeology and consequently these questions are not widely discussed among archaeologist. The structure of archaeological research does not favour the challenging of the current paradigm because there is only a vague distinction between the auteurs producing, analysing, publishing, and using a specific archaeological data set. More critical evaluation of the careers of individual researchers are focussed on, in particular their papers published in prestigious journals, rather than also taking in account the data sets that are easily reusable by others.

Yet archaeology is increasingly dependant on software to generate results, and funding bodies and journals increasingly request publication of data. Current and future projects based on the reuse of data from other projects have to develop a workflow to aggregate, clean, analyse, and visualise a growing body of data, always gaining in resolution. By creating different modules of (reusable) scripts, the use of Free Software appears to be the best solution in the long term. Starting and maintaining a project with Free Software does not cost more time compared to proprietary software; however, the transition

[7] For example, see the meeting during the SAA 2015 in San Francisco, 'Electronic Symposium Open Methods in Archaeology: How to Encourage Reproducible Research as the Default Practice?' organised by Ben Marwick, Mark Lake and Andrew Bevan.

for proprietary software to Free Software is time consuming. Therefore, it seems now critical to adopt Free Software and develop a transparent research pipeline, otherwise the current aspiration to do 'big data analysis' may turn from dream to nightmare.

8 Conclusion

Free Software challenges the authority of science and provides a means to transform computational archaeology and, indeed, the practice of archaeological research as a whole by questioning transmission and reuse of research. Free Software coupled with reproducibility by means of scripting makes the entire research pipeline available to the scrutiny of the community and reconciles data, processes, and results. Making the complete research available for free online has the potential to change archaeology into a research environment more robust and open to everyone.

Bibliography

Bartling, S. and Friesike, S. 2014. Towards Another Scientific Revolution. In S. Bartling and S. Friesike (eds.), *Opening science*: 3-15. Springer. [Online] Available from: http://dx.doi.org/10.1007/978-3-319-00026-8_1

Ducke, B. 2012. Natives of a connected world: Free and open source software in archaeology. *World Archaeology* 44, 4: 571-9. [Online] Available from: http://dx.doi.org/10.1080/00438243.2012.743259

Ducke, B. 2013. Reproducible data analysis and the open source paradigm in archaeology. In A. Bevan and M. Lake (eds.), *Computational approaches to archaeological spaces*: 307-18. Left Coast Press.

Fanelli, D. 2013. Redefine misconduct as distorted reporting. *Nature* 494: 149. [Online] Available from: http://dx.doi.org/10.1038/494149a

Garrison, J. C. 2015. Getting a 'quick fix': First-year college students' use of Wikipedia. *First Monday* 20, 10. [Online] Available from: http://dx.doi.org/10.5210/fm.v20i10.5401.

Heller, L., The, R., Bartling, S. 2014. Dynamic Publication Formats and Collaborative Authoring. In S. Bartling and S. Friesike (eds.), *Opening science*: 191-211. Springer. [Online] Available from: http://dx.doi.org/10.1007/978-3-319-00026-8_13

Kansa, E.C., Kansa, S.W., Arbuckle, B. 2014. Publishing and Pushing: Mixing Models for Communicating Research Data in Archaeology. *International Journal of Digital Curation* 9, 1: 57–70. [Online] Available from: http://dx.doi.org/10.2218/ijdc.v9i1.301

Kelty, C. M. 2001. Free software/free science. *First Monday* 6, 12. [Online] Available from: http://pear.accc.uic.edu/ojs/index.php/fm/article/view/902 [Accessed: 30 June 2015].

Kelty, C. M. 2008. *Two bits: The cultural significance of free software*. Durham, Duke University Press. [Online] Available from: http://twobits.net/pub/Kelty-TwoBits.pdf

Latour, B. and Woolgar, S. 1979. *Laboratory life: The Social Construction of Scientific Facts*. Beverly Hills, Calif., Sage.

Marwick, B. 2015. *Doing Quantitative Archaeology with Open Source Software*. [Online] Available from: *software.ac.uk*. http://www.software.ac.uk/blog/2015-04-24-archaeology-open-source-software-its-getting-easier [accessed: 30 June 2015].

Marwick, B. (forthcoming). *Basic computational reproducibility in archaeological research: Basic principles and a method for their implementation*.

Morin, A. *et al*. 2012. Shining Light into Black Boxes. *Science* 336, 6078: 159-60. [Online] Available from: http://dx.doi.org/10.1126/science.1218263

Serlorenzi, M. (ed.) 2013. *ARCHEOFOSS free, libre and open source software e open format nei processi di ricerca archeologica. atti del VII workshop (Roma, 11-13 giugno 2012)*. All'Insegna del Giglio. [Online] Available at: http://www.progettocaere.rm.cnr.it/databasegestione/open_block_pages_sup.asp?IDyear=2013-01-01

Vinck, D. and Clivaz, C. 2014. Les humanités délivrées. Savoir et culture réinventés hors du livre. *Revue d'anthropologie des connaissances* 8, 4: 681–704. [Online] Available from: http://dx.doi.org/10.3917/rac.025.0681

Digital Resources for Archaeology. The Contribution of the On-Line Projects by Isma-Cnr

Alessandra Caravale
alessandra.caravale@isma.cnr.it

Alessandra Piergrossi
alessandra.piergrossi@isma.cnr.it

Istituto di Studi sul Mediterraneo Antico – Consiglio Nazionale delle Ricerche

Abstract: The paper discusses some examples of electronic resources for antiquity sciences, outlining the activities carried out in this field of study by our Research Institute of the National Research Council, the Institute for the Study of the Ancient Mediterranean, whose ancient origins date back to the late Sixties. A large use and sharing of these resources could help improve significantly archaeologists' work in speed, precision and, especially, diffusion and dissemination, improving and modifying the more traditional ways of study.

Keywords: Digital resources, On-line repositories, Digital corpora, Open data, Open access journals

Since 1990, the quantitative and qualitative progress of digital resources for ancient world studies has changed the face of our disciplines as their presence improves and modifies the more traditional ways of research. The constant growth, the large use and sharing of these resources have helped improve significantly our work in speed, precision and, especially, diffusion and dissemination, even if a large part of the research community still uses them in a restricted way or even ignores their existence. The digital productions make possible the interaction between research, didactics and diffusion, giving birth to new forms and media of communication that are accessible and usable by the public at large.

In the context of data documentation, applications are now oriented to overcome the level of data cataloguing, using the Internet as an environment for consultation and knowledge sharing which facilitate the integrated work of the various institutions responsible for the preservation and enhancement of cultural heritage. Collections of documents in digital format, produced or acquired for cultural purposes, are increasing and new standards have been recognized as reference logical models for formalising the procedures of acquisition, integration and access to digital information. Also on-line archaeological journals are gaining a growing success due to several factors, such as the need of new means for knowledge dissemination, as well as the gradual but constant emergence of 'open access' and 'open data' philosophy, which offers free access to scientific information.

Archaeological corpora, databases, digital repositories and open access journals constitute an effective and efficient instrument in archaeological research. However, the panorama of digital resources in which the archaeologist should navigate is still rather fragmented and not very systematic. As often happens in the early stages of transition, new initiatives continually arise, often of extemporaneous nature; some experiences consolidate, while others wreck quickly; some interesting projects remain isolated and circumscribed within the institutions that have promoted them, not being made available to the wider scientific community. Therefore, the continuous widening of resources deserves to be followed, constantly monitored and reviewed in its development.1

Although we need more projects that address the fragmentation[2] of archaeological digital resources, wanting to outline what is currently on the web for the archaeological studies we can distinguish some large clusters:

- Databases: made especially to file large categories of ancient materials or museum collections, they allow to search easily in large repertoires, supporting the ongoing work of analysis and comparison that the archaeologist faces in his research.
- Excavations reports: facilitate knowledge, discussion and dissemination of research data in the field, also during their execution, without having to wait for the long time the print publication takes.

[1] Some guides and reviews of digital tools for the study of antiquity: http://www.archaeological.org/fieldnotes/digitalresources; http://www.rassegna.unibo.it/index.html; http://classics.williams.edu/resources/online-resources-2/; http://ancientworldonline.blogspot.com/.

[2] For the selection and organization, but also the analysis and visualization of data, the creation of cultural portals and e-infrastructure - large research networks - for cultural heritage and humanities are assuming a crucial role. See, among others: ARIADNE, completely devoted to bring together and integrate existing archaeological research data infrastructures (Available from: http://www.ariadne-infrastructure.eu/ [accessed: 23 June 2015]); DARIAH (Digital Research Infrastructure for the Arts and Humanities, available from: http://dariah.eu/ [accessed: 23 June 2015]); EUROPEANA, the European digital library, a multi-lingual online access point to millions of digitized items from European museums, libraries, archives and multi-media collections (Available from: http://www.europeana.eu/portal/ [accessed: 23 June 2015]); ATHENAPLUS, a best practice network started in March 2013 which aims to facilitate access to networks of cultural heritage, (Available from: http://www.athenaplus.eu [accessed: 23 June 2015]).

- CRM: indispensable points of reference for the knowledge, protection and enhancement of a geographical or cultural area.
- Electronic journals: increased substantially in recent years, they offer an alternative to the traditional printed publication, being cheaper and globally shared.
- Digital libraries: vast catalogues, not only focused on archaeology, which allow consulting on-line, articles, books and materials from different contexts, times and languages.

The Institute for the Ancient Mediterranean Studies (ISMA) of the National Research Council has been engaged for a long time in this area of studies, in fact, since the late Sixties CNR has paid particular attention to the methodological renewal started by these new tools.

One of the first pioneering projects (as a few years ago no one could imagine the sheer number of today's already digitised objects and texts and the fast growing number of new digital material) was the automation of Etruscan *corpora*. It concerned, in particular, stone funeral urns made in the Hellenistic age in Volterra and its cultural and political territory, by means of the experimentation of mathematical and statistical techniques (Moscati 1994; 1995; 1997; 2004). The aim of the project was to go beyond the more traditional encoding method boundaries based on presence/absence, and the iconographical and stylistical description and to achieve a textual formal description to be analysed through the application of textual 'correspondence analysis'.

With regard to the application of computer techniques for the study and classification of archaeological artefacts, in the early 1980s our Institute devoted a research line that has found since 1990 a steady editorial point of reference and place of convergence for theoretical as well as methodological debate in the international journal *Archeologia e Calcolatori*. The journal, which became open access in 2005 (http://soi.cnr.it/archcalc/ [accessed: 25 June 2015], Fig. 1), was established with the idea of publishing in a homogeneous and systematic way the results of computing researches carried out in the field of historical archaeology, offering an up-to-date edition of projects in progress both in Italy and abroad. The journal follows the open access 'platinum' distribution model, so that the publisher obtains a grant to cover costs, with no author or reader fee, as indicated by the recent ALLEA (All European Academies) E-Humanitites Working Group Report. Going Digital: Creating change in the Humanities (2015) (Available from: http://www.allea.org/Pages/ALL/33/583.bGFuZz1FTkc.html [accessed: 23 june 2015]).

Looking at the recent developments of the journal (that has now reached issue 25) we could mention three important new advances. The first is the growing number of supplements that annually accompany the regular issue. In 2014 ARCHEOSEMA appeared; Artificial Adaptive Systems for the Analysis of Complex Phenomena, Collected Papers in Honour of David Leonard Clarke, edited by M. Ramazzotti, and this year saw the publication of the ARCHEOFOSS conferences (Archaeological free open source software); and the SITAR (the Territorial and Archaeological Informatics System of Rome) proceedings are also scheduled.

The second advance is that the web site registered an increasing number of visitors from almost all countries of the world, including China, Brazil and Australia. Every day there are about 20/30 accesses to the site, reaching an annual figure of about 6000, and the journal is indexed at position 39 among Italian journals on Google Scholar.

Thirdly, we have recently created a Twitter account (like other valid projects on-line, such as Internet Archaeology and Fasti on-line) that reports the latest news on the journal, but also, more generally, on open access and archaeological computing.

In the 1990s, the Institute started new research projects in the field of archaeological data processing.

First of all, there is the Caere Project (available from: http://www.progettocaere.rm.cnr.it/ [accessed: 23 June 2015]), started in 1996 by Mauro Cristofani. It concerned the computerization of the excavations carried out by our Institute, together with the Soprintendenza Archeologica per l'Etruria Meridionale, in the central area of the urban plateau of the ancient Etruscan town of Cerveteri (Barchesi 2001; Bonincontro 2001; Moscati 1998; 2001; Moscati, Mariotti, Limata 1999).

This project resulted in the setting-up of a multimedia excavation Geographical Information System, which allowed operating inside a flexible and dynamic data-processing model, where it was possible to simultaneously visualize and analyse information of different kind, by emphasizing the concept of the geographical and historical context of the archaeological evidences. It represented a model as a basis for future reinterpretations and analyses of the results.

In the framework of this project, an innovating procedure was followed, in order to recover the textual data from the fieldwork: in order to encode the yearly excavation diaries in hypertext format, the eXtensible Markup Language was used. This has allowed testing new kinds of queries and information retrieval, in order to investigate diachronically the different excavation stages and to organise the documentation relative to the different areas, until finally reaching the essential association and the subsequent analysis of finds using a statistical approach.

Over recent years other projects of the Institute have been uploaded on-line, all supported by a wide-ranging engagement, aiming at exploiting the web as an environment for consulting and sharing research and for free circulation of scientific data.

In 2006 the use of innovative technologies related to communication and multimedia have been behind the project 'Principi Sabini', based on the results of the archaeological research conducted by our institute in the Sabina area. A dedicated website hosts the reconstruction of the funerary set and the three-dimensional animated reconstruction of the cart from tomb XI of the necropolis of Colle del Forno (Available from: http://www.principisabini.it/ [accessed: 25 June 2015], Fig. 2). The tomb belonged to a prominent member, a prince, who held control over the expanding village of the ancient *Eretum*, a Sabine settlement. The multimedia project intend to virtually reuniting all the objects found in the tomb, presently exhibited in two different museums: the Ny Carlsberg Glyptotek and the Museo Civico Archeologico of Fara in Sabina.

Fig. 1. Homepages of ISMA websites: Archeologia e Calcolatori, Virtual Museum of Archaeological Computing, Sethlans. Bronzi del Museo Faina.

The website, spreading archaeological knowledge on the Sabine culture, is divided into four sections (the settlement of Eretum, the nearby necropolis of Colle del Forno, the discovery of Tomb XI, the cart finds and its virtual 3D reconstruction), which are integrated with information files, a glossary and bibliographic references. Virtual Reality was applied here for the first time in reconstructing an Etrusco-Italic vehicle (Emiliozzi, Moscati, Santoro 2007) and the virtual dimension exponentially increases the comprehension of the mechanisms of reconstruction. An interactive application allows users to experiment with a dynamic representation, and offers the possibility of seeing the image and reading the description of each component of the cart. The visitor, moreover, can choose the option to see the single components mounted in the original position on the structure shown on a transparent image of the cart.

Recently some more projects have been started, realized by using the Content Management System open source Museo&Web (Natale, Saccoccio 2010). This CMS is a content management platform that allows for the creation and updating of quality websites easily accessible, intended for museums and cultural institutions (in several languages). The software, which is free, was developed a few years ago as part of the European project MINERVA,[3] launched in 2002 under the aegis

[3] MINERVA is a network of European Ministries created to discuss, correlate and harmonize activities carried out in digitization of cultural

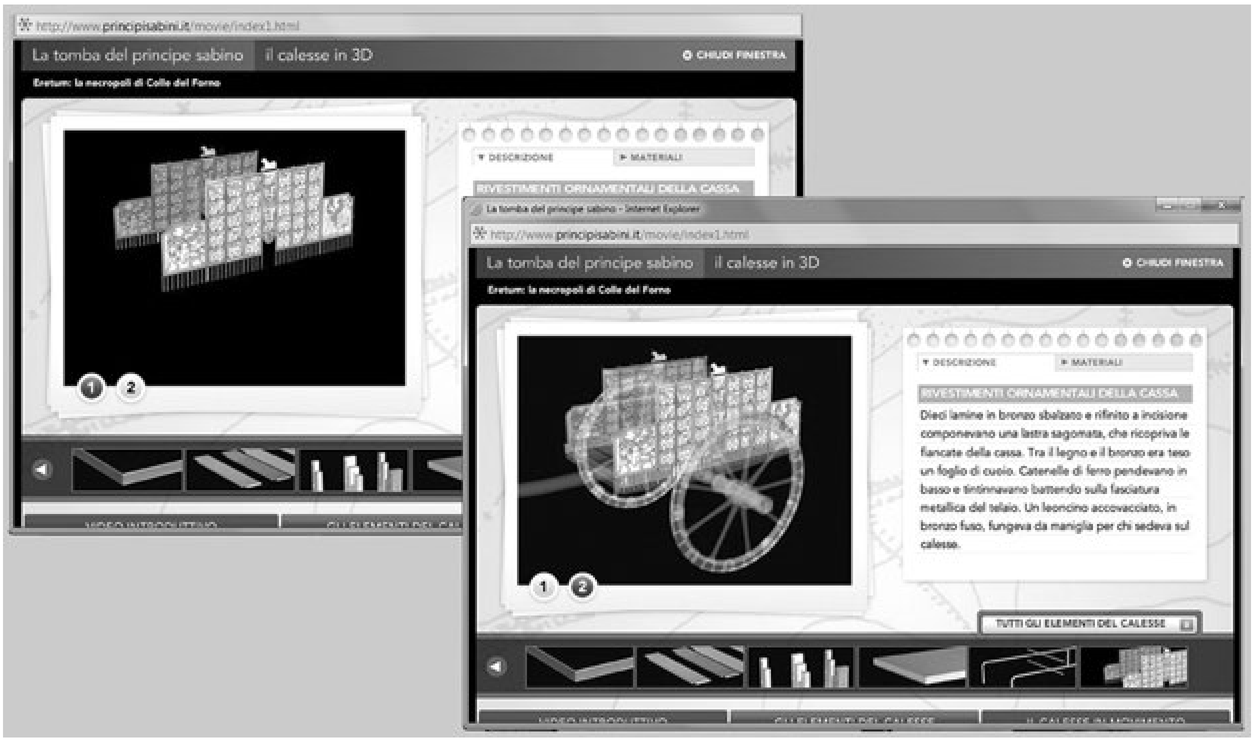


Fig. 2. The 3d reconstruction of the princely cart find from the Sabine necropolis Poggio del Forno.

of the Ministry of Culture. The CMS allows those who run the website to insert easily the content in autonomy, yet providing also a strong interactivity for on-line browsing. A user-friendly website also meets the need to effortlessly update the individual records or add new ones in parallel with the progress of the research. The system includes a series of standard ‘forms’ for the management of content, which may be hierarchically organized. These features include the record card ‘Opere’, for the publication of artwork data sheets, containing fields that are a synthetic expression of the OA/RA record proposed by Istituto Centrale per il Catalogo e la Documentazione (ICCD).

Museo&Web was chosen to implement three projects different in nature, content and purpose. The agile CMS structure has enabled us to build products of high scientific level, yet direct to a large user base, including both specialized readers and large public interested in some aspects of the archaeological research conducted in our country, with the aim of increasing the weight of web resources as research, teaching and dissemination tools.

The first project developed with this platform is the one devoted to the Cerveteri necropolis, realized in 2010 after Unesco declared the Etruscan necropolis of Cerveteri and Tarquinia as a world heritage site. The website (available from: http://www.cerveteri.beniculturali.it/index.php?it/163/cerveteri/ [accessed: 25 June 2015]) was conceived as an instrument of knowledge for the well-known Etruscan centre, able to offer also ideas and suggestions for tours and cultural itineraries. It is built with a number of pages (the territory; the city; the necropolis; the Banditaccia necropolis; the Museum) that allow the user to get information on the Etruscan city, integrating data with photo galleries, coming from the extensive documentation preserved in the archive of our CNR Institute. Some of the most important works on display in the Museum are analysed through detailed data sheets, while descriptive routes and specific files on single graves facilitate the visit to the necropolis of Banditaccia.

CMS was also applied to the website of the Virtual Museum of Archaeological Computing, managed by Paola Moscati in cooperation with the Centro Linceo Interdisciplinare ‘Beniamino Segre’ of the Accademia Nazionale dei Lincei and some ISMA researchers (available from: http://archaeologicalcomputing.lincei.it/ [accessed: 25 June 2015], Fig. 1). This website aims to show the roots and the development of this discipline, by pointing out the studies, the related institutions and main actors, at an international level. Moreover the website provides several itineraries, not geographical but theoretical and methodological, to reach some important stages of archaeological computing in an interactive way (Moscati 2014).

The website features a useful tool for researchers interested in archaeological computing, a bibliography of the 1990s, taken from the *Archeologia e Calcolatori* issues, which has been inserted into a database provided by the CMS and made interactive through links to the on-line available material. Now the implementing of the sections relating to the 1950s–1970s is under way, especially with regard to the researchers who in those years have marked the history of the discipline with their research and the innovative projects.

Web potential and advantages are exploited mainly in the section ‘Cultural Itineraries’, where it was decided to present insights to some key issues of informatics archaeology in a multimedia way. Within these files, in addition to the text, you can also

and scientific content for creating an agreed European common platform, recommendations and guidelines about digitization, metadata, long-term accessibility and preservation.

Fig. 3. One of the Cultural Itineraries of the Virtual Museum of Archaeological Computing website.

listen to short audios, watch films, explore deeper into the covered topics with references to the repository of *Archeologia e Calcolatori* or, more generally, to other resources on the web.

One enhancement is devoted to the digital cataloguing of the archaeological heritage in Italy. As can be seen in Figure 3, at the centre of the page with text and images two icons appear that link to interventions by Oreste Signore and Edoardo Vesentini, on the first projects of informatic cataloguing in Italy in the 1970s, while the icons below provide useful research tools to explore the topic in its various aspects.

Another online project realized with CMS Museo&Web concerns the rich bronze collection of the Museum Claudio Faina in Orvieto. This website is called 'Sethlans. Bronzi del Museo Faina' (available from: http://bronzifaina.isma.cnr.it/ [accessed: 25 June 2015], Fig. 1). In this case, the choice of Museo&Web was mainly determined by the presence within the CMS of the module 'Opere', which allows the online publication of data sheets on antiquity, based on the criteria established by ICCD cataloguing. A database was then made that includes about half of the bronze objects that forms part of the Orvieto collection. Each record provides summary information on objects, with a black-and-white or colour photograph. A larger space is dedicated to the most significant artefacts of the collection. They are divided into categories and analysed through more in-depth records (Caravale 2015).

A key concept of digital culture on the web is without doubt interactivity. In this case it was implemented by the creation in

FIG. 4. BRONZE *OINOCHOE* FROM THE FAINA COLLECTION.

the richest records of links to other online databases from major museums, such as the British Museum and the Metropolitan in New York, or regional ones, such as the database of Umbrian Superintendence for Archaeological Heritage. Thus, for example, a bronze *oinochoe* (Fig. 4), dated 4th-3rd century BC, which belong to a group of rare *oinochoai* attested in Umbria and south-central Etruria, is virtually connected to a similar specimen preserved in the Metropolitan Museum of Art in New York. While the plate depicting Heracles fighting Kyknos (Fig. 5) from the necropolis of the Crocefisso del Tufo is connected to a similar one in the British Museum in London.

The site offers also some information about the history of the Faina collection and its main protagonists (Caravale 2003; 2006). The first, Mauro, collected antiquities in the years immediately before his death in 1868, especially from the antiquities markets of Chiusi, Perugia and Orvieto. The second, Eugenio, heir of the collection, was more interested in the antiquities that were found in his time during the important excavations in the Orvieto necropolis.

The website sets a benchmark especially for bronze productions dated between the Archaic and Hellenistic period from the territory of Chiusi and Orvieto and its 'success' is demonstrated by the numerous accesses from Europe (Italy, Spain, France, Germany and Russia) and from the United States and some Asian countries.

As for the engine web, the CMS Museum and Web is designed so as to encourage researches made by 'spiders', the agents of the research engines, that explore the web to retrieve content and information. In accordance with the guidelines of the World Wide Web Consortium, Museum & Web, CMS makes it possible to easily create metadata for various web pages, in accordance to the structure given by the Dublin Core and, offers the possibility to group the data according to the hierarchical structure of the site. In doing so those who complete the records can avoid repeating data entries in all the pages of the site they wish to use. Google is particularly sensitive to keywords and descriptions. In the case of the Faina bronzes site these metadata fields have been filled out for the general pages and for those on the bronzes of greater importance.

In conclusion, we would like to mention an interesting project of our institute realized by Francesco Di Filippo and Maurizio Del Freo. This does not concern the Italic sector but focuses on Linear B texts (Del Freo, Di Filippo 2014). The project, called LiBER (available from: http://www.liber.isma.cnr.it/cgi-bin/home.cgi/ [accessed: 25 June 2015], aims at producing a fully featured digital edition of the Linear B documents available to date, with the substantial addition of a brand new search engine for the treatment of logo-syllabic scripts. The ultimate goal of LiBER is to provide Linear B scholars, and all those who are interested in the Mycenaean world, with an updated edition of Linear B documents, as well as with an integrated searching tool, able to sort, filter and combine the documents on the basis of textual, archaeological, palaeographic and topographic criteria. All documents stored in LiBER are reproduced from the current paper editions and are updated with any new relevant information about classifications, readings, joins, scribal hands, find spots or chronologies.

Looking at our experience, it would seem desirable that every academic institution and research centre should aim to promote and support a culture of sharing and collaborative use and re-use of archaeological data across disciplinary, organizational and national boundaries. It means overcoming the reluctance of many archaeologists to make data openly available to others, and fostering a research culture that values open sharing and re-use of data.

The proper management and sharing of data should be considered already in the project-planning phase, hence the whole research lifecycle could be as transparent and accessible as possible in a broader vision of open science. It is also essential to provide an appropriate description of the methods used to collect, analyse and present the data, trying to establish common metadata standards as largely as possible for interoperability and quality of digital cultural contents and access services.

The information society presents enormous possibilities for cultural heritage and the web gives the opportunity to share, as never before with traditional means, massive amounts of the visual data gathered in archaeology, images, three-dimensional reconstructions, computer animation, audio and video resources with a worldwide audience at an unseen speed. Also the non-expert users benefit from this approach, giving a huge resonance to the work of the specialists and raising culture to the forefront of the well-being of society.

Fig. 5. Helmet plate depicting Heracles fighting Kyknos, from the necropolis of the Crocefisso del Tufo.

Bibliography

Barchesi, C. 2001. Progetto Caere: un'applicazione Internet attiva per l'Information Retrieval di documenti SGML. *Archeologia e Calcolatori* 12: 70-89. Firenze, All'Insegna del Giglio.

Bonincontro, I. 2001. Progetto Caere: prospettive di applicazione degli standard internazionali per la codifica dei dati testuali. *Archeologia e Calcolatori* 12: 55-69. Firenze, All'Insegna del Giglio.

Caravale, A. 2003. *Museo Claudio Faina di Orvieto. Bronzetti votivi*. Perugia, Electa Editori Umbri Associati.

Caravale, A. 2006. *Museo Claudio Faina di Orvieto. Vasellame*, Perugia, Electa Editori Umbri Associati.

Caravale, A. 2015. Archaeology and Computer Applications: the automatic cataloguing of Italian archaeological heritage. In Giligny, F., Djindjian, F., Costa, L., Moscati, P., Robert, S. (eds.), *Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA)*, *Paris, 22-25 April 2014*: 35-40. Oxford, Archaeopress.

Caravale, A., Piergrossi, A. 2015. Archaeological open access journals: the case of 'Archeologia e Calcolatori'. In Giligny, F., Djindjian, F., Costa, L., Moscati, P., Robert, S. (eds.), *Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA)*, *Paris, 22-25 April 2014*: 257-63. Oxford, Archaeopress.

Del Freo, M., Di Filippo, F. 2014. LiBER: un progetto di digitalizzazione dei testi in scrittura lineare B. *Archeologia e Calcolatori* 25: 33-50. Firenze, All'Insegna del Giglio.

Emiliozzi, A., Moscati, P., Santoro, P. 2007. The princely cart from Eretum. In Moscati, P. (ed.), *Virtual Museums and Archaeology* (*Archeologia e Calcolatori*, Suppl. 1): 143-62. Firenze, All'Insegna del Giglio.

Moscati, P. 1994. Un gruppo di urne etrusche di produzione volterrana: prospettive di analisi quantitative. In Moscati, P. (ed.), *Choice, representation and structuring of Archaeological Information*. *Archeologia e Calcolatori* 5: 87-110. Firenze, All'Insegna del Giglio.

Moscati, P. 1995. Quantitative analysis of Etruscan cinerary urns. In Huggett, J., Ryan, N. (eds.), *Proceedings of the 22nd Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Glasgow 1994*: 101-4. Oxford, Tempvs Reparatvm.

Moscati, P. 1997. Ricerche informatiche sulle urne volterrane. In Maetzke, G. (ed.), Aspetti della cultura di Volterra. *Atti del XIX Convegno di Studi Etruschi ed Italici, Volterra, 15-19 ottobre 1995*: 339-45. Firenze, Olschki.

Moscati, P. 1998. Mauro Cristofani, Computerised Archaeology and the 'Caere Project'. In P. Moscati (ed.), Methodological Trends and Future Perspectives in the Application of GIS in Archaeology. *Archeologia e Calcolatori* 9: 13-8. Firenze, All'Insegna del Giglio.

Moscati, P. 2001. Progetto Caere: questioni di metodo e sperimentazioni. *Archeologia e Calcolatori* 12: 47-53.

Moscati, P. 2004. Per la descrizione computerizzata delle urne volterrane. Problemi di formalizzazione. In M. Fano Santi (ed.), *Studi di archeologia in onore di Gustavo Traversari*: 647-55. Roma, Giorgio Bretschneider.

Moscati, P. 2014. Parcours culturels pour une histoire de l'informatique appliquée à l'archéologie. In Costa, L., Djindjian, F., Giligny, F. (eds.), *Actes des 3èmes Journées d'Informatique et Archéologie de Paris, JIAP 2012*. *Archeologia e Calcolatori*. Supp. 5: 9-17. Firenze, All'Insegna del Giglio.

Moscati, P., Mariotti, S., Limata, B. 1999. Il 'Progetto Caere': un esempio di informatizzazione dei diari di scavo. *Archeologia e Calcolatori* 10: 165-88. Firenze, All'Insegna del Giglio.

Natale, M.T., Saccoccio, R. 2010. Museo & Web: un kit pratico per le istituzioni culturali che vogliono realizzare un sito web di qualità. *Archeologia e Calcolatori* 21: 27-47.

Ramazzotti, M. (ed.) 2014. ARCHEOSEMA (Artificial Adaptive Systems for the Analysis of Complex Phenomena), Collected Papers in Honour of David Leonard Clarke. *Archeologia e Calcolatori*. Supp. 6. Firenze, All'Insegna del Giglio.

A Swabian in the Orient.
In the Footsteps of Julius Euting

Matthias Lang[(1)]
matthias.lang@uni-tuebingen.de

Virginia Hermann[(2)]
virginia.herrmann@uni-tuebingen.de

Manuel Abbt[(1)]
mail@m-abbt.de

Kevin Körner[(1)]
kevin.koerner@uni-tuebingen.de

Gerlinde Bigga[(1)]
gerlinde.bigga@uni-tuebingen.de

Fabian Schwabe[(1)]
fabian.schwabe@uni-tuebingen.de

Jason T. Herrmann[(2)]
jason.herrmann@uni-tuebingen.de

Dieta Svoboda[(1)]
dieta-frauke.svoboda@uni-tuebingen.de

[1] eScience-Center, University of Tübingen
[2] Institute for Ancient Near Eastern Studies (IANES), University of Tübingen

Abstract: At the end of the 19th century, the orientalist Julius Euting travelled several times to the Middle East to investigate and record pre-Islamic monuments, artefacts, and inscriptions. His journals and sketchbooks are preserved in the University Library of Tübingen where they recently were completely digitized (Digitue 2012). The aim of the presented project is to connect these texts with additional sources and data in a common interface (eScience-Center 2013-2015).

This system is based on the web-framework Neatline, developed at the University of Virginia (Scholar's Lab 2015) to manage and visualize heterogeneous data within a common interface. The system was extended with a functionality to store and display XML-encoded texts according to the recommendations of the Text Encoding Initiative (TEI Consortium 2015a).

Furthermore, every entry in the journals is connected to a date or a time-span displayed in a timeline that could also be used to access the text. Beyond this, it is possible to upload or to link scientific articles to monuments, artefacts or archaeological sites mentioned by Euting. All geographical information in the diary can be directly connected to different maps provided within the system.

Besides the technical basics, the paper will discuss also scientific possibilities and values of digital presentations and publication in general.

Keywords: Digital Text edition, Spatial Humanities, Research History

1 The Diaries of Julius Euting

Julius Euting's detailed descriptions and lively illustrations make his sketchbooks and travel journals unique research objects that provide insight into everyday life and landscapes of the Middle East in the 19th century. They are also a valuable record of the 'Orientbegeisterung' of 19th-century researchers and their perspective on Near Eastern history and culture in this epoch.

Euting's eight expeditions to the Middle East began after his graduation in Oriental Studies at the University of Tübingen (1962) during his employment as a librarian for the Protestant Seminary in Tübingen and later for the University Library of Tübingen (Graner 1962: 310-1; Notz 1983). Although he was interested in everyday life scenes, the primary aim of his expeditions was to locate inscriptions in different oriental languages. Some of the inscriptions he encountered were preserved in his documentation and others he tried to acquire for his collection. His initial trips to Constantinople and Smyrna (1867), Tunis and Carthage (1869) and again Constantinople (1870) were self-financed. While personal records of these journeys have not been found, these trips yielded several monographs that describe a set of Phoenician inscriptions (Euting 1871; Euting 1874; Euting 1875; Euting 1883).

Euting's 1871 appointment as honorary professor and later promotion to Director of the University Library of Strasbourg in 1900 (Graner 1962: 317) permitted him to continue his expeditions to the Middle East with funding from the proconsul of Alsace-Lorraine (Graner 1962: 317; Lozachmeur, Briquel-Chatonnet 2010). The publication of his diaries from his first major expedition to 'Inner Arabia' included documentation of more than 900 inscriptions (Euting 1896; Euting, Littmann 1914). A few years later (1889-1890) he undertook an expedition to Turkey and Northern Syria and spent several months at the excavations in Zincirli as expert for Oriental Epigraphic (Luschan 1893). This expedition constitutes the core of the Tübingen eScience-Center project (eScience-Center 2013-2015). Euting visited the excavations at Mschatta and other sites in Syria and Egypt (1903-1904) during his final expedition (Didier 2010: 110; Troelenberg 2014).

Besides epigraphy, Euting was also interested in the daily life that surrounded him as evidenced by his collection of quotidian items and descriptions of traditional dress and practices in his journals, complemented by detailed watercolour drawings and sketches. Euting himself travelled in Bedouin costume under the name *Abd el wahhâd* ('Servant of the Almighty'), which presumably enabled him to access the local societies (Graner 1962: 320-1). Hence Euting's records are not only an interesting research object for ancient history, epigraphy and archaeology but are also valuable records of 19th-century history and culture in the Middle East.

In total, 26 journals, including diaries and sketchbooks, are preserved in the University Library Tübingen (Digitue, 2012). In addition, many of the objects of Euting's collection can be found at the Linden-Museum in Stuttgart, to whom he gave his private collection in 1912. These objects comprised a crucial part of a special exhibition held in occasion of the 100th anniversary of the scholar's death on 11 of July 1913.[1]

2 Technical Background

The fundamental component of the system architecture is the open source content management system Omeka (CHNM 2015) combined with the *Neatline*-plugin (Schloar's Lab 2015). It can be used to manage and publish project representations consisting of text, pictures, geographical information, and even time information within a browser based web interface, making it accessible to those with no specialized knowledge. Omeka is implemented in PHP and offers JavaScript based interaction with a MySQL database structure that is hidden from users, but can be achieved for modification by the backend. Access requires a username and password so that multiple Omeka instances may operate on the same data stored in a centralized database. Geoserver (OGC 2014) software is used to store geospatial data including archaeological maps. The Omeka system provides interfaces linking georeferenced maps in geoserver instances to our projects using the Web Map Service (WMS) standard (OGC 2015a).

So-called *Neatline Exhibits* are used to initialize the presentation of a project and connect the different types of data. Whenever a project is accessed Omeka loads the associated data from the MySQL database, creates an HTML description based on the data, and includes JavaScript source code for user interaction. The result is sent to the accessing web browser that now can load additional data from the Geoserver. The interested user may now simply browse through the project representation.

We extended the Omeka core functionality by adding several JQuery Libraries and adding Cascading Style Sheet descriptors to achieve another dimension: textual comparison. The main requirement was to find a solution that allows comparison between text scans, digital transcript, and normalization in an Omeka project. Moreover, additional interesting information is highlighted and linked to relevant sources.

To that end, we implemented an XSLT-Generator in the user interface. Based on the TEI norm the user can create an XML-based transcript of the text including additional markup for normalization of text parts, and notes. This description is used by the XSLT-Generator to create HTML-snippets that are stored inside a folder besides the Omeka-Installation. We extended the HTML generation by additional JQuery code that is delivered to the accessing browser. This loads the HTML descriptions including pictures from the server when they are accessed the first time in the browser. Similar information from third-parties is also loaded, e.g., from Wikipedia.

[1] Julius Euting 1839-1913. Ein schwäbischer Orientforscher, Kabinett-Ausstellung im Linden-Museum Stuttgart, 13 July 2013 - 11 January 2015.

3 Geographical Information

Vector-based information is stored using the well-known text format WKT (OGC 2015b), a standardised mark-up language that is able to describe most of the current geodata file formats, so that all vector-based information in the database can directly be connected to textual information. The interface includes a built-in interface to implement web-based map services like *Google Maps* (Google 2015) or *Bing Maps* (Microsoft 2015), which are effective for illustrating Euting's broader movements but less useful for high-scale data such as excavation drawings.

Access to current satellite image services is augmented with scans from the Historic Map Collection of the department of geography of the University of Tübingen, which were digitized and georeferenced with the support of the University Library Digitisation Centre. These maps provide a valuable frame of reference for historic research questions that could be obscured by the various political and environmental changes that followed World War I.

Another technical component made possible by *Neatline* is the possibility to implement georeferenced maps through a standardised WMS interface (OGC 2015a). Within the project, the open source tool *Geoserver* (OGC 2014) was installed to transfer the digitized maps to this interface and the defined WMS layer is delivered as JavaScript source code. The maps are then loaded into the browser via *GeoServer* and are made available to the user.

4 Text encoding

Both text forms in the presentation, the transcription of Euting's journals and the declarative annotations, are XML-encoded and automatically transferred into HTML and inserted into the *Neatline* framework. The background is one XML-file holding all relevant information of the project. XML (e**x***tensible* ***m****arkup* ***l****anguage*) as a markup language offers a simple method to structure text-based information via an extensive tag set. In addition it is possible to enrich the data with non-textual information that links to images, audio and video files.

The main idea of XML-structured information is an intensive and thorough description of the content detached from endless possibilities of presenting the information. While using so-called elements and attributes all information can be structured in classes and subclasses. Each of them can additionally be described with metadata. Therefore, an XML-file with its highly structured form is perfectly suitable for the exchange of data (W3C 2015).

The text encoding refers to the proposals of the *Text Encoding Initiative* (TEI), a well-known and widely accepted standard (TEI Consortium 2015a). The main benefit lies in the detailed and online available documentation, so that everybody can understand the encoding and – when the XML-file is finally published – work on with the stored information. This will ultimately support the cooperation between scholars, since the machine-readable and highly structured data can be reused for a new related project.

Every XML-file, which is valid to TEI, must have two core sections: the head section with metadata over the file itself and the encoded text (<teiHeader>) and the real core section for the

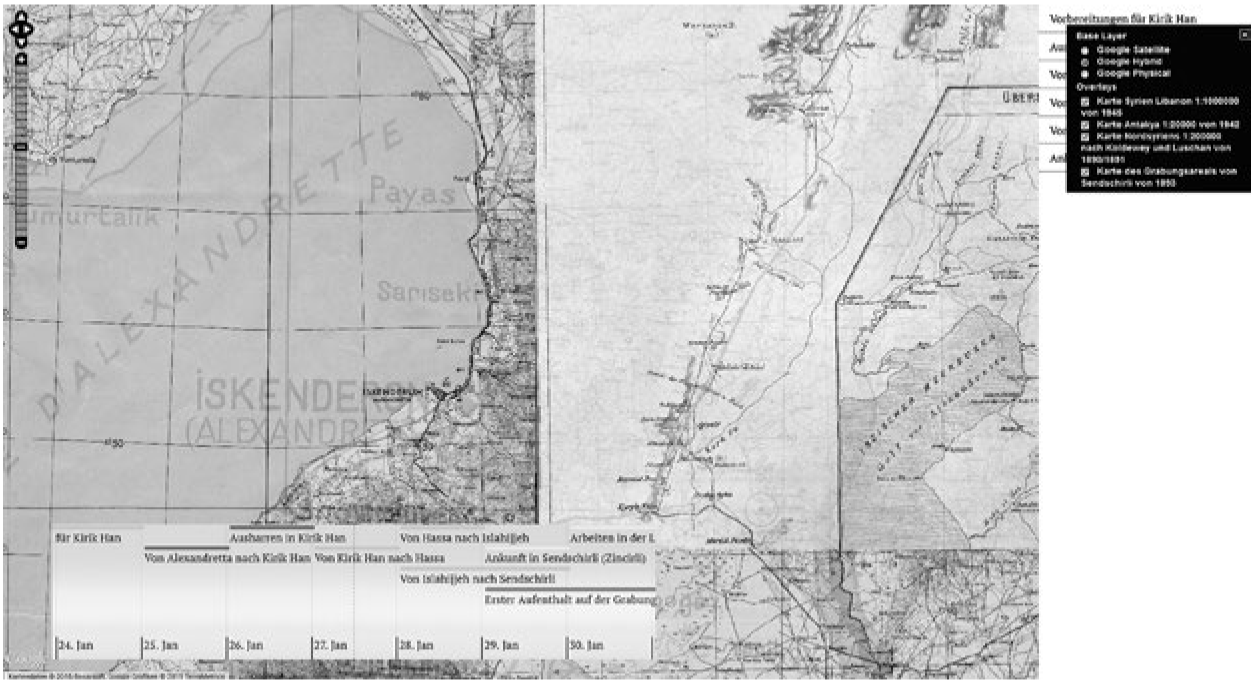


FIG. 1. IMPLEMENTATION OF HISTORICAL MAPS.

encoded text (<text>). Furthermore there is a section for the connection between text and images of that text (<facsimile>). The core area <text> can be parted again in the three sections <front>, <body> and <back>. The encoded source text should be stored in <text> and is mandatory. <front> and <back> are additional and can left out. In order to encode the journals and some annotation the sections <body> and <back> were used. All annotations were place in <back>, because this is information given to the journals and no source text. The structure of the XML-file is as follows:

All main sections are structured with more specific XML-elements in order to distinguish all relevant information for the project. So-called pointers link to other parts within the XML-file or outside of the file, this way, and a digital representation of from one part of the journal can be linked with transcribed text or the linkage of a declarative annotation with a certain word or text passage. Eventually the XML-file consists of small blocks of information stored as a unit.

The header (<teiHeader>) section is preserved for information about the project (TEI Consortium 2015b). In the facsimile section (<facsimile>) is done the linkage between the digital representation of the journals and their machine-readable texts as said above. All image files are stored in two different resolutions for the various needed visualization in *Neatline*. Moreover, there are parts of an image on every side of the journals defined. This enables a very precise linkage between a certain text passage in the digital representation and in the text, in order to create a familiar visualization of a facsimile and its text as a vis-à-vis during the transformation into HTML. One such image is sufficient to figure all passages on one side of the journals.

The transcription of Euting‘s journals about his journey to the North of Syria in 1889/90 does not cover all entries, but is done in extracts. Every text passage exits in two encodings. The first shows a faithful transcription of the text as Julius Euting has written it. The second version shows all abbreviations expanded implicitly. All text passages stand for themselves and are encoded within the element <div>. All omissions between two text passages or within one text passage are tagged with the element <gap> and its attributes to determine the extent of the omission. The function of <gap> is purely for organizing the metadata and the added information is not displayed in *Neatline*. Still it is important information for users who may be interested in the journal text as a whole.

Three categories exist for the enrichment of the journal text with added information as text, image, hyperlink and download of free articles: person, place, and free annotation. This distinction enables the standardization of annotations on persons and places regarding the structure and mandatory information, in order to ensure a fixed homogeneous visualization of all given information during the transformation into HTML.

The main benefit of the described method is the flexibility of the encoding of text and other information. At all times it is possible to change the vantage point on annotations as one wishes. The annotations can contain as much information as necessary, in order to give adequate answers to new emerging questions.

Interface

The interface[2] is comprised of four elements. The constant background is always a map consisting of different layers that may be turned on and off by the user through a drop-down

[2] A screencast showing the functionalities of the interface is available from https://www.youtube.com/watch?v=9XrWU_4hYiM&feature=youtu.be [accessed: 29 June 2015].

```
<TEI xmlns="http://www.tei-c.org/ns/1.0">
    <teiHeader>
        the encoded text and meta data over the XML-file
    </teiHeader>
    <facsimile>
        adresses of all image files and information about them
    </facsimile>
    <text>
        <body>
            selected passages of the journals
        </body>
        <back>
            annotations of persons, places and words etc.
        </back>
    </text>
</TEI>
```

Fig. 2. TEI-XML structure.

menu. Referenced maps can be displayed as semi-transparent overlays. However, style options are set in a separate editor, a dynamic user-based access to these options is at this moment not currently possible.

The interface displays a list of the individual entries on the right side of the browser window. These entries are already enhanced with geographical information, which are shown as point or polygon features. The chosen form differs depending on whether an activity can be tied to a certain place or happened during the journey. The style and colour of the polygons depends on the means of transportation: boat journeys are displayed as arrows, train trips as rail tracks and overland travels as camel tracks. Additionally, different colours are used to distinguish between private and scientifically motivated activities.

When a tile from the listing or geographical information on the map is chosen, the corresponding entry from the diary is chosen and displayed in a new window on the left side of the browser window, which contains the excerpt of the digitized page of the diary and a transcription of the manuscript. The complete digitized page is available by selecting the excerpt. A normalized transcription is displayed with a mouse-over. Relevant linked information, such as papers cited by Euting, is also linked and can be downloaded in .pdf format. Moreover, every single entry of the diary is connected to a point on a timeline displayed at the bottom of the browser window, which can be used to navigate the diary via color-coded spans that correspond to travel vectors.

5 Sustainability

An increasing problem of digital data from humanities projects is the sustainable conservation of digital environments. In contrast to conventional publication formats, such as monographs, these environments require constant maintenance which cannot always be ensured due to limited funding and changing formats. For this reason, complex and expensive projects can become obsolete after only a few years. As a preventative measure, the Tübingen Euting project uses only standardised technologies and file formats that require minimal maintenance. Nevertheless, this is not a final solution because it may be inevitable that technological enhancements are going to limit or wholly prohibit project accessibility, and resources for future data migration are anticipated.

To preserve the collected data, data and data environment have to be considered as two different components. While the conservation of the data environment cannot be guaranteed, the infrastructure for archiving these data in the long-term currently exists on the premise that standardised file formats and the detailed metadata ensure future user access (Ullrich 2008). Euting project data will be preserved in the eScience-Center archiving system (eScience-Center 2014a) and will be available by an Open Access licence.

In contrast to conventional publication media that are only provided by specialised libraries and usable for some scholars, web-based publications offer results to a broad and diverse public. Global accessibility ensures a wide reception of results by scholars in different countries and different research focuses can be expected. One possible benefit is that interesting scientific exchanges und innovative research approaches could result.

6 Added Scientific Value

The integrated analysis of historic geographical information with the spatial representation of journal elements presents scientific value beyond being only another type of visualisation. This highly dynamic system is easily updatable and presents a versatile framework open to a variety of research questions and foci (Meusberger 2013: 244).

Since the ‘spatial turn’, researchers in the humanities and social sciences have worked on ways to connect text with spatial information, regardless of whether space is understood on a geographical or social background (Soja 1989: 10-42; Günzel 2008; Bachmann-Medick 2009: 288-90; Warf, Arias 2009; Piltz 2009: 87; Frank 2009: 66). While the analysis and presentation of historic contexts based on maps is not completely new (Schlögel 2004: 278-9), spatial information has to be regarded as a valuable repository for information and is therefore an additional and equally important attribute (Döring, Thielmann 2008: 16-7). The incorporation of maps in text analysis supports not only the visualization of spatial information used

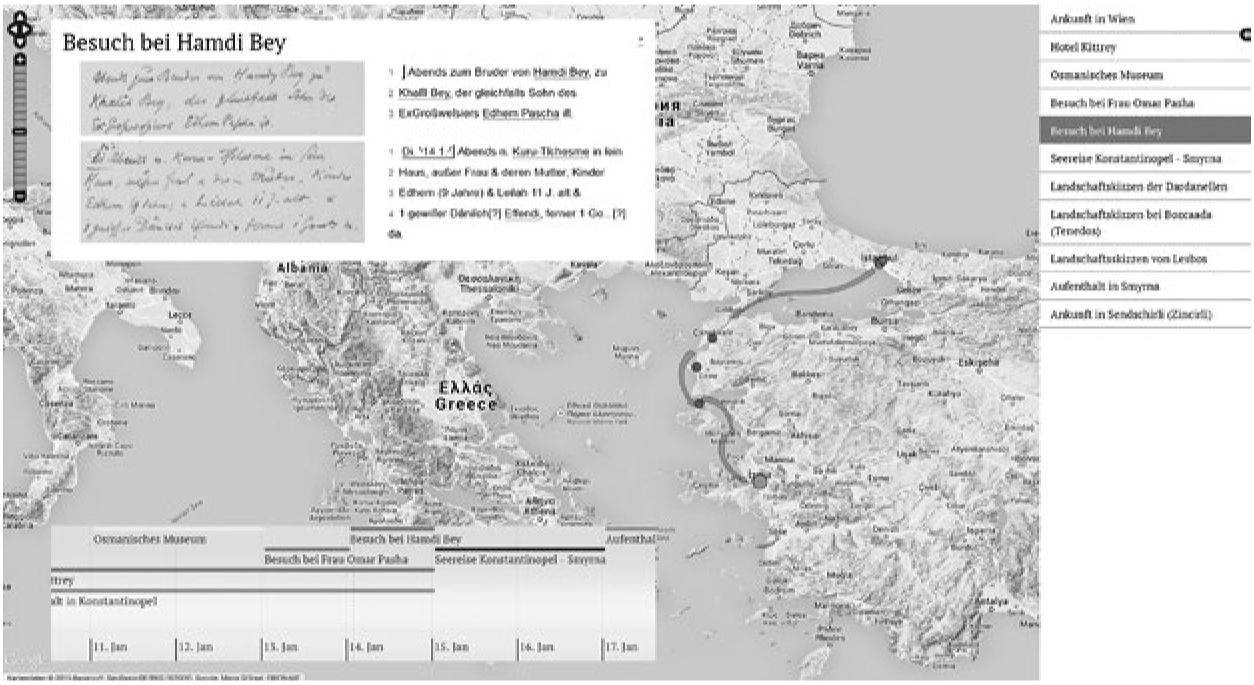


Fig. 3. The interface of the Euting project.

in the manuscript – in this case the Euting diaries – and reveals the changes in social, administrative, ethnographic, economic, ecologic and morphologic organization of a predefined region over time. From this, further research based on these records is not restricted to focusing on the history of the expedition or the region.

Some testing is necessary to prove the value of the described tools in academic research. The Chicago-Tübingen Archaeological Project in Samal (Schloen 2009; University of Chicago Oriental Institute 2015) will function as a suitable case study. The project continues the archaeological excavations at Zincirli, ancient Sam´al, where Felix von Luschan and Robert Koldewey (Luschan 1893) began work in 1888 and where Euting stayed for several months in 1890. The collaboration between Chicago and Tübingen has two main aims: On the one hand, the findspots mentioned in Euting´s diaries will be identified (in the summer of 2015) and comparisons between the historic description and today´s situation are intended. On the other hand, the pre-modern landscape will be reconstructed using Euting´s texts, sketches and maps. As a starting point, Euting´s observations were included into the system and were supplemented with other historic spatial information of that region. Already his records have advanced the Chicago-Tubingen research project in detailing several finds that are previously unpublished and providing alternative perspectives and accounts of the excavation project.

7 Further Perspectives

The next step is to integrate Euting´s diaries of his first trip to northern Syria completely into the system. Furthermore, the Chicago-Tubingen Expedition to Zincirli will explore the scientific value of the system in their coming field season. The integration of further analysis tools into the browser environment is planned in order to allow also complex data queries within the system. Finally, an evaluation of the system architecture and its applicability to other texts and genres is in preparation, including the *Imperial Trans-Antarctic Expedition* conceived by Ernest Shackleton (Shackleton, 1920).[3]

Bibliography

Bachmann-Medick, D. 2009. *Cultural Turns: Neuorientierungen in den Kulturwissenschaften*, *3rd edition*. Reinbek bei Hamburg, Rowohlt-Taschenbuchverlag.

Chnm 2015. *Omeka*. Roy Rosenzweig Center for History and New Media. George Mason University. [Online] Available from: http://omeka.org/ [accessed: 21 June 2015].

Didier, C. 2010. Portrait d'un fondateur: Julius Euting. *La revue de la BNU* 2: 104-15.

Digitue 2012. Euting, J., *26 Tagebücher und 10 Skizzenbücher über die Reisen in den Orient, nach Nordafrika und zu den Orientalistenkongressen.* [Online] Available from: http://idb.ub.uni-tuebingen.de/diglit/Md676-22 [accessed: 21 June 2015].

Döring, J., Thielmann, T. 2008. Einleitung: Was lesen wir im Raume? Der Spatial Turn und das geheime Wissen der Geographen. In J. Döring, T. Thielmann (eds.), *Spatial Turn. Das Raumparadigma in den Kultur- und Sozialwissenschaften*: 7-45. Bielefeld, transcript Verlag.

Escience-Center 2013-2015. *The Euting project.* [Online] Available from: http://ecenter.uni-tuebingen.de:8012/neatline/fullscreen/start [accessed: 21 June 2015].

Escience-Center 2014a. *Aufbau eines Archivsystems für die Geisteswissenschaften* [Online] Available from: http://www.escience.uni-tuebingen.de/infrastruktur.html [accessed: 21 June 2015].

Escience-Center 2014b. *Endurance-Expedition unter der Leitung von Sir Ernest Shackleton (1914-1917).* [Online] Available from: http://www.escience-lehre.uni-tuebingen.

[3] Available online from: http://www.escience-lehre.uni-tuebingen.de/omeka/neatline/fullscreen/shackleton [accessed: 29 June 2015].

de/omeka/neatline/fullscreen/shackleton [accessed: 21 June 2015].

Euting, J. 1871. *Punische Steine*, Mémoires de l'Académie Imperiale des Sciences de St. Petersbourg 3. St. Petersburg, Académie Imperiale des Sciences.

Euting, J. 1874. *Erläuterungen einer zweiten Opferordnung aus Carthago*. Strasbourg, Trübner.

Euting, J. 1875. *Sechs phönikische Inschriften aus Idalion*, Strasbourg, Trübner.

Euting, J. 1883. *Sammlung der Carthagischen Inschriften Bd. 1*. Strasbourg, Trübner.

Euting, J. 1885. *Nabatäische Inschriften aus Arabien*. Berlin, Reimer.

Euting, J. 1896. *Tagebuch einer Reise nach Inner-Arabien Bd. 1*. Leiden, Brill.

Euting, J., Littman, E. 1914. *Tagebuch einer Reise nach Inner-Arabien Bd. 2*. Leiden, Brill.

Evans, C., Jasnow, B. 2014. Mapping Homer's Catalogue of Ships. *Literary and Linguistic Computing* 29, 3: 317-25.

Frank, M. C. 2009. Imaginative Geography as a Travelling Concept. Foucault, Said and the Spatial Turn. *European Journal of English Studies* 13, 1: 61-77.

Google 2015. *Google Maps*. [Online] Available from: https://www.google.de/maps [accessed: 21 June 2015].

Graner, H. 1962. *Julius Euting. Lebensbilder aus Schwaben und Franken* 8: 305-34.

Günzel, S. 2008. Spatial Turn – Topographical Turn – Topological Turn. Über die Unterschiede zwischen Raumparadigmen. In J. Döring, T. Thielmann (eds.), *Spatial Turn. Das Raumparadigma in den Kultur- und Sozialwissenschaften*: 219-37. Bielefeld, transcript Verlag.

Lozachmeur, H., Briquel-Chatonnet, F. 2010. Charles Huber und Julius Euting in Arabien nach französischen, auch heute noch nicht veröffentlichten Dokumenten. *Anabases* 12: 195-200.

Luschan, F. von 1893. Ausgrabungen in Sendschirli 1: Einleitung und Inschriften. *Mittheilungen aus der orientalischen Sammlungen* 11. Berlin.

Meusburger, P. 2013. Wissenschaftsatlas der Universität Heidelberg. In I. Runde (ed.), *Universitätsarchive in Südwestdeutschland. Geschichte. Bestände. Projekte. Tagungsband anlässlich des 625-jährigen Jubiläums der Ersterwähnung einer Archivkiste der Universität Heidelberg zum 8. Februar 1388*: 241-49. Heidelberg, Winter.

Microsoft 2015. *Bing Maps*. [Online] Available from: http://www.bing.com/maps/ [accessed: 21 June 2015].

Musacchio, J. M., Bartle, J., Mcclure, D., Bhatt K. 2014. Mapping the 'White, Marmorean Flock': Anne Whitney Abroad, 1867-1868. *Nineteenth-Century Art Worldwide 13 (2)*. Available from: http://www.19thc-artworldwide.org/index.php/autumn14/musacchio-introduction [accessed: 31 January 2015].

Notz, H. 1983. *Sechzehnsprachenmännle, Ruhesteinvater und Feuerteufel: Professor Dr. phil. Julius Euting*. Freudenstadt, Schwarzwaldverein.

Nowviskie B., Mcclure, D., Graham, W., Soroka, A., Boggs, J., Rochester, E. 2013. Geo-Temporal Interpretation of Archival Collections with Neatline. *Literary and Linguistic Computing* 28, 4: 692-9.

Ogc 2014. *GeoSever*. [Online] Available from: http://geoserver.org/ [accessed: 21 June 2015].

Ogc 2015a. *Web Map Service*. Open Geospatial Consortium. [Online] Available from: http://www.opengeospatial.org/standards/wms [accessed: 21 June 2015].

Ogc 2015b. *Simple Feature Access*. Open Geospatial Consortium. [Online] Available from: http://www.opengeospatial.org/standards/sfa [accessed: 21 June 2015].

Piltz, E. (2009) Trägheit des Raumes. Fernand Braudel und die Spatial Stories der Geschichtswissenschaft. In J. Döring, T. Thielmann (eds.), *Spatial Turn. Das Raumparadigma in den Kultur- und Sozialwissenschaften*: 75-102. Bielefeld, transcript Verlag.

Schloen, J., Fink, A. S. 2009. Searching for Ancient Sam'al: New Excavations at Zincirli in Turkey. *Near Eastern Archaeology* 72, 4: 203-19.

Scholar's Lab 2015. *Neatline*. Scholar's Lab University of Virgina. [Online] Available from: http://neatline.org/ [accessed: 21 June 2015].

Shackleton, E. 1920. *South*. New York, The Macmillan Company.

Soja, E W. 1989. *Postmodern Geographies. The Reassertion of Space in Critical Social Theory.* London-New York, Verso.

Tei Consortium 2015a. *TEI: P5 Guidelines*. [Online] Available from: http://www.tei-c.org/ [accessed: 21 June 2015].

Tei Consortium. (2015b) *TEI Header.* [Online] Available from: http://www.tei-c.org/release/doc/tei-p5-doc/en/html/HD.html [accessed: 21 June 2015].

Troelenberg, E. M. 2014. Mschatta in Berlin. Grundsteine Islamischer Kunst. *Connecting Art Histories in the Museum* 1. Dortmund, Kettler.

Ullrich, D. 2008. Digitale Speichermedien, In *Eine kleine Enzyklopädie der digitalen Langzeitarchivierung. Nestor Handbuch 1.5* [Online] Available from: http://nestor.sub.uni-goettingen.de/handbuch/artikel/nestor_handbuch_artikel_41.pdf [accessed: 29 June 2015].

University Of Chicago Oriental Institute 2015. *The Neubauer Expedition to Zincirli* [Online] Available from: http://zincirli.uchicago.edu/ [accessed: 21 June 2015].

W3c 2015. *Extensible Markup Language (XML)* [Online] Available from: http://www.w3.org/XML/ [accessed: 21 June 2015].

Warf, B., Arias, S. 2009. Introduction: the Reinsertion of Space into the Social Sciences and Humanities. In B. Warf, S. Arias (eds.), *The Spatial Turn. Interdisciplinary* Perspectives: 1-10. London-New York, Routledge.

GQBWiki Goes Open

Stefano Costa
(steko@iosa.it, http://orcid.org/0000-0003-1124-3174)

Alessandro Carabia
(alessandrocarabia@gmail.com)

Department of Historical Sciences and Cultural Heritage, University of Siena, Italy

Abstract: GQBWiki is a wiki website for the archaeological research project on the Byzantine city of Gortyn, based on open source software and publicly accessible under the CC-BY-SA license. It has been used since 2005 to record excavation data together with other content ranging from bibliography to reflexive documentation. While the MediaWiki software lacks native capabilities for structured querying, the Semantic MediaWiki extension has been used to provide all the infrastructure necessary for linked open data. GQBWiki is the on-going result of collaborative work and strives to give attribution to all contributors in a transparent way, with all the challenges that a non-traditional publication workflow brings.

Keywords: Multivocality, Collaborative authorship, Open data, Open source

1 GQBWiki

GQBWiki is an online wiki website (http://www.gortinabizantina.it/wiki/) dedicated to the archaeological research project in the Byzantine Quarter near the Pythion shrine in Gortyn (Crete), run by the University of Siena. It has been operational since 2006. While fieldwork at the site started in 2001, it was only in 2005 that we decided to start building a digital archive where the documentation could be collectively created and curated, not limited to excavation data *strictu sensu*, migrating over content from previous relational databases for stratigraphic data. In 2005, choosing a wiki over other available systems seemed to provide strategic advantages, such as being online, always available when and where an Internet connection was available and more generally facilitating the creation of an encyclopaedic resource about the research project. GQBWiki has always been restricted to the research team members until April 2015, so there was no benefit in terms of visibility of the resources that were created and updated. In retrospect, the choice of an online platform brought several 'revolutionary' advantages that took us some time to appreciate their full potential. In this paper, we outline the current status of GQBWiki and what we think we learned in the past 10 years, particularly with respect to our first discussion on the same topic (Zanini and Costa 2006) and a wider overview of the situation for knowledge sharing in the archaeological world (Zanini and Costa 2009).

The research project at GQB has a focus on the Late Antique and Early Byzantine phases of the urban area of Gortyna, and is therefore part of the rather large topic about the end of the ancient Mediterranean city. With this premise in mind, it seemed natural for GQBWiki to become a comprehensive archive where the archaeological record could become part of a hypertext, and could be linked to historical evidence, broader interpretive texts and so on.

On the technical side, GQBWiki is based on the popular MediaWiki software, better known for being used by Wikipedia and other related websites, but also available for use by third parties under the GNU General Public License. Since we adopted it in 2005, MediaWiki has been constantly updated and improved by the Wikimedia Foundation and by other contributors, so far reducing the risk of finding ourselves with an obsolete tool – while other pieces of wiki software were abandoned in the meantime – acknowledging that the maintenance of such a complex tool is well beyond the technical capabilities of a small team, not to mention the increasing need to keep web-based software free from security bugs that may put the privacy of users at risk. MediaWiki is built on the well-known LAMP platform (Linux, Apache, MySQL, PHP) and can be run with no difficulty on any web hosting service, at least in its basic functionality. GQBWiki is used all year round, but it is essential during the fieldwork season. Due to the lack of an Internet connection at the mission house in Agioi Deka near Gortyn, it was only in 2012 that we could work directly on GQBWiki using a commercial mobile broadband Internet provider. In the previous years, we would simply take advantage of software freedom and the flexibility of GNU/Linux systems to install a local wireless network with a web server running MediaWiki on a spare laptop and a local 'clone' of GQBWiki (the online version was put in read-only mode). At the end of each field season, the updated content has been put online again until the next year. This approach does not seem very widespread and in our case in has become obsolete, but in our case it worked well as an alternative to file-based collaboration, where all team members work separately and there is a collation process at the end, while retaining a 'slow' pace as described by Caraher (2015).

The entire content of GQBWiki is in Italian: our team is not international and it would be unnatural to write our documentation in English. Italian is also known by many scholars of the ancient world. In fact, it could be argued that Greek is the language that is actually missing from GQBWiki, because the research project is taking place in Greece, under control by the Greek authorities. The prevalence of the English language on the Web and in academic literature is undebatable (especially in a paper written in English), but its advantages over multilinguism are less clear. The Wikimedia movement has taken a clear practical stance in favour of multilinguism, with hundreds of Wikipedias in minority languages. Since we adopted the software platform of the Wikimedia movement, it seems appropriate to reflect on this global issue, not just from our privileged point of view and with the concern of visibility and academic value of our work, but also from the perspective of making knowledge available to as many people as possible.

The wiki home page guides both the casual reader and the regular contributors to the various sections of the website, acting as a table of contents for the various areas of interest and the levels of detail. At a glance, the contents range from excavation data to interpretive texts, providing a necessary companion to the final GQB publication, the tone of which will be narrative and holistic rather than enumerative. There are certainly parallels with other similar systems that were built in the same years, like the one developed for Villa Magna (developed by Andrew Dufton and Elizabeth Fentress), both in terms of types of content and of technical solutions.

When comparing GQBWiki and our use of MediaWiki to other 'archaeological information systems', one aspect that should be immediately clear is that we are not proposing wiki systems as the best solution for any archaeology research project, particularly from a technical standpoint. There are limitations that make GQBWiki imperfect, if not in principle at least in practice, and it is important to recognise these limitations. The most substantial limitation is with spatial data (context plans, sections, etc.) that MediaWiki is completely unable to support natively. Looking at this seemingly unacceptable issue from a broader perspective, we can observe that in 'traditional' site archives and archaeological information systems, alphanumeric, graphic and spatial data are managed in the same platform, while interpretation and publication are left on their own. On the other hand, GQBWiki is missing spatial data that is managed through separate software tools, but all other content is part of the same platform. Spatial data consists mainly of context plans that are rendered as static raster images and uploaded to the wiki in batch, and then dynamically loaded in the relevant pages based on the semantic features outlined below.

A wiki page is a free form web page, where a lightweight markup is used instead of HTML to ease authoring. Therefore, any schematisation (such as the requirement that all stratigraphic context records have the same appearance and minimum information) is obtained by means of discipline and templates, not unlike Wikipedia content. There can be as many templates as needed in a wiki page, for formatting parts of content in specific ways (e.g. the well-known 'infobox' in the top right) or more complex tasks.

Wiki systems are by definition multi-user, both technically and socially. The net result is that GQBWiki is an incarnation of written multivocality, probably not of the same kind envisaged by Ian Hodder, but nevertheless stimulating, especially when we consider that all users/members have access to the same total amount of information, both for reading and editing. Users can edit any page as they see fit, fixing small typos or changing the functional interpretation of a deposit. The reality is less radical than what it may seem, though. Each wiki page preserves its own 'history' of edits, providing an overview of who has been adding (or removing) content, when, etc., as anyone familiar with Wikipedia will find normal (we hope that members of an academic audience have a basic understanding of these tools). This allows relevant meta-information to be immediately available, such as the last date when a page was updated – and therefore whether the content is possibly outdated. In a general sense, the page history provides an overview of 'who contributed what' with respect to the page under examination.

The big step we are taking in 2015 is opening GQBWiki to the public, even before there is a print edition of the research project, under a Creative Commons – Attribution – Share-Alike license (again, the same used by Wikipedia). By doing this, we hope to provide a useful digital resource for those working in Mediterranean archaeology, for example by sharing digital images of finds from dated contexts (a very common quest in this field of studies). At the same time making GQBWiki open is a straightforward way to elicit and stimulate feedback about our archive as a whole. Unfortunately, for the moment the ability to edit content is limited to team members and registered users (mainly due to the need to avoid spam): this is perhaps not even considered in most cases when similar digital resources go online, but it seems worth pointing out that it would be very interesting for anyone and especially other scholars to be able to comment on pages and even provide alternate interpretations for site features and finds. We are keen on registering new users on demand, but not with an effortless registration procedure that is standard for modern websites. However, this limitation is in our available time, not in the software.

2 Dealing with limitations, exploring possibilities

A quick numerical summary of GQBWiki shows that, at the time of writing, there are 2089 pages, with 16190 internal links and 27618 single edits. Pages range from stratigraphic units to find records, but it is journal entries that play a central role in the navigation path, rather than the useful but confusing list of stratigraphic units. There are also pages about team members, both as a means of collective memory and as a kind of meta-documentation. GQBWiki contains data about who excavated a certain stratigraphic unit, so in a sense we have become part of the data we create, and made it explicit. There is a category of pages devoted to bibliographic references, usually with extensive notes linking evidence from other sites and regions to GQB and, as noted above, 'incubators' for ideas and written content that will be included in the print publication. Internal links are certainly one of the main strengths of wikis, and GQBWiki makes no exception: looking at the broad categories outlined above, it is important to point out that there is no restriction to links, and any page can point to any number of other pages, regardless of their 'category'.

The consequence of the 'flat nature' of wiki is that in several cases, the content ends up being very raw, not just in a technical sense of 'raw data', but also in terms of human readability and usability: if, for example, on a certain day the archaeologist did not feel like writing more than one sentence in their journal, that will be the content for that day – there are minimum requirements that are directly derived from those of paper recording sheets, but since our methodological toolbox leaned towards using multimedia, the amount of mandatory data has been reduced (Zanini and Costa 2006). The structure of a wiki is only created by adding content and links. Having no predefined structure is stimulating on an intellectual level, because every bit of information has the same theoretical importance within the documentation system and there is room for both data and discussion of uncertainty, but in practice we need to create lists of pages, entry points and navigation paths that will guide both contributors and readers, keeping in mind that MediaWiki has a very good internal search engine, and that is usually the quickest and most effective way of finding a specific page. Having no separation between structure and data also means that both can be changed by editing wiki pages, and that this can be done at any moment. Following in the steps of Wikipedia, structured information in GQBWiki is stored in lists and 'infobox' templates. If we decide to record a new piece of information in a page, or a category of pages, there is no underlying structure separate from the frontend 'Edit this page' button. Another significant enabler is that MediaWiki markup encourages the kind of copy-and-paste editing made of trial and error (edit, save, review, edit again) that was so beneficial to the early development of the Web in the 1990s.

Again, great advantages come together with limitations: despite being based on a relational database (MySQL), MediaWiki is not a database and there is no native support for retrieving structured information using SQL-like queries. After an initial period of confidence in this 'dictatorship of the unstructured', it became clear that it was impractical to be left without the capability of doing structured queries on our knowledge base. At the same time, the amount of information we already had in place was substantial, and team members were pleased with the general functionality of the wiki, despite a slow learning process. Using Semantic MediaWiki, an extension to the base software package, we added a 'thin ontology' layer to GQBWiki, not with the aim of building a Semantic Web resource, but as the most convenient way of adding typical 'relational' functionality into our wiki. So, we could add dynamic content blocks like 'a gallery of images of the context at the bottom of each context page'. In practice, this works by turning internal wikilinks into 'typed' links: an image page is linked to the page of the item it depicts, conveying both the link and the relationship between these two pages; a page about a stratigraphic unit is linked to another stratigraphic unit by expressing the type of stratigraphic relationship between the two (following the Italian standard of highly descriptive 'physical relationship' as opposed to the British/MoLAS 'earlier than/later than' standard). At a basic level, Semantic MediaWiki usage is equivalent with the creation of a custom ontology that is only valid for the wiki in use, based on properties, but there is a possibility of 'mapping' the internal properties to universal URI-based properties. In the example of the image-item link, the 'depicts' relation becomes a local mirror of the equivalent FOAF property, where FOAF is the 'Friend of a Friend' ontology, one of the earliest and most widespread Semantic Web vocabularies in use. This makes for another case of serendipity: we started using a tool that worked natively on the web, before it was widely acknowledged that it would have been the only sensible choice in just a few years. GQBWiki had unique, clean URLs for every excavation context and find, since the very beginning, even though it was only in more recent years that we understood how this represented a possibility for doing other things, such as linked open data. The idea that external vocabularies (such as Nomisma.org for coins) can be used to link content from GQB to other online archives and catalogues is based on the assumption of an 'open world' of information where there are both internal (wiki)links and external links in a continuum.

3 Collaborative authorship and attribution

Apart from the technical aspects discussed above, there is a second set of problems that are of equal interest and touch on the intrinsic difference of wiki authorship from traditional publication, again from a standpoint where GQBWiki is first of all the recording of a research process, and the archaeological excavation is only one part of that process, as is the digital archive. The material wiki practice of creating content confronts us with problems such as: how do we manage contributions ranging from simple digitisation and data entry of analog records to fully digital stratigraphic data?

In a traditional setting, the path from content creation to publication is more or less linear, from the bottom up, with checks for consistency at each step. With thousands of pages, each one accessible separately, the need for a solid review is even stronger, but the difficulty is in the systematic application of review procedures in a way that is both efficient and quick, otherwise new contributions will stagnate. Therefore, content review happens on an opportunistic basis in GQBWiki, and it is not enforced. In general, the internal review process has worked well for us, but some content is still outdated or missing, and a complete external peer review seems unlikely and we do not expect a substantial amount of feedback even after opening the wiki, as most potential contributors would have their own archives to curate.

Another issue we think we are dealing with is attribution for all the digital work done by supervisors and undergraduate students alike. The approach seen in GQBWiki is taking inspiration from initiatives like Fair Cite (2012), which tackles the problem of 'how best to cite a web-based collaborative project developed in the humanities' and whose names should be included in the citation. At the bottom of each wiki page, a list of all contributors has links to each user page and the suggested citation for a single page contains the URL of a special visualisation showing that list. Furthermore, 'bot' users like the prolific GQBot (controlled by the pywikibot software) give us a chance to reflect upon the contribution of machines to our work, not only as mere tools, but as executors of instructions that we only prepare, for repetitive work like batch uploading of images or importing from databases. Our work is collaborative in this sense, too.

4 Conclusions

After ten years working with GQBWiki we are convinced that the benefits exceed the disadvantages, and that making this body of knowledge open will further increase its value for the wider archaeological community.

A decade could seem a long time span, since most digital works can easily become obsolete even in less time: the truth is that we are collectively used to rapid decay cycles of our digital archives and publications, while traditional paper-based publication has stood the test of time. When, in an academic context, we put our data and studies online, it usually means that we want them to be accessible and we want to ensure them a long life. Being on the Web does not make data automatically linked and open, but as described above GQBWiki is incrementally going in that direction, finding common ground with other existing initiatives in the field of ceramic studies (Gruber and Smith 2015), numismatics (Gruber *et al*. 2014) and ancient world studies in general (Elliott and Gillies 2009) with a very practical, URI-focused stance, and we hope that GQBWiki URIs will make appearance in linked open data graphs. That said, we also think that a more pronounced focus on the human components of any technological platform is needed, and Web 2.0 is no different in this respect (Shanks and Whitmore 2012). In our experience, a wiki needs to be actively used in order to have a chance to survive, and having a long-term archival of wiki content or any other archaeological data in a 'freezed' form is increasingly unsatisfactory, since the discoverability of such content is not getting better. Other, separate wikis that we started for other research projects are unfortunately not as thriving as the one described in this paper.

So far, GQBWiki is the virtual workplace of our research team: consulted and updated by users all the time from many places in Europe, with huge peaks of activity reached during the excavation campaigns (Carabia 2013). The availability of excavation data, interpretive texts, diaries, pictures and so on, all on the same platform concurrently and without any hierarchical limitation, has been a transformative environment for our work.

We believe that this approach is fruitful at the research team level and can be adopted on a wider basis. In an ideal situation, new studies about specific aspects of archaeological interest (for example, the type of artisanal activity recognised in 8th-century contexts from Byzantine Gortyn) would result not only in a specialist, peer-reviewed publication, but also in the updating of a range of 'wiki pages' about Byzantine craftsmanship, the history of Crete, or the work of Italian archaeologists abroad.

At a global scale, Wikipedia represents the main way of accessing the knowledge landscape for a majority of Internet users. Archaeology is well represented on Wikipedia but expert contributions are scarce, driven by the lack of incentive for academics to contribute and the rarity of collaboration-driven publication among archaeologists (Hadley 2013). For very general topics, Wikipedia is recognised as the right platform and there are known patterns for contributing content, debating contrasting views, accommodating for different types of source material and so on. It is less clear whether more specialist content (for example the chronology of a very specific type of ceramic production – even a minor one – or the calibrated radiocarbon date for an occupation sub-phase in an otherwise settlement) can fit in the Wikipedia notability guidelines. As we have shown, the tools and some of the good practice to develop long-term collaborative platforms are already in place.

Should we start working in a collaborative and incremental fashion, rather than starting from scratch at each new study?

Bibliography

Carabia, A. 2013. Wiki=beta: il modus vivendi di un sistema per documentare la ricerca. *Archeologia e Calcolatori Supp*. 4: 209-13. Firenze, All'Insegna del Giglio.

Caraher, W. 2015. *Industrial Archaeology and Student Resistance*. [Online] Available from: https://mediterraneanworld.wordpress.com/2015/06/26/industrial-archaeology-and-student-resistance/ [accessed: 8 July 2015]

Elliott, T., Gillies, S. 2009. Digital Geography and Classics, «Digital Humanities Quarterly» 3, 1. *Changing the Center of Gravity: Transforming Classical Studies Through Cyberinfrastructure*. [Online] Available from: http://www.digitalhumanities.org/dhq/vol/3/1/000031/000031.html [accessed: 13 November 2015].

Fair Cite 2012. *Current Citation Practices in Academia*. [Online] Available from: https://faircite.wordpress.com/ [accessed: 31 March 2015].

Gruber, E., Heath, S., Meadows, A., Pett, D., Tolle, K., Wigg-Wolf, D. 2014. Semantic Web Technologies Applied to Numismatic Collections. In P. Verhagen (ed.), *Archaeology in the Digital Era: Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 264-74. Amsterdam, Amsterdam University Press.

Gruber, E., Smith, T. J. 2015. Linked Open Greek Pottery. In F. Giligny, F. Djindjian, L. Costa, P. Moscati, S. Robert (eds.), *Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology. CAA 2014 - 21st Century Archaeology*: 205-14. Oxford, Archaeopress.

Hadley, P. 2013. *WikiProject Archaeology*. [Online] Available from: http://pathadley.net/projects/wikiproject-archaeology/ [accessed: 8 July 2015].

Mediawiki Contributors 2015. *MediaWiki*. [Online] Available from: https://www.mediawiki.org/ [accessed: 8 July 2015]

Semantic Mediawiki Contributors 2015. *Semantic MediaWiki*. [Online] Available from: http://www.semantic-mediawiki.org/ [accessed: 8 July 2015].

Shanks, M., Whitmore, C. 2012. Archaeology 2.0? Review of Archaeology 2.0: New Approaches to Communication and Collaboration. *Internet Archaeology* 32. [Online] Available from: http://dx.doi.org/10.11141/ia.32.7

Zanini, E., Costa, S. 2006. Organizzare il processo conoscitivo nell'indagine archeologica: riflessioni metodologiche ed esperimenti digitali. *Archeologia e Calcolatori* 17: 241-64.

Zanini, E., Costa, S. 2009. Sharing knowledge in archaeology: looking forward the next decade(s). In M. Tsipopoulou (ed.), *Digital Heritage in the new knowledge environment*: 69-72. Athens, Hellenic Ministry of Culture.

Archaeological Contents:
from Open Access to Open Data

Aurélie Monteil
aurelie.monteil@persee.fr

Viviane Boulétreau
viviane.bouletreau@persee.fr

UMS 3602 Persée. École Normale Supérieure, Lyon

Abstract: The activity of the researcher takes place within a global process of development of the scientific knowledge, which relies on data sharing. He or she needs both to access existing data (sources, publications), and to distribute the material produced. Open access provides a suitable tool for reaching these two objectives.

Researchers must also overcome new challenges: selecting relevant information within the huge quantity of data and ensure optimal visibility and re-usability of the data they produce. In this context, open access is not sufficient, hence the emergence of the concept of open data, which deals with technical interoperability, quality of referencing and permanence of access.

Persée is a French, publically funded, program for the digitization and online publishing of printed academic journals in the field of Humanities and Social Sciences. Beyond the publication of a huge digital collection, Persée endorses the core principles of the open data movement (open access, handle/DOI, standard formats, SEO, interoperability, long term preservation).

The original mission of Persée is now expanded to a new project: producing and disseminating scientific content beyond published journals. Persée will apply its knowledge to a corpus composed of heterogeneous material. A wide range of tools is being developed in order to process, disseminate, share, and allow scientific uses of these bodies of documents.

Among the collections that will be processed with these new tools in 2015, two are dedicated to archaeology:

- The collection 'Monuments of Cairo' is about the digital publication of the minutes and reports of the Committee for the Conservation of the Monuments of Arab Art (published from 1882 to 1953). We intend to enrich the original material with a multilingual index for toponyms and monuments. This index uses international standards and proposes to associate to each entry the several ways it is mentioned over the whole collection.

- The collection relating to the excavation of 'Salamis of Cyprus' concerns the study of material and architectural remains. It aims at firmly identifying artefacts and establishing links between several resources related to these objects: catalogues, photographs, publications, index cards.

These two projects will demonstrate the potential brought by open data regarding the constitution of digital collections. One of our objectives is to build a large-scale platform that will both federate data and be enriched, project after project, by a collection of tools addressing researchers' needs. Both data and tools will be fully and freely available to the community.

Keywords: Open access, Open data, Interoperability, XML, Linked data

Introduction: the French UMS *Persée*

Persée is a French publically funded program for the digitization and online publishing of printed academic journals in the field of Humanities and Social Sciences.

In 2003, the French minister of Research and High Education conducted a general call for proposals. The University Lumière Lyon 2 was selected to realize the *Persée* program.

Since 2012 *Persée* has developed new partnerships with the École Normale Supérieure de Lyon, which physically hosts the team, the French Centre of Scientific Research (CNRS) and the University of Lyon. The program became a unit (UMS, Unité Mixte de Service), devoted to digitization, enrichment and dissemination of scientific documentation.

The goal set for the unit is to provide a support service for the development of scientific research. It aims to enhance the visibility of French scientific production with several key objectives:

- promote free access
- disseminate enriched data
- carry out an active policy of content referencing within international systems (author databases, search engines, Cross-Referencing DOI)
- ensure the interoperability of data (OAI-PMH and Z3950)
- use open formats (METS > descriptive, administrative and structural metadata; MODS, DC, MarcXML >bibliographic

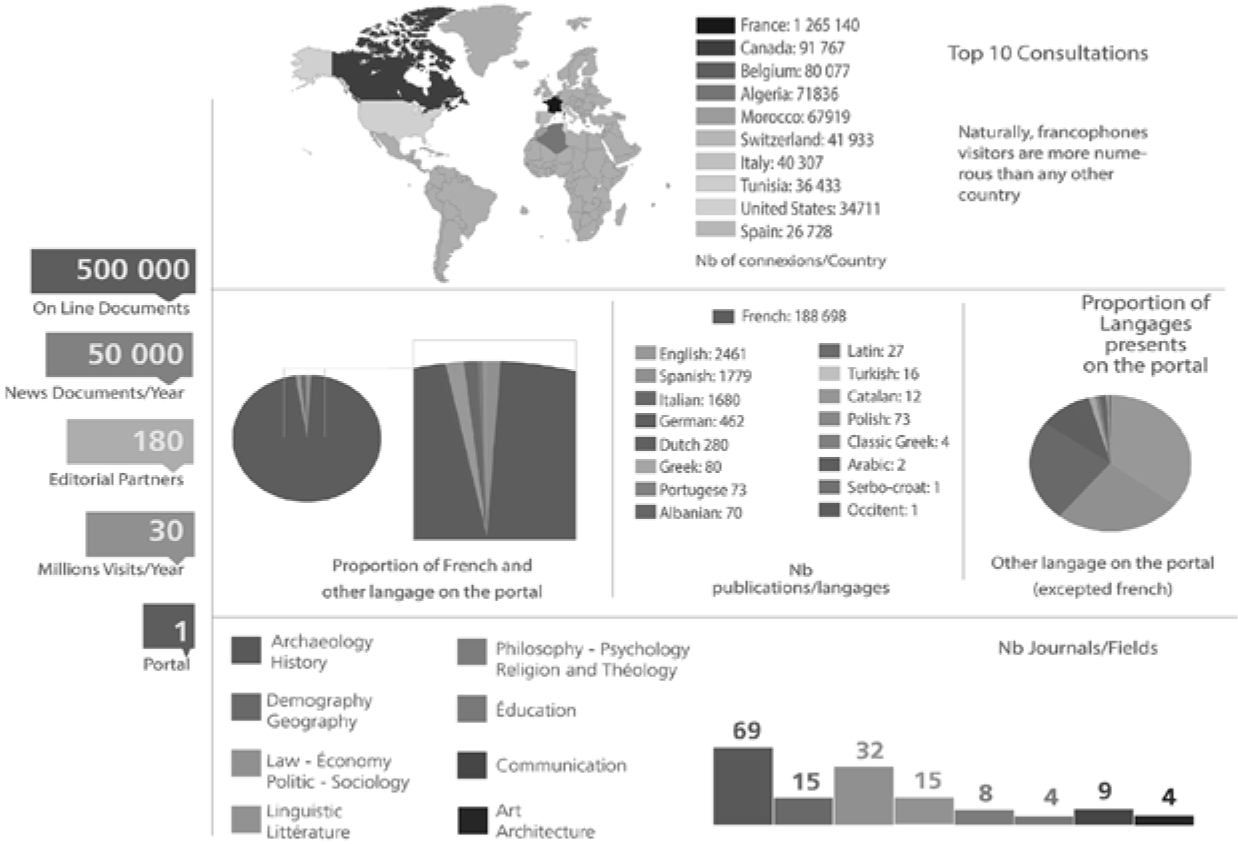


Fig. 1. Characterization of collections available on the *Persée* platform.

metadata; MADS > authority metadata; Erudit schema, TEI > full text)

- promote enriched uses (bibliographic tool, browser software, output/portable enriched format)

1 Collection Holdings

Our Journals collection is characterized by 3 specialities:

- Language: our collection is mainly composed of francophone journals, in its initial demand of the Ministry sought to promote the French scientific production,

- Scope: since the foundation of the program, our specialty has been the field of humanities and social science. Since the beginning of 2015, we have been completing our collection with other subjects such as earth and life sciences (collections in biology, mineralogy, botany, glaciology are currently being processed), medical sciences or engineering sciences and techniques.

- Selection: The last speciality is the selection of the journals we disseminate: they should respond to a high level of scientific standard, and must be listed by an Institutional Reference Index, such as: ERIH (the European Reference Index for the Humanities) or the AERES (the Evaluation Agency for Research and Higher Education). The selection of journals is achieved by a board of scientific examiners.

Once selected, the journal contracts a non-exclusive agreement with the unit, then the whole process of digitization and documentation is endorsed by *Persée*.

With 559,088 publications in French, this language is mostly representative because of our policy to concentrate on the promotion of French journals. It is followed by English language (8,647 publications), then Spanish (2,491) and Italian (1,955).

Of course, this goes hand in hand with the leading connexions by country, which, unsurprisingly, come from francophone countries or with a well-established francophone culture (Algeria, Morocco).

2 Process line

Persée processes exhaustive collections, from the first published issue to the most recent ones. The process line has two entries: the first process is based on the paper journal. All books are cut and therefore the treatment is destructive for books. The second entry is based on the processing of digital documents like PDFs. From both entries, we produce images and texts in XML format and process data with our own application. Then the document is enriched with a bibliographical metadata record and an internal structure description, i.e. the titles, footnotes, bibliographic areas, illustrations, etc., are fully described.

The process line leads to a complete set of data allowing us to reach our objectives:

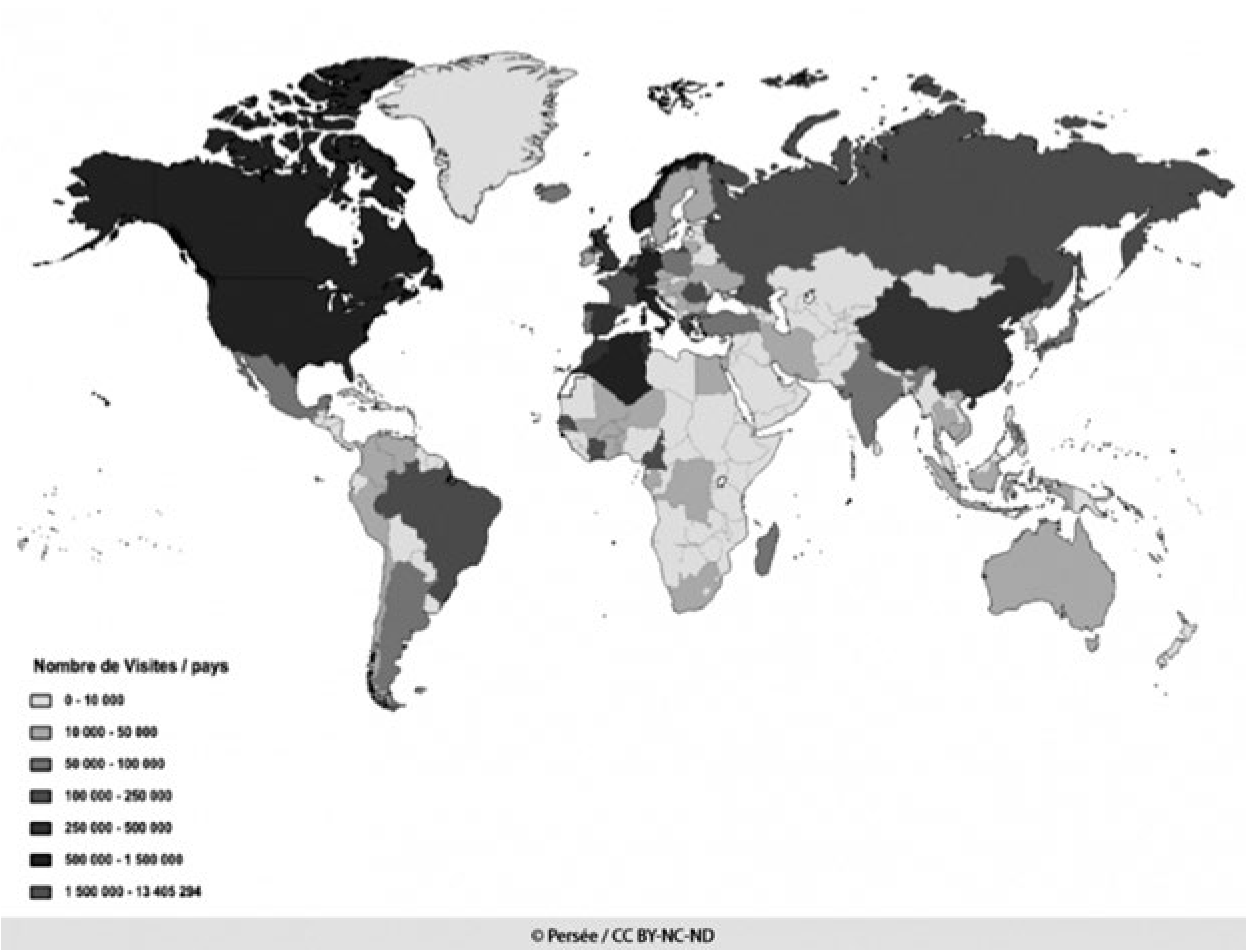


Fig. 2. Global distribution of visits to persee.fr.

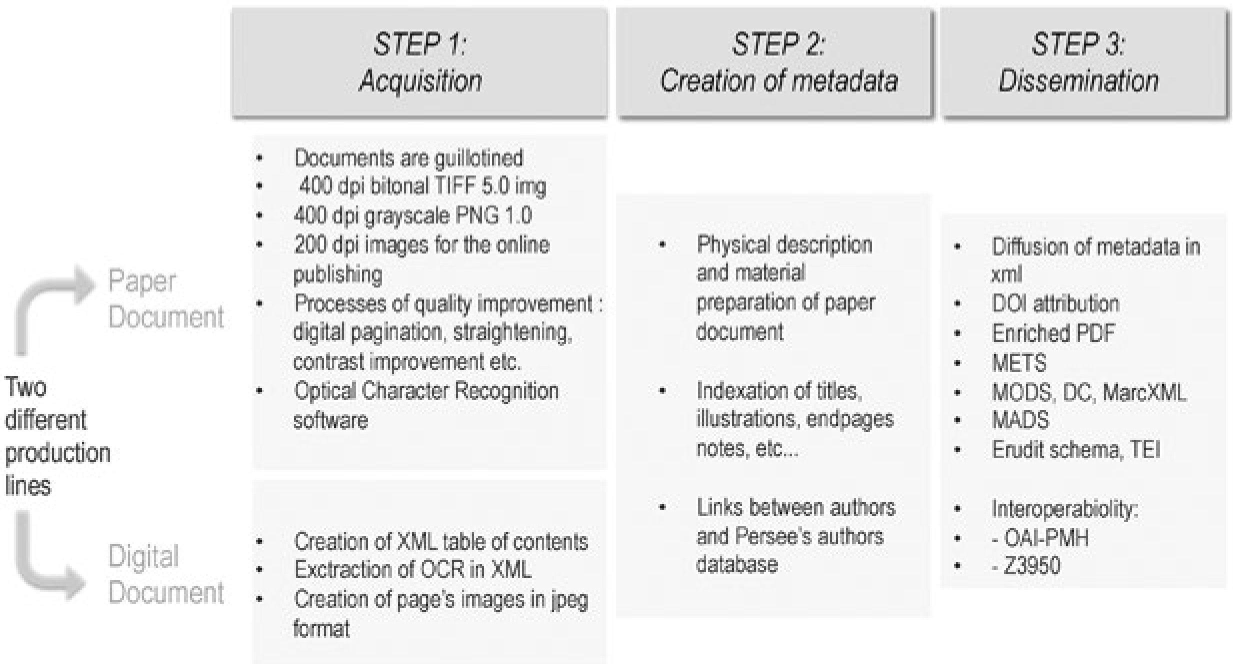


Fig. 3. Graphical overview of the *Persée* process line showing the most important steps.

- upload the *Persée* portal with complete numeric collections
- allow rich uses of documents (browse, query, cite, …)
- facilitate data sharing (use of standard formats)
- ensure the preservation of data by archiving them on a long term preservation platform

3 *Persée's* main objective: reaching Open Data?

What are the main principles of Open Data? The best answer is given by the 'BBB definition', this acronym stands for 3 declarations known as Budapest (2002), Bethesda (2003) and Berlin (2003) (The BBB Definition is identical to the definition of the Budapest Open Access Initiative, see Budapest 2002). The 'Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities' (Berlin 2003) written on October 22, 2003 defined Open Access as: 'a comprehensive source of human knowledge and cultural heritage that has been approved by the scientific community'. This declaration is completed by this consideration: 'In order to realize the vision of a global and accessible representation of knowledge, the future Web has to be sustainable, interactive, and transparent. Content and software tools must be openly accessible and compatible.'

In order to succeed in the open access dissemination of data, several main criteria must be validated: the data must be correctly generated in order to be understandable and re-usable, their localization must be stable and known, tools for the management of their update and sharing must be settled. For each of these points, we will mention the 'bad way', give main keys for the 'good way' and illustrate our point with examples from the world of XML and archaeology.

3.1 The representation of data

When creating digital data, searchers are mainly concerned with the use they plan to make of it. The uses that others may develop are not envisaged. This leads to databases produced with very specific models, XML documents based on local (mostly unpublished) schemas, indexes built upon personal vocabularies, etc. Hence, most of the time, the way the producer represents its data is not documented. Such practices make it difficult, even impossible, to use the data outside the original creation context.

Adopting two main good practices can ensure the future usability of data.

First, whatever the technology may be (SQL, XML, etc.) the choice of the model on which the representation of data will be based is a main concern. The producer should favour a standard one.

In the XML world, two schema are widely used for the representation of data: the Text Encoding Initiative (TEI), devoted to the representation of texts, their annotation, interpretation, etc., and the Encoded Archival Description (EAD), which is inspired from TEI but is devoted to archival material (images, objects, etc.). Both of these models are very rich, fully documented and have a large community of users. The fullness of these models may alarm the searcher when he is unfamiliar with them, but in most cases he or she will not have to deal with the whole complexity of the model but will focus on a subset of it, making obsolete the need for a complete understanding of model refinements.

The application field of this first principle should not be limited to data, metadata must also be considered. All the knowledge that goes with the main resource should rest on the use of standards: the Dublin Core for documentary description, international identifiers for persons (ISNI[1]) or places (Geonames[2]), and referencing vocabularies each time one is available.

The second good practice is even less well respected by data producers: it is the documentation of the data creation process. Since the production of data is mostly punctual, associated to a particular project, funding or researcher, the particular scientific context in which they are conceived necessarily leads to choices in the way data are represented.

3.2 The dissemination of data

The way data is disseminated should also be a main concern for researchers. If it is convenient to hold them on the lab website, it is not enough to make them trustfully usable in a medium-term perspective. The system hosting the site may change, the researcher who manages it may leave, etc. The sustainability of the solution must be considered. The dissemination solution must give some guarantees in terms of accessibility, stability and sustainability. It should also endorse an active policy of web referencing in order to ensure the visibility and the promotion of data.

3.3 The identification of data

Once data are accessible, there is one additional condition for their re-use by other systems; it is the trustworthiness that one can grant to its accessibility. No one would spend time to base work on data that is susceptible to move, disappear, etc., without offering any warranty of constancy. The existence of an identification of a resource, in the intellectual sense, regardless of its current location of the web, is the only way to preserve the user (data provider or re-user) from broken links. The attribution of such identifiers should be ensured by the producer or by the system on which the dissemination is based. In the academic world, two main international systems are available to identify resources: DOI maintained by CrossRef[3] is devoted to published material; handle.net[4] can be used for any type of content.

3.4 The preservation of data

Of course, a protocol for the Long Term Preservation of data (storage and format) is welcome. This main concern is not limited to data itself, but also to the technology suited to their use. The norm proposed by the Open Archival Information System (ISO-14721[5]) defines several requirements in order to guaranty the preservation of digital material.

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1 International Standard Name Identifier (ISO 27729), http://www.isni.org/

2 GeoNames geographical database, http://www.geonames.org/

3 CrossRef: http://www.crossref.org/

4 Handle.net: http://www.handle.net/

5 OAIS, ISO-14721 norm, http://www.iso.org/iso/catalogue_detail.htm?csnumber=57284

Their implementation is quite heavy, but in each country, several institutions have settled up such archives and propose to host data.

3.5 The mutualisation of data

Last, but not least, the system chosen for dissemination should not be limited to a web interface, but should also provide standard gateways to communicate with other platforms, both for the initial sharing of data (harvesting), and for the management of their eventual updates.

The system should also provide interfaces allowing a true exploration and exploitation of data by other programs (Application Programming Interface, widgets, etc.). This particular facet of data sharing is called interoperability. It allows anyone to re-use data with approaches or objectives different from the original ones.

3.6 Rights management

Openness has two facets: technical and legal. Making data available in a way that technically suits their use by other researchers is not sufficient in itself – the user should also be granted with the adequate rights to use them. Many licences exist to define which the user's rights regarding data are. In the scientific world, the most commonly used are 'Creative Common [1]' licences, which offer a wide variety of solutions, from very restrictive licences to public domain ones. All 'Creative Common' licences are ruled by common conditions: to provide a non-exclusive licence to produce, distribute and transmit the data to the public freely; to respect the author copyright; to allow a peer to peer network.

Persée opted for the 'Attribution-NonCommercial-NoChange' licence (CC BY-NC). This allows redistribution in a commercial and non-commercial way, as long as it is passed along unchanged and in whole, with credit to its original provider (https://creativecommons.org/examples/).

In summary, *Persée* only authorizes the reproduction and distribution of the original work, this licence requires those using data to credit us for our work, and not to suggest that we approve its use or give our endorsement or support, and finally, we allow others to copy/distribute without changes. We refer to these conditions on the first page of all our downloadable documents.

4 Implementation of these principles

The advantages of using Open Access are obvious: the main argument is the free licensing software, which is an essential point for academics. Then, thanks to free sharing, we can assure the durability of data thanks to a huge community of users. The Open Data is necessarily commutative and thus collaborative. The huge and free dissemination of scientific knowledge is a necessary way for scientific progress. Now we know what the principles and the benefits of open access sharing are. To implement an active policy of Open protocol, one should apply several uses in terms of technical competencies and applications.

The researcher and the scientific institution must set up a technical infrastructure to assume open data diffusion. Most of the time this economic investment is a problem for a laboratory, in this case the researcher can make the choice to use an external open access platform so as to disseminate his work, i.e. the French HAL, or Academia.com, ResearchGate, etc. Whatever the dissemination method you choose, the open data corresponds to a community of customs and uses. Among these different formats, *Persée* has chosen the most frequently used. For sharing data, we must keep in mind the three types of existing exchanges:

- the users looking for information.
- the computer gathering from, or querying the data repository.
- the user downloading data for further use.

The 'users' must be guaranteed the free and unlimited access and the consultation of the document in full text without limitation. The 'computer' must allow the collection of information using standard formats. Specifically in the case of the *Persée* program this approach is reflected by the selection of the formats we have implemented:

- Data are represented both according to the TEI[6] and the Erudit [7]schemas.
- Metadata are stored in Dublin Core, XMLMarc and MODS[8].
- Authority records are in MADS[9].
- The organization of data (structure of issues, of collections, etc. is stored according to the METS[10] schema.
- The services associated with the data are numerous:
- In order to identify resources, we attribute DOI to each of the articles available on the *Persée* platform.
- Procedures for long-term preservation are integrated in our process line. Archiving is realized by CINES (French national platform for higher education and research).
- An OAI-PMH[11] server allows automated harvesting of metadata and full-text from any archive repository.
- A Z39.50[12] gateway is set up for interoperability with library catalogues.

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[6] Text Encoding Initiative: http://www.tei-c.org/index.xml

[7] Erudit schema: https://apropos.erudit.org/en/erudit-en/technologies/

[8] Metadata Object Description Schema (MODS): http://www.loc.gov/standards/mods/

[9] Metadata Authority Description Schema (MADS): http://www.loc.gov/standards/mads/

[10] Metadata Encoding and Transmission Standard (METS): http://www.loc.gov/standards/mets/

[11] Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH): https://www.openarchives.org/pmh/

[12] Z39.50 (ISO-23950): 'Information Retrieval: Application Service Definition and Protocol Specification': http://www.loc.gov/z3950/agency/

- Soon, a 'triple store' will be opening to allow researchers to perform specific and/or complex searches via the *Persée* collections.

- Collaborations have been established with the main editors of discovery tools in order to include *Persée* contents in their tools.

- Technical choices and procedures have been described and published in order to be shared with the community. For example, our guidelines have already been taken up by French digital libraries as Revue.org and Cairn.

- For the portal user, mechanisms allowing feeds to its bibliographic tools are available (EndNotes, Zotero, etc.).

- Authors are identified and linked to the referential managed by the national bibliographic agency, the national library, Wikipedia, etc.

- Citations are identified and declared to CrossRef.

- Up to now the *Persée* data and metadata are disseminated with quite restrictive licences: CC-BY-NC-ND. Users are allowed to use them in a non-commercial context, have to mention the origin of the data, and are not allowed to distribute any derived form of the content.

- The *Persée* team advocates the adoption of more open licensing for metadata and 'old publications'. The scientific board of the unit should decide (Spring 2016) whether this material can be disseminated on a CC-BY-SA or ODbL[13] licence, which would allow any user to do anything (including commercial uses) with the data provided they include a mention of the data's origin and keeps the core data open.

5 The Persée Project

Since 2003, this reflection has underlined our work for scientific Journals. We now apply all these principles to new kinds of materials: 'corpus' characterized both by the heterogeneity of the documents and by the specialized tools to be settled up in order to satisfy the searcher's needs. Following are two cases which illustrate these points, two projects in the fields of archaeology.[14] The objectives of these new projects are the processing of scientific corpus, the digitization of exhaustive documentation and the input of an added value with augmented metadata:

- the first project is the 'Athar Project' – on Cairo's ancient monuments.

- the second project is on 'Salamis (Cyprus)' – concerning the complete archaeological excavation documentation.

Both projects are based on the digitization by *Persée* of a printed collection, but each one is enriched involving different approaches. For Salamis the printed material constitutes the 'global information' from which a refined indexing of smaller objects has been achieved. For Athar, it is precisely the opposite approach: the printed material is the refined material. Associated with the toponyms, it becomes substantially extended by knowledge of various factors, such as a SKOS toponymic and multi-linguistic index, the geolocation of monuments, etc.

In the next section, we will describe how we have decided to structure this documentation, how to disseminate it and how these choices lead to considerable added value.

5.1 The Athar Project

The 'Athar' project aims to digitize and make available the works of the Committee for the Conservation of the Monuments of Arab Art. This yearly publication identifies, lists and describes all ancient Islamic and Copt monuments in order to underpin the management of their restoration. For the historian or art historian who studies the historiography of Islamic art, the history of preservation and the patrimonial monument of Egypt, this corpus constitutes a unique data source. Its value is based on the number of described monuments, the quality of architectural and historical information, the amount of technical documentation taken from restoration worksites, the prosopography of actors and all the photographic archive, etc. Its great scientific interest is based on the fact that so many ancient monuments have been destroyed (today, of the 800 monuments identified since 1880, 300 have already disappeared). The preservation and dissemination of these data are considered as important by the scientific community. Our project consists of disseminating this collection and allowing a classical document display and an enriched TEI text for more refined searching. The main difficulty is the typological treatment for the transliteration of Arabic names. Our chief goal was the elaboration of methodological tools and the provision of a large index for the enhancement of this textual and iconographic corpus. This project illustrates the method used for transforming a collection, which is very hard to access, into a rich set of information available in an open way, giving a new life to this information.

The tool known as 'Jgalith', developed by the *Persée* team, allows the creation of metadata. The first step for indexation is the insertion of the index of ancient monument names index built by the researchers themselves and provided by our partners. Once this index is inserted in our information system, it is first used as a supplementary dictionary which can be involved in the optical character recognition process and enhances the quality of the text produced from the analysis of images of pages. Then, when the monument name is recognized, a specification about its typographical form is given: Is it a cursive Arabic form? A transliteration? Once this work is achieved, the multilingual Index with the name of all ancient monuments integrating all information about them and presenting all the existing typographic forms for its names will be spread. The final objectives are to propose a large set of XML (encoded in TEI) documents with tools for their indexation. The Corpus constitutes the global base for the dissemination of information. The name index has been inserted in the geocorpus Geonames and presents the site and its location within the city.

This information also feeds other platforms:

[13] ODbL: http://opendatacommons.org/licenses/odbl/summary/
[14] *Persée* has also selected projects in other scientific areas: NOOEE: is a corpus in biology. The goal is the digitization of publications and collections of specimens and the indexation of taxonomic names of species.

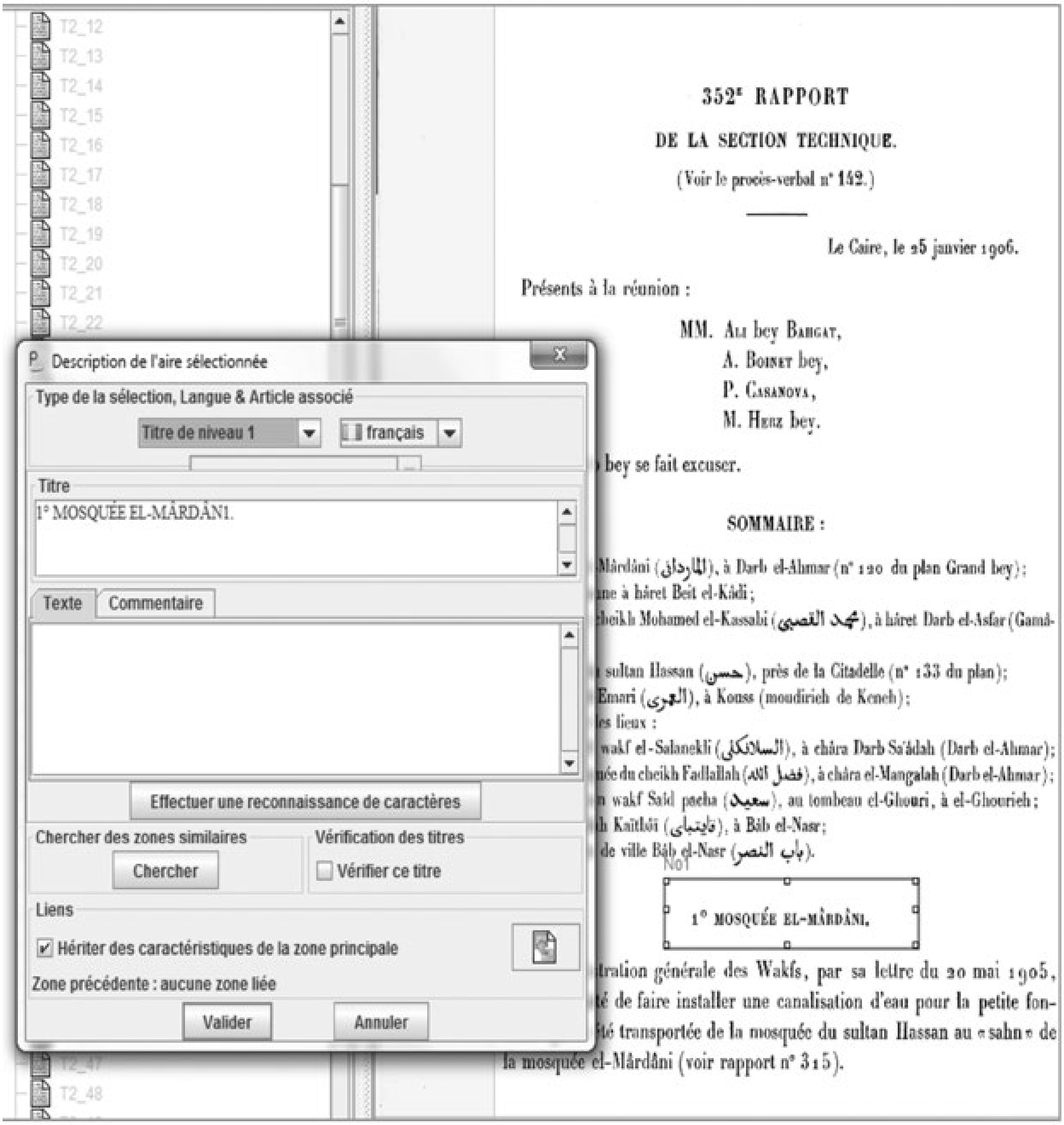

Fig. 4. Example of the 'JGalith' *Persée* application.

- the MarcXML metadata feeds the Sudoc and the library catalogue.
- The Dublin Core and TEI are used for the interoperability with other Open Access platforms, such as the Canadian Érudit or the French platform Isidore, for open dissemination within the fields of the social sciences and humanities. Lastly, a 'triple store' will be set up with a SPARQL endpoint for querying.

5.2 The Salamis of Cyprus Project

The second project is the digitization of the archives of the French archaeological survey to Salamis (Cyprus). This corpus constitutes a vast and unique documentary collection about this ancient site. The excavations started in 1964 under the direction of Jean Pouilloux and have been continuing until 1974. At this date, half of the island became Turkish, and the access to Salamis became forbidden, all the work on the former city stopped at that time. From this date, the ancient site has remained inaccessible to research. Today, most of the artefacts are destroyed or have disappeared, making even more important the preservation of the remaining objects. This documentation constitutes the only available documentation on the archaeological site of Salamis. This project is of particular importance since it allows at the same time the scientific and patrimonial enhancement and ensures the preservation of the remaining documents. The digitization ensures a huge dissemination of these primary data, the development and renewal of research about this archaeological site and provides

Fig. 5. Results of digitization and enrichment on persee.fr.

for the good conservation of the documentation. Some of the files are so old that they are starting to deteriorate; these older documents are fragile and digitization would allow access without risk of damage or destruction. Both partner institutions provide the production of data:

- The Maison de l'Orient et de la Méditerranée provides the digitization of the excavation documentation (field notebooks, excavation photographs, index cards, maps and drawings) which constitutes all the documentation relevant to an excavation. All documents and information are represented with the XML MODS schema which allows the complete description of various kinds of resources.
- *Persée* digitizes the scientific publications and creates metadata and bibliographical records, attributes Digital Object Identifier for each document, establishes links between the authors and the database IdRef, and produces all the metadata that usually accompanies serial publications.

When the production step is achieved, the dissemination of all data begins. Figure 5 illustrates the potential of interoperability between our data and the data provided by the Maison de l'Orient et de la Méditerranée. It presents a sketch of what the consultation interface may be for the Corpus of Salamis of Cyprus: a query within this corpus leads to parallel resources: on the left side, the content of the printed material is provided by *Persée* and the list of other material, with their identification numbers, produced by the archaeologist during the excavation. Additionally, links between terms found in the text of the publication and the same terms in the index of the grey literature allow the provision of external links to several associated documents.

As a conclusion, it needs to be stressed that open data requires a strong application support, which supposes a technical team and thus, a sustainable and solid investment from institutional structures. Even if institutions develop policies of open access, there is no guarantee that these policies will be prolonged, which constitutes a main difficulty. The best way for researchers is to resort to larger institution specialized in the management of Open Data. Today, the offer is wide and the selection of the appropriate solution should meet two main conditions:

- Human and technical support
- Political and economic stability

These two conditions are essential for the viability of a project. Today, relying on such institutions is the best way for a researcher to succeed in the good spreading of scientific data. The multiplication of open scientific platforms encourages the personal and voluntary action of open dissemination. This individual action must be supported by active policies from universities and research institutes.

Bibliography

Budapest 2002. The Budapest Open Access Initiative. [Online] http://www.budapestopenaccessinitiative.org/read [accessed: 26 June 2015].

Berlin 2003. The Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities.

[Online] http://openaccess.mpg.de/Berlin-Declaration [accessed: 26 June 2015].

Budapest 2012. Ten years on from the Budapest Open Access Initiative: setting the default to open. [Online] http://www.budapestopenaccessinitiative.org/boai-10-recommendations [accessed: 26 June 2015].

Berners-Lee, T. 2006. *Linked Data - Design Issues*. [Online]. https://www.w3.org/DesignIssues/LinkedData.html

Bizer, C. 2009. The Emerging Web of Linked Data. In Intelligent Systems IEEE 24, 5: 87–92. [Online] doi: 10.1109/MIS.2009.102

CHAPTER 13
Computers and Rock Art Studies

Archaeoacoustics of Rock Art: Quantitative Approaches to the Acoustics and Soundscape of Rock Art

Margarita Díaz-Andreu
ICREA, Universitat de Barcelona, Spain

Tommaso Mattioli
Universitat de Barcelona, Spain

Abstract: Archaeoacoustics refers to the field of study concerned with the effects of sound in past societies. Scholars interested in acoustics try to understand the human past beyond its materiality by recovering a set of less evident, less tangible cultural signs relating to the sense of hearing. Of the many contexts in which the intangible evidence of acoustics can be analysed, this paper pays attention to its expression in rock art. Our aim is to explore the quantitative analyses undertaken for the study of acoustics in rock art landscapes by focusing on the three main lines of evidence that rock art researchers are following: (i) landscapes with special naturally occurring sounds; (ii) lithophones, ringing rock, and rock gongs; (iii) intentionally produced sound. Three acoustic effects have been usually subjected to quantitative measurement: echoes, resonance, and reverberation. We will argue that not all lines of evidence have been explored in equal measure by scholars and that there are specific types of acoustic measurements and analysis, the potential of which are still to be assessed.

Keywords: Archaeoacoustics, Rock art, Quantitative analysis, Post-Palaeolithic, Soundscape

Introduction

Archaeoacoustics, or the combination of archaeology and acoustics, refers to the field of study that aims to investigate sound in the past. Scholars interested in acoustics try to understand the human past beyond its materiality by recovering a set of less evident and intangible cultural signs related to the sense of hearing. Of the many contexts in which the intangible evidence of acoustics can be analysed, this article will pay attention to rock art. The archaeoacoustics of rock art studies how past communities engaged with acoustics by choosing areas with particular acoustic properties to be decorated and/or to create acoustical environments in which to set all the activities related to the production and experiencing of rock art. Studies in this field usually reflect on why acoustics were sought after by past societies, and data are drawn from fields as diverse as psychology, iconography, and anthropology (see e.g. Lahelma 2012; Morley 2006). The spatial association of rock art and acoustic phenomena should not automatically be considered as significant, however, as it may be coincidental. It is important to analyse such a relationship through a landscape survey to test whether there is a positive association between the places where particular acoustic effects are present, and those where they do not exist or are of lesser importance. If a positive relationship is found, then it is reasonable to assume that acoustic effects were meaningful and desirable for the communities that produced the rock art in the past.

Methodologically this field of research is still in its infancy. Although the first articles on what we now call archaeoacoustics were produced in the 1950s and there has been a sharp increase in its study in the last decade, there is still much to do. Most authors looking at the connection between rock art and acoustics discuss the latter based on the perception of scholars. Those who attempt to quantify the acoustic properties valued by prehistoric communities are still in the minority. The point of departure is that the auditory experience sought by people in the past is measurable in terms of acoustic parameters. There are several acoustic phenomena, such as echoes, resonance, and reverberation, that are related to the transmission, reflection, refraction, interference, diffraction, scattering, absorption, and dispersion of sound (Rossing 2007: 16). These can be measured in terms of temporal pattering, spatial characterization, and frequency domain (Rossing 2007).

Echoes are the sound a listener hears reflected from a hard (usually vertical) surface. From an acoustical standpoint an echo signature is clearly visible when the digital file is converted into a graphic display (sonogram or echogram), but in order for it to be perceived by the human ear several conditions must be met. First of all, due to the psycho-acoustic phenomenon known as forward masking, the reflections will be inaudible if they arrive very soon after the direct sound and/or their level is very low in relation to the direct sound. Thus, there exists a threshold of audibility dependent on delay and direction of incidence relative to the direct sound. Only if the level of the reflection is above this threshold will the reflections have an audible effect, which again depends on their level, delay, and direction of incidence. Echo threshold is typically observed for delays beyond 50 ms and at high reflection levels (Rossing 2007: 305). If the delay is shorter, the direct signal and the reflection are perceptually merged, causing a variation in level, clarity, spaciousness, or change in localization direction (e.g. 'precedence effect' or 'Haas effect'; see Litovsky *et al*. 1999). Because human hearing is generally in the frequency range of 20Hz to 20 kHz (Levitin 2006: 22) and because sound travels at about 343 m (1125 feet) per second at typical temperatures and atmospheric pressures, the listener must be 17 m (55 ft) from the reflecting surface to hear echoes.

The second type of acoustic effect studied in the archaeoacoustics of rock art is resonance, a phenomenon that occurs in enclosed or semi-enclosed spaces, consisting of the amplification of a specific sound the frequency of which matches one of its own natural vibrational frequencies (Rossing 2007: 213). It is caused by standing waves that occur when the mirror sound images reflect off each side to set up a stationary pressure pattern in the space. This effect generates unexpected higher or lower levels of sound (dB) at some locations and a specific frequency because a standing wave is reinforcing or cancelling the sound pressure.

The third acoustic effect discussed by scholars looking at the relationship between acoustics and rock art is reverberation. This is defined as the build-up of sound within an enclosed or semi-enclosed space resulting from repeated sound wave reflections off all of its surfaces. It can increase sound levels up to 15 dBA and can also distort the perceived frequency of sound or the intelligibility of speech (Rossing 2007: 394), as the sound reflections lose important details (e.g. consonants or pitches) that are masked by louder, lingering sounds. Reverberation is described by a parameter known as the reverberation time (EDT, RT). For example, the RT60 can be physically defined as the time (in seconds) it takes for the sound pressure level of a sound source to decrease by a factor of 60 dB after that sound source has been silenced.

There are three major contexts in which rock art and acoustics can be discussed. Firstly, there are landscapes where scholars have observed the correlation between particular naturally occurring sounds and rock art. Secondly, there are resonant geological formations with rock art producing bell- or gong-like sounds when subjected to percussive impacts (lithophones, ringing rocks, rock gongs, or stone bells). Finally, there are decorated spaces where an intentionally produced sound may result in an exceptional number of echoes, or create abnormal resonance and reverberation. It will be the focus of the following pages to present an overview of the methods that have been followed in the quantitative study of acoustics in rock art areas, and to propose fields in which we believe further development is necessary.

1 Rock art landscapes with special naturally occurring sounds

Soundscapes, or the particular set of sounds that characterize a landscape, have recently been classified by the ecologist Almo Farina as sonotopes (Farina 2014). Sonotopes are the sonic combination of geophonies, biophonies, and anthrophonies in the landscape. Geophonies include all those sounds produced by non-biological natural agents such as winds, volcanoes, sea waves, running water, rain, thunderstorms, lightning, avalanches, earthquakes, and flooding. Biophonies are sounds coming from living beings such as animal vocalizations (song, contact and alarm calls, and voices). One particular type set of biophonies, which is treated as a third type of sound, are anthrophonies or human-produced sounds. In archaeology some recent attention has been paid to anthrophonies (Boivin *et al*. 2007; Mills 2005a; 2005b), whereas geophonies have been dealt with by scholars interested in rock art in Portugal (Blake and Cross 2015), Sweden and Scandinavia (Goldhahn 2002), South Africa (Mazel 2011), and Chile (Waller 2002: 12).

Geophonies have been analysed in Scandinavian rock art, where suggestions that the sound of water may have been equally as important as vision in locating rock art (Coles 1991: 133; Sognnes 1994: 39, see also Lødøen 2010: 45–46). The methodology used by the rock art specialist Joakim Goldhahn was to quantify the sound pressure level (SPL) created by running water at regular intervals along river sections in rock art areas. His results showed that rock art placement in proximity to loud roaring rapids and waterfalls was not just governed by the availability of a suitable surface to engrave, but was a deliberate choice to select places with loud noises. Goldhahn argued that the ‘roaring’ sound of water (up to 110 dB) played a vital part in shamans’ desire to enter and return from an altered state of consciousness, as it acted as a liminal border between the person at the rock engravings and the rest of the world (Goldhahn 2002).

In the Côa Valley rock art area in Portugal, Elizabeth Blake and Ian Cross (2015) mentioned the method developed by Mills (2005b) to generate ‘soundmaps’. Mills partitioned the modern soundscape of a Cornwall mining area into features deriving from the landscape, ranging from the faunal environment to human activities. He generated visual ‘soundmaps’ in which the predominant sound types were mapped in terms of long-term average spectrum (LTAS). Although Blake and Cross did not provide any direct field measurements in their study of the Côa Valley, they developed hypotheses of long-term average spectrum (LTAS) on the basis of landscape features and archaeological evidence. They found a highly differentiated landscape, ranging from scrub vegetation, that would probably be fairly acoustically absorbent, and river flow, with either moderate background noise levels affording masking effects (turbulent flow) or low background noise level affording refraction effects (regular flow, calm surface), to highly reflective granite and schist slabs. They argued that the locations of petroglyphs, at the boundary between the rocky valley slopes and the floodplain mostly on fluvial rock terraces in proximity to the river, could give rise to psycho-acoustic anomalies (reflections, resonances, or echoes, or — in still water conditions — refractions leading to relatively distant sound sources appearing nearer than they are), or aiding in the masking biophonies or anthrophonies by reinforcing river sounds when the flow is turbulent. Thus, the petroglyphs seem to have been placed on the edge of the soundscape, affording atypical, ‘liminal’, and diverse sonic experiences quite distinct from those in the rest of the surroundings.

Discussing the rock art of the Didima or Ndedema Gorge in South Africa, Aron Mazel has argued that the acoustics of thunderstorms was the reason for the selection of this landscape to be decorated. Inspired by the remarks made by Harald Pager (1971) regarding the concentration of rock art at Didima Gorge and its landscape acoustic properties during thunder, Riaan F. Rifkin’s comments on the similarities between acoustic and spiritual phenomena (Rifkin 2009), and the growing interest in archaeoacoustics (Scarre and Lawson 2006), Mazel argued that Didima Gorge was a special place for hunter-gatherers. Although he did not make any quantification of the effects, he proposed that the excellent acoustics inside the rock art sites and the intense reverberation of the whole gorge after thunderstorms would have been considered as meaningful by the communities who produced the rock art. He observed that the original name of the gorge itself suggested the importance of acoustics, as ‘Ndedema’ could be translated as ‘the reverberating one’; in the gorge the sound of thunder crashing produces a clattering vibration as it echoes through the steep sandstone cliffs (Mazel 2011).

2 Lithophones, ringing rock, and rock gongs

Rock art is not only found at places where naturally occurring sounds are common, but also at lithophones. Catherine Fagg defines them as 'naturally situated and naturally tuned rocks, boulders, exfoliations, stalactites and stalagmites which resonate when struck and show evidence of human use as idiophones' (Fagg 1997: 2). As lithophones are used as instruments, their study was considered much earlier in the history of archaeology than any of the other types of acoustic context. The existence of rock gongs was first pointed out in Africa by museum curator Bernard Fagg, who showed his surprise that they had not attracted attention before and explained that many were still in use.[1] As he put it:

'The contemporary uses of these rock gongs varies greatly though they are most frequently used in secret religious ceremonies, often in connexion with circumcision at initiation rites (Mbar, Bokkos, Daffo, Fobur). They are used at Nok in the ceremonies just prior to the harvest of the first acha [a cereal crop] when certain grass seeds are carried up to the cave by the unmarried girls and ground on the solid rock. Here and in several other places the gongs are closely associated with corn-grinding grooves worn down into the solid granite. At Kusarha Hill in Northern Cameroon they are said to be used for communicating with spirits whose reply is received in the form of echoes from the depths of the cave. At Nok and elsewhere in Jabaland they are said to have been used as warning signals of the approach of Fulani cavalry during the Holy Wars of the nineteenth century, and indeed the sound will carry up to two or three miles in favourable conditions. They are in addition used in many places also for merry-making, for they provide an excellent accompaniment for singing and dancing, resembling in sound and rhythmic use the conventional double hand-gongs of iron, which are so widespread in Equatorial Africa. They are frequently closely associated with rock slides, sometimes as long as 150 feet, on which the boys amuse themselves by sliding down on small rock sledges from the tops of bare granite hills' (Fagg 1956: 18).

Bernard Fagg discussed this evidence in several publications (Fagg 1957a; 1957b) but never made any attempt to quantify the sound produced by rock gongs. Farther to the south in Africa and many years later Sven Ouzman surveyed a sample of 762 San rock-engraving sites located in an area of over 800 000 km^2 and found that eighty-four sites (11% of sample) co-occurred with rock gongs, although only in six cases was the rock the same (Ouzman 2001). Following D.M.L. Fock (1972) and Catherine Fagg (1997: 35-40), he explained that:

'When struck, even with a bare hand, these gong rocks emit a harsh metallic sound rather like striking a blacksmith's anvil with a hammer. The sound is usually restricted in tone and timbre, though some gong rocks have a three-octave range.' (Ouzman 2001: 241)

In addition to Africa, ringing stones have been identified in most continents. Maja Hultman undertook a landscape survey of ringing stones in Sweden and even looked at how far the sound of a sonorous stone could travel, but as no method was explained in her publication, the assumption is that she just did this by listening without using any measuring instruments (Hultman 2010, 2014). Neither has any quantifying method been used to study the ringing stones connected to rock art in France (Hameau 2002: 80, 174), Portugal (Bastos 2010), India (Boivin 2004), the USA (Devereux 2008; Hedges 1993), or Sudan (Kleinitz 2004), although in the latter sound samples were taken, but no musicological study was ever carried out (Kleinitz 2008: 136). Only Hans-Joachim Ulbrich had attempted a quantitative investigation of a lithophone by measuring the acoustics of Peña de Luis Cabrera basalt-stone formation in Lanzarote (Canary Islands, Spain). He recorded the percussive sound produced a stone pebble by means of a Cardioid Microphone Uher Report Mod. 4400, and he analysed the frequency spectrum running the Blackman-Harris algorithm in Syntrillium's Cool Edit Pro software. With such methods, and a set of samples obtained from percussions of different intensities, the frequency-curves exhibit a median resonance frequency at 6550 Hz (Ulbrich 2003).

Bernard Fagg's studies had an impact beyond ringing stones and included other types of lithophones such as stalactites and stalagmites. He explained that on returning to England he decided to check whether the connection between rock art and rock gongs could be seen in France. He visited the Palaeolithic caves of Cougnac in the Dordogne where he noticed an 'infinite variety of "metallic" notes which could be produced by tapping the stalactites with a pebble, and also by the presence — not far from the paintings — of horizontal fragments of stalactite with new vertical growths forming on top of them' (Fagg 1957c: 30). He argued that 'this naturally suggests the possibility that they were broken in antiquity, perhaps by the men who made the paintings' and suggested that this could have also happened at Font-de-Gaume (Fagg 1957c: 30). A few years later his proposal was followed up by the French rock art specialist, Abbé André Glory at the caves of Cougnac, Pêche-Merle, and Fieux in France, as well as in Nerja, Spain (Glory 1964, 1965) and the caves of Escoural in Portugal (Glory *et al*. 1965). Neither Glory nor Lya Dams (Dams 1984, 1985), who revisited the caves, quantified the sounds, although Dams published some staves with the tones obtained when striking the lithophones (Dams 1985: 43).

In summary, despite the interest raised by lithophones, only one quantitative study has so far been carried out.

3 The archaeoacoustics of intentionally produced sound in rock art landscapes

The universal importance of acoustics and music in society (Trehub *et al*. 2015) has led scholars reasonably to assume that some communities in the past may have purposely prospected, surveyed, and located the places in the landscape — including the subsoil — with better acoustics. It also seems reasonable to consider that, even if not deliberately sought, the astonishing acoustic response of some places (caves, boulders, shelters, or rock surfaces) would have not gone unnoticed and would have been used for ritual and/or other purposes. Some communities then selected these acoustically optimum sites to be decorated.

3.1 Echoes

There is ethnographic information about the importance of echoes for a wide range of small-scale societies around the world (Waller 2002). The positive relationship between the

[1] Only a decade later, but in a different part of the country, no memory of their use remained (Jackson *et al*. 1965).

presence of rock art and echoes in several rock art sites and landscapes has been noted by many scholars in Spain (Díaz-Andreu and García Benito 2012, 2015; Díaz-Andreu *et al*. 2014), Finland (Lahelma 2010), Canada (Waller and Arsenault 2008) and the USA (Waller 2002; Waller *et al*. 1999).

Most authors note the number of echoes without using special devices for this, but there are some exceptions. The methodology followed by Steve Waller consisted in producing a single loud percussion noise via a spring-loaded device (duration < 0.1 sec, mean 53 dB, standard deviation 9 dB). Each experiment at each location was conducted in triplicate to assess the reproducibility of the impulse. The ambient sound before, during, and after each impulse was recorded on a portable cassette recorder using an omnidirectional microphone placed 1 m from the impulse generating device. These recordings were then digitized at a sampling rate of 22 kH and quantitatively analysed for sound intensity as a function of time and frequency, using computer software (Waller 2002).

A different sound source has been used at Lakes Nuuksionjärvi, Vitträsk and Juusjärvi in Helsinki (Finland). In an article published in 1995, Iégor Reznikoff explained his tests with voice used from D2 to D3, with a powerful open-air singing technique (100–110 dB at the source), in order to obtain a good echo effect at a given point, in front of a picture and facing the lake (Reznikoff 1995: 551). Two decades later a project undertaken by a Finnish team decided to use a 6 mm cal. starting pistol as an impulse sound, the sound of handclap, and a wooden percussion plate at the Värikallio rock art site at Somerjärvi Lake (Finland). Sound was recorded with a Zoom H4n portable recorder (48 kHz/16 bit), coupled with two Neumann KM 183 microphones that were used as an AB stereo pair pointed upwards and separated by 22 cm, that is, roughly equivalent to the typical distance from ear-to-ear on a human head. The AB stereo pair allowed the researchers to measure the angle of arrival of the reflected impulses based on the time difference of the respective impulse and then to the point of origin of echoes (Rainio *et al*. 2014: 144). It seems that the massive smooth rock surface with paintings is the most efficient sound reflector in the area, as it reproduces the impulse rather accurately in respect of the intensity, structure, duration, and spectrum of the sound, even from afar, on the other side of the lake. It also reinforces and prolongs the echo from the opposite shore by creating a repetitive flutter echo between parallel shorelines. It also provides a strong argument in support of the significance of echoes in rock paintings, as during the fieldwork they identified a probable depiction of a drummer that had been overlooked in the previous documentation work carried out at Värikallio (Rainio *et al*. 2014: 144).

3.2 Resonance

In the late 1980s the acoustic specialist Iegor Reznikoff and the archaeologist Michel Dauvois analysed the intensity and duration of resonance in painted caves in France. Although they used non-technological devices to produce impulse sound, such as the voice in a continuous register ranging from C1 to G3 complemented by the high harmonic emission and whistles up to G5 (Reznikoff and Dauvois 1988: 240), they were able to superimpose the resonance map of the cave on the motifs, arguing that there was a coincidence between resonant places and specific iconographies (Reznikoff and Dauvois 1988).

More recently new research has been undertaken in the El Castillo cave system in northern Spain, where Jose Miguel Gaona Cartolano and his team measured the variation in sound pressure level (SPL) using a set of 31 audio tones of different frequencies from 80 Hz to 1kHz, pink noise, and sine sweep driven by an omnidirectional speaker (Gaona *et al*. 2014), recorded with a condenser microphone and converted to digital files with a sampling rate of 48 kHz/16 bit. A distinct increase in sound level was observed as the frequency of the emitted tone shifted towards the 100 Hz range, reaching a maximum peak at 108 and 110 Hz (-1 dB). This simple finding is remarkably consistent with other archaeoacoustics investigations of megalithic structures (Devereux *et al*. 2007; Jahn *et al*. 1995; Manaud and Barrandon, forthcoming 2015), which have shown significant sonic resonance features within this precise range of frequencies (Gaona *et al*. 2014).

3.3 Reverberation

Reverberation has been measured in archaeoacoustics studies undertaken in Spain. Díaz-Andreu and García Benito explored the reverberation of post-Palaeolithic rock art sites using as sound sources repeated clapping (to create percussive sound), wind devices (two whistles with frequencies of C7/C#7 and G7/G#7 played together; the G7/G#7 whistle played at intervals), and vocal music (male and female voices together using the ‘a’ sound as in mat; a solo male voice and a solo female voice). Digital recordings were made and comments on the results were noted *in situ* in a purpose-built acoustics recording form. Reverberation was measured from 0 to 2 — no reverberation (0), short and soft reverberation of one second duration or less (1), and longer reverberation (2). Tests included locations where rock art had been created and other places in the landscape with an apparently similar geological nature (i.e. shelters) where, despite their relatively large number, no rock art had been found. The results of the recordings were analysed using Sonic Visualiser software and included in a database that served as a basis for comparison between sites with more or fewer motifs and areas with and without rock art. In this way four areas were tested, three with Levantine rock art (Díaz-Andreu and García Benito 2012, 2015) and one with schematic art (Díaz-Andreu *et al*. 2014), all with positive results, especially those with Levantine art.

Rupert Till and his team have very recently begun to investigate the acoustics of a series of caves where art was produced during the Upper Palaeolithic. Their studies in the Tito Bustillo cave in Asturias (Spain) aimed to assess, analyse, and interpret the affordances these acoustics offered to human sound production and music-making in the cave (Till *et al*. 2013; Till 2014). They captured the impulse responses through the use of a sine sweep signal played through an omnidirectional loudspeaker. This signal sweeps through all the frequencies within the range of human hearing, from 16 Hz up to 20000 Hz, systematically stimulating the response of the space to each frequency. They used both a calibrated measurement microphone attached to a laptop computer to record the acoustics and a Soundfield microphone, capable of capturing sound arriving from all directions, which provides a useful insight into the 3D direction of arrival of reflections. From this impulse response numerous acoustical parameters were calculated, including metrics for reverberation (T20, T30, EDT) and speech intelligibility (STI), as well as those often used to characterize the acoustics of enclosed spaces and concert halls, such as Definition or

Deutlichkeit (D50), Clarity (C80), Lateral energy (LEF), and Envelopment (LG80). They argued that there are some significant matches in the Tito Bustillo cave between large painted motifs and distinct and delayed reverberation effects, which sound like an echo. This provides support for the idea that rock art producers would have been aware if the space was acoustically 'live' (with reverberation) or 'dead' (without reverberation), and that the acoustics of a place could well have had some influence on whether it was selected as the position for a painting or engraving.

4 Further developments

Archaeoacoustics is now facing new challenges in establishing itself as a proper traceable tool, which can provide the necessary scientific evidence to support archaeologists and historic theories.

So far no rock art studies have explored the methods indicated by acoustics experts for measuring sounds in sonotopes. These consist of measuring the long-term average spectra (LTAS) of sonotopes (Ge *et al*. 2009) typically expressed as Leq (the continuous sound that contains the same sound energy as a time-varying sound over a given time period, expressed as a single value in dB) or LAeq (the same as Leq but referring to the differential sensitivities of the human auditory system to different frequency ranges). In addition to Leq and LAeq, another type of measuring method includes the modulation transfer function, a measure of how well the temporal envelope of a sound signal is preserved in a given acoustical environment (Houtgast *et al*. 1980). A final method of measuring sonotopes proposed by the ecologists Mark Naguib and R. Haven Wiley is attenuation, which calculates the sound pressure level in a particular environment at a distance from a sound source and corrected for air absorption (Naguib and Wiley 2001).

Further developments in the field of lithophones, ringing rock, and rock gongs are needed because, as explained, to date only one quantitative analysis has been made of them. Many different studies can be proposed. Regarding cave lithophones we suggest that an analysis of the resonance frequency obtained when playing both the painted and unpainted areas of the lithophone with different percussion tools should be done. The results of this study should be then compared with the frequencies obtained in other undecorated stalactites and stalagmites. Techniques used for the study of megalithic structures could be applied to lithopones in caves (Devereux and Jahn 1996: 665: Jahn *et al*. 1995; Watson 2006; Watson and Keating 1999). Regarding ringing rocks, in addition to similar comparisons of resonance frequency between decorated and undecorated rocks, the acoustic coherence could also be tested.

Concerning the archaeoacoustics of intentionally produced sound in rock art landscapes, we would like to suggest three new areas of research development: (i) the investigation of the 3D spatial properties of sound to gain a better understanding of the acoustic prospecting of past rock art producers; (ii) the simulation of past soundscapes through the use of GIS tools for noise evaluation combined with palaeoenvironmental data; and (iii) the prediction of the acoustic conditions of rock art sites using auralization virtually to recreate the behaviour of any type of sound.

The first future possible avenue of research, the 3D sound characterization, would allow to ascertain scientifically the direction from which the sound, including that of echoes, arrives. This has been put in practice in a range of other archaeological contexts: these are the Chavín De Huántar Archaeological Acoustic Project (Abel *et al*. 2009), the Stonehenge acoustical investigation (Fazenda and Drumm 2013); the acoustical study of a sample of historical monuments (including the megalithic structure of Maes Howe, Orkney) (Murphy 2006); and, finally, the project related to historical opera houses (Farina and Tronchin 2011). All four of these projects have been addressed at developing new microphone arrays combining omnidirectional, binaural, and hybrid Ambisonic microphones. It is important to add that Tronchin and Farina have developed a MatLab program that allows a very simple and cost-effective post-processing of the 3D spatial analysis of sound. This works in a very similar way to the very high-priced acoustic camera (Heilmann *et al*. 2014), creating both a false-colour map of the arrival of sound reflections (Fig. 1) and an animated colour video rendering of the sound map, overplotted on the 360° x 180° panoramic image (Farina and Tronchin 2011).

The second method is the modelling noise propagation tools developed for GIS software. This can be a useful procedure to study past soundscapes or to investigate whether or not rock art sites are acoustically connected in a sort of signalling/communication network. The GIS modelling of noise propagation was first devised for studying noise pollution in human-dominated ecosystems, including noise from urban and industrial areas or aircraft and highway traffic. It incorporates important factors, however, that are likely to affect the sound propagation in natural ecosystems, such as changes in topography, weather conditions, vegetation cover, etc. which allow for alternate frequency weighting better to represent the way a different noise can be heard. Among the various available tools we should mention SPreAD-GIS, a very flexible, open-source software for incorporating field measurements and model noise propagation for any type of source and environment (Fig. 2) (Reed *et al*. 2012). This GIS tool has been applied to the analysis of sound propagation in Levantine, macro-schematic, and schematic rock art sites in the Alicante area (Valencia, Spain) (Díaz-Andreu *et al*. forthcoming).

The third and final research carried out for a different type of project, but that could be applied to analysing the archaeoacoustics of rock art with intentionally produced sound, relates to the exploration of the possibilities offered by the 'auralization' of high-quality Impulse Response (IR) measurements by the convolution-based reverberation technique developed and refined in Farina's recent acoustic measurement work (Farina and Ayalon 2003; Farina and Tronchin 2004). From such an accurate IR dataset there is no longer any need to test different types of sound impulse at the rock art sites, as it is possible to recreate virtually (or 'auralize') the behaviour of any type of frequency or to extract the sound of virtually all acoustical parameters.

5 Conclusion

The archaeoacoustics of rock art is a multidisciplinary field of research, as there is no single discipline that can be drawn on to understand the acoustic and auditory aspects of past human behaviour. Archaeologists are usually well prepared to deal

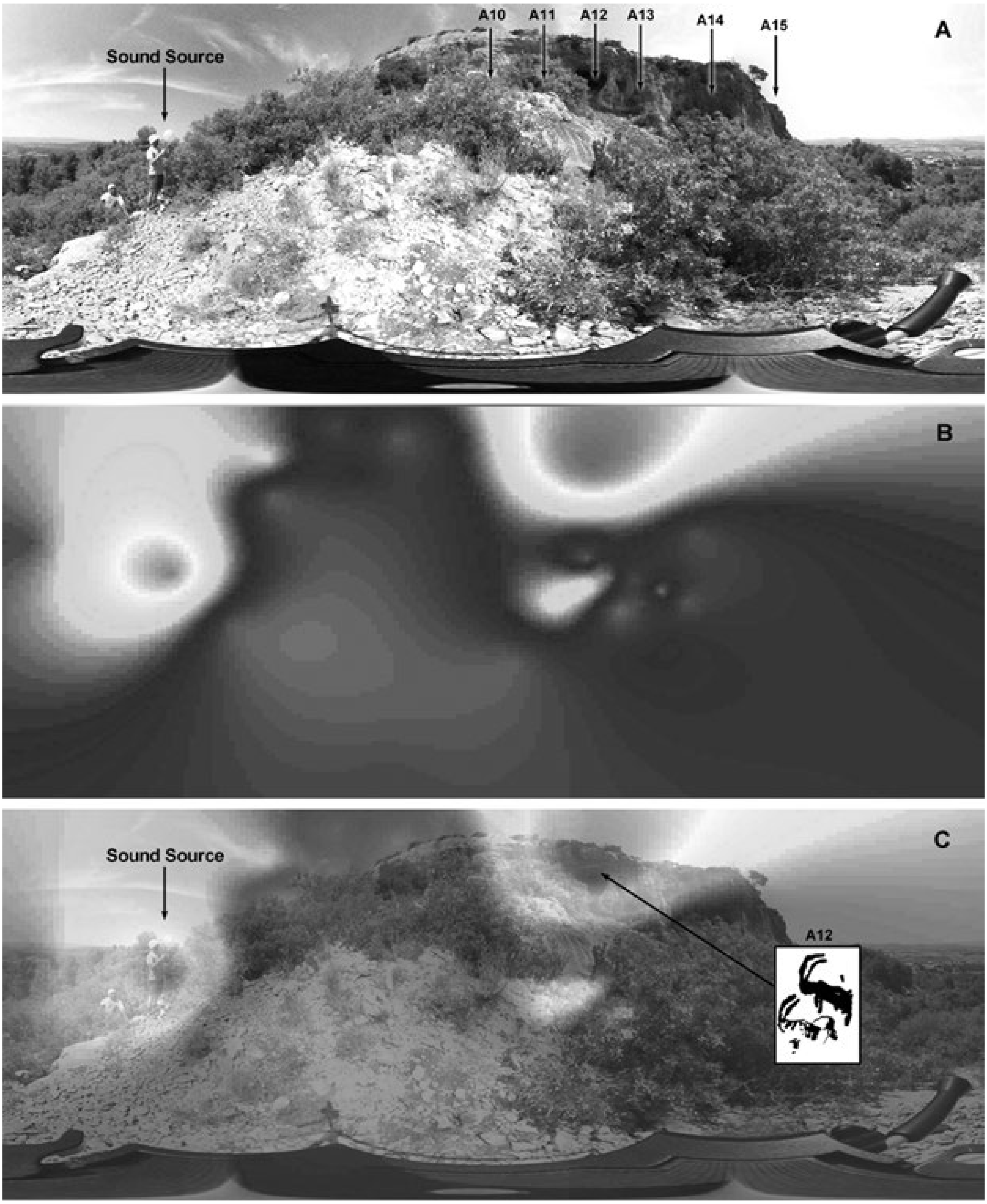

Fig. 1. An example of a false colour map of the IR (Impulse Response) analysis carried out in July 2015 by M. Díaz-Andreu, T. Mattioli, and P. Hameau in the rock art site of Baume Brune (Joucas, Provence-Alpes-Côte d'Azur, France) using an air-balloon as impulse sound. The acoustic recordings were made by Ambisonic microphone array and data were processed by IR Spatial Analysis MathLab software: (a) 360° picture of a section of the Baume Brune cliff; numbers refer to shelters; only shelter no. 12 has rock art; (b) false colour map of the impulse sound and acoustic reflections; (c) overlapping of images (a) and (b) onto one another, the main motifs painted in shelter no. 12 have been added in the bottom right section of the figure.

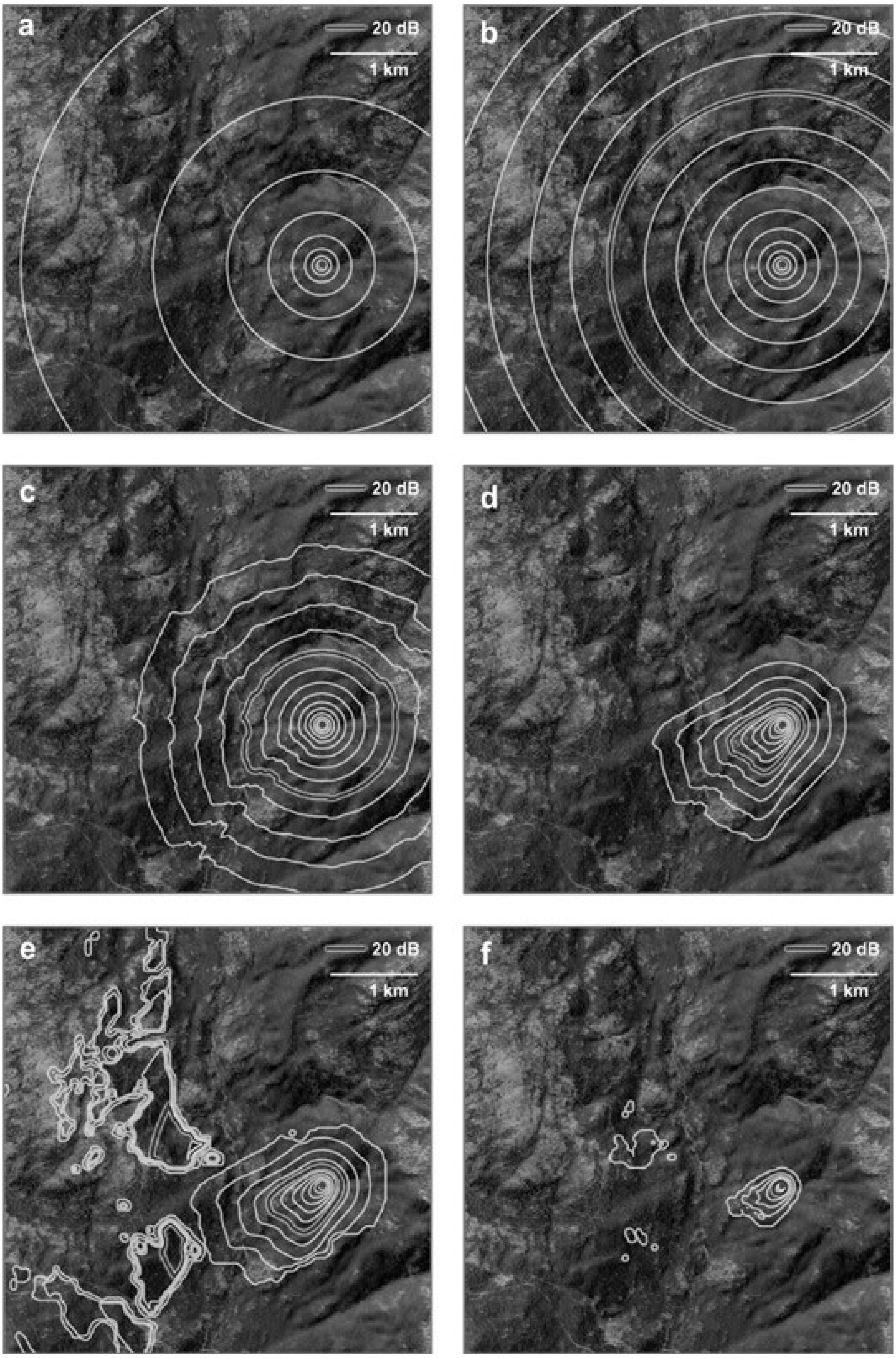

Fig. 2. An example of model calculation of sound propagation using the Spread-GIS tool: (a) spherical spreading loss; (b) atmospheric absorption loss; (c) foliage and ground cover loss; (d) downwind and upwind loss; (e) terrain effects; and (f) summary results, including predicted sound propagation patterns and excess sound levels. In (f), areas where introduced noise is likely to be audible can be identified (from Reed *et al.* 2012).

with the qualitative aspects of research, being well trained to read literature produced by a diverse set of other disciplines such as anthropology and psychology. The technicalities of the quantitative aspects of measuring acoustics are usually further apart from their specialization, however, as the techniques come from the disciplines of music, physics, and engineering. That is why interdisciplinary teams are desirable for rock art projects willing to deal with the quantitative aspect of acoustics.

In this article we have surveyed the different quantitative analyses made so far in the study of rock art acoustics. We have divided the research into three main areas according to the sound source, natural or human, and the sound producer, a geological formation or sound produced by instruments or voices. The resulting three clusters of studies are the rock art landscapes with naturally occurring sounds, lithophones, and the archaeoacoustics of intentionally produced sound in rock art landscapes. In them different acoustic effects have been the subject of measurements: echoes, resonance, reverberation, variation in sound pressure level (SPL), the direction of arrival of reflections, and the long-term average spectrum (LTAS). As a result of our survey we can say that the study of lithophones is in urgent need of quantitative analysis. A similar situation has been found in the studies of rock art landscapes with naturally occurring sounds, with the exception of an analysis of the sound pressure level. The state of the art in the last group of studies — the archaeoacoustics of intentionally produced sound in rock art landscapes — is somewhat healthier, as there are quantitative analyses of echoes, resonance, and reverberation. As we have argued in the 'further developments' section, however, much more could be done. We have proposed several avenues for future research.

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Bibliography

Abel, J. S., Bryan, N. J., Skare, T., Kolar, M., Huang, P., Mostowfi, D., Smith Iii, J. O. 2009. A Configurable Microphone Array with Acoustically Transparent Omnidirectional Elements. *Audio Engineering Society Convention Paper Presented at the 127th Convention, 9–12 October 2009, New York NY: USA.*

Bastos, P. L. 2010. Small Holes of Wonder. In W. Goebl (ed.), *Proceedings of the Second Vienna Talk on Music Acoustics.* Vienna, Institute of Musical Acoustics (Wiener Klangstil), University of Music and Performing Arts Vienna.

Blake, E. C. and Cross, I. 2015. The Acoustic and Auditory Contexts of Human Behaviour. *Current Anthropology* 56: 81-103.

Boivin, N. 2004. Rock Art and Rock Music: Petroglyphs of the South Indian Neolithic. *Antiquity* 78: 38-53.

Boivin, N., Brumm, A., Lewis, H., Robinson, D., Korisettar, R. 2007. Sensual, material, and technological understanding: exploring prehistoric soundscapes in south India. *Journal of the Royal Anthropological Institute* 13: 267-294.

Coles, J. M. 1991. Elk and Ogopogo. Belief systems in the hunter-gatherer rock art of northern lands. *Proceedings of the Prehistoric Society* 57: 129-48.

Dams, L. 1984. Preliminary findings at the 'organ' sanctuary in the cave of Nerja, Málaga, Spain. *Oxford Journal of Archaeology* 3: 1-14.

Dams, L. 1985. Palaeolithic lithophones: descriptions and comparisons. *Oxford Journal of Archaeology* 4: 31-46.

Devereux, P. 2008. The association of prehistoric rock-art and rock selection with acoustically significant landscape locations. In G. Nash and G. Children (eds.), *The archaeology of semiotics and the social order of things.* British Archaeological Reports International Series 1833. Oxford, Archaeopress.

Devereux, P. and Jahn, R. G. (1996) Preliminary investigations and cognitive considerations of the acoustical resonances of selected archaeological sites. *Antiquity.* 70, p. 665–666.

Devereux, P., Krippner, S., Tartz, R. and Fish, A. (2007) A Preliminary Study on English and Welsh 'Sacred Sites' and Home Dream Reports. *Anthropology of Consciousness.* 18, p. 2-28.

Díaz-Andreu, M. and García Benito, C. (2012) Acoustics and Levantine Rock Art: Auditory Perceptions in La Valltorta Gorge (Spain). *Journal of Archaeological Science.,* 39, p. 3591-3599.

Díaz-Andreu, M. and García Benito, C. (2015) Acoustic rock art landscapes: a comparison between the acoustics of three Levantine rock art areas in Mediterranean Spain. *Rock Art Research.* 32, p. 46-62.

Díaz-Andreu, M., García Benito, C. and Lazarich, M. (2014) The sound of rock art: the acoustics of the rock art of southern Andalusia (Spain). *Oxford Journal of Archaeology.* 33, p. 1-18.

Díaz-Andreu, M., García Atiénzar, G., García Benito, C. and Mattioli, T. (forthcoming) Decorating acoustics? Macroschematic rock art and sound. The soundscape of Macroschematic rock art.

Fagg, B. (1956) The discovery of multiple rock gongs in Nigeria. *Man.* 56, p. 17-18.

Fagg, B. (1957a) The cave paintings and rock gongs of Birnin Kudu. In Clark, J. D. and Cole, S. (Eds.) *Third Pan-African Congress on Prehistory, Livingstone 1955.* London: Chatto and Windus.

Fagg, B. (1957b) The rock gong complex today and in prehistoric times. *Journal of the Historical Society of Nigeria.* 1, p. 27-42.

Fagg, B. (1957c) Rock gongs and rock slides. *Man.* 57, p. 30-32.

Fagg, M. C. (1997) *Rock Music,* Oxford: Pitt Rivers Museum.

Farina, A. (2014) *Soundscape Ecology Principles, Patterns, Methods and Applications,* Dordrecht, Springer.

Farina, A. and Ayalon, R. (2003) Recording concert hall acoustics for posterity. *Proceedings of the AES 24th International Conference on Multichannel Audio, Banff, Canada, June 26-28 2003.* Available from: URL http://pcfarina.eng.unipr.it/Public/Papers/185-AES24.PDF. [Accessed: July 2015]

Farina, A. and Tronchin, L. (2004) Advanced techniques for measuring and reproducing spatial sound properties of auditoria. *International Symposium of Room Acoustics: Design and Science, Kyoto, Japan, Apr 11-13.* Available from: URL, http://pcfarina.eng.unipr.it/Public/Papers/190-RADS2004.pdf. [Accessed: July 2015].

Farina, A. and Tronchin, L. (2011) New measurement technique for 3D sound characterization in theatres. *The acoustics of Ancient Theatres*. Online

Fazenda, B. and Drumm, I. (2013) Recreating the sound of Stonehenge. *The Acoustics of Ancient Theatres Conference Patras, September 18-21, 2011*. Available from: URL http://www.ancientacoustics2011.upatras.gr/ [Accessed: July 2015].

Fock, D. M. L. (1972) Rock gongs at Keurfontein. *South African Journal of Science*. 68, p. 246.

Gaona, J. M., Rouleau, N., Caswell, J. M., Tessaro, L. W. E., Burke, R. C. and Schumacher, D. S. (2014) Archaeoacoustic Investigation of a Prehistoric Cave Site: Frequency-Dependent Sound Amplification and Potential Relevance for Neurotheology. *NeuroQuantology*. 12, p. 455-463.

Ge, J., Lu, J., Morotomi, K. and Hokao, K. (2009) Developing soundscapegraphy for the notation of urban soundscape: its concept, method, analysis and application. *Acta Acustica United with Acustica*. 95, p. 65-75.

Glory, A. (1964) La Grotte du Roucadour (Lot). *Bulletin de la Société Préhistorique Française. Comptes rendus des séances mensuelles*. 61, p. CLXVI-CLXIX.

Glory, A. (1965) Nouvelles découvertes de dessins rupestres sur le causse de Gramat. *Bulletin de la Société Préhistorique Française*. 62, p. 528-536.

Glory, A., Vaultier, M. and Farinha Dos Santos, M. (1965) La grotte ornée d'Escoural (Portugal). *Bulletin de la Société Préhistorique Française*. 62, p. 110-117.

Goldhahn, J. (2002) Roaring Rocks: An Audio-Visual Perspective on Hunter-Gatherer Engravings in Northern Sweden and Scandinavia. *Norwegian Archaeological Review*. 35, p. 29-61.

Hameau, P. (2002) *Passage, Transformation et Art Schematique: L'exemple des Peintures Neolithiques du Sud de la France,* Oxford: British Archaeological Reports 1044.

Hedges, K. (1993) Places to see and places to hear: rock art and features of the sacred landscape. IN Steinbring, J., Watchman, A., Faulstich, P. and Taçon, P. S. C. (Eds.) *Time and Space. Dating and spatial considerations in rock art research*. Melbourne: Australian Rock Art Research Association.

Heilmann, G., Navvab, M., Boek, M. and Vonrhein, B. (2014) Acoustic study and visualisation of a complex echo at the Klondike Bluffs, in the Arches National Park, Utah, USA. *Inter-noise,* 2014.

Houtgast, T., Steeneken, J. M. and Plomp, R. (1980) Predicting speech intelligibility in rooms from the modulation transfer function: general room acoustics. *Acustica*. 46, p. 60-72.

Hultman, M. (2010) The Known Yet Unknown Ringing Stones of Sweden. IN FUGLESTVEDT, I.,

Goldhahn, J. and Jones, A. (Eds.) *Changing Pictures: Rock Art Traditions and Visions in the Northernmost Europe*. Oxford: Oxbow.

Hultman, M. (2014) Soundscape Archaeology: Ringing Stone Research in Sweden. *Time and Mind*. 7, p. 3-12.

Jackson, G., Gartlan, J. S. and Posnansky, M. (1965) Rock Gongs and Associated Rock Paintings on Lolui Island, Lake Victoria, Uganda: A Preliminary Note. *Man*. 65, p. 38-40.

Jahn, R. G., Devereux, P. And Ibison, M. (1995) *Acoustical resonances of assorted ancient structures,* Princeton (NJ], Princeton University. Available from: URL www.princeton.edu/~pear/publications.html [Accessed: July 2015].

Kleinitz, C. (2004) Rock art and 'rock gongs' in the Fourth Nile Cataract region: the Ishashi island rock art survey. *Sudan & Nubia (The Sudan Archaeological Research Society)*. 8, p. 11-16.

Kleinitz, C. (2008) Soundscapes of the Nubian Nile Valley. 'Rock Music' in the Pourth Cataract Region (Sudan). In Both, A. A., Eichmann, R., Hickmann, E. and Koch, L.-C. (Eds.) *Challenges and Objectives in Music Archaeology*. Rahden, Westf.: Deutsches Archäologisches Institut.

Lahelma, A. (2010) Hearing and Touching Rock Art: Finnish rock paintings and the non-visual. IN Fuglestvedt, I., Goldhahn, J. And Jones, A. (Eds.) *Changing Pictures: Rock Art Traditions and Visions in the Northernmost Europe*. Oxford: Oxbow.

Lahelma, A. (2012) Strange Swans and Odd Ducks: Interpreting the Ambiguous Waterfowl Imagery of Lake Onega. In Cochrane, A. and Jones, A. M. (Eds.) *Visualising the Neolithic. Abstraction, Figuration, Performance, Representation*. Oxford: Oxbow Books.

Levitin, D. J. (Ed.) (2006) *This is your brain on music: understanding a human obsession,* New York: Dutton.

Litovsky, R. Y., Colburn, H. S., Yost, W. A. and Guzman, S. J. (1999) The precedence effect. *Journal of the Acoustical Society of America,* 106, p. 1633-1654.

Lødøen, T. (2010) Concepts of Rock in Late Mesolithic Western Norway. In Fuglestvedt, I., Goldhahn, J. And Jones, A. (Eds.) *Changing Pictures: Rock Art Traditions and Visions in the Northernmost Europe*. Oxford: Oxbow.

Manaud, O. and Barrandon, C. (forthcoming 2015), «Echo-graphi» intérieure du cairn de Gavrinis. Etude exploratoire des caractéristiques acoustiques et lecture symbolique. *Archéothéma* 39.

Mazel, A. (2011) Time, color, and sound: revisiting the rock art of Didima Gorge, South Africa. *Time and Mind: The Journ.al of Archaeology, Consciousness and Culture*. 4, p. 283-296.

Mills, S. (2005a) Sensing the place: sounds and landscape archaeology. In Bailey, D. W., Whittle, A. And Cummings, V. (Eds.) *(Un)settling the Neolithic*. Oxford: Oxbow.

Mills, S. (2005b) *Applying Auditory Archaeology to Historic Landscape Characterisation. A pilot project in the former mining landscape of Geevor and Levant Mines, West Penwith, Cornwall. A report for English Heritage,* Truro: Historic Environment Service, Planning Transportation and Estates, Cornwall County Council.

Morley, I. (2006) Hunter-gatherer music and its implications for Identifying Intentionality in the use of acoustic space. In Scarre, C. and Lawson, G. (Eds.) *Archaeoacoustics. Acoustics, space and intentionality: identifying intentionality in the ancient use of acoustic spaces and structures*. Cambridge: McDonald Institute for Archaeological Research, University of Cambridge.

Murphy, D. T. (2006) Archaeological acoustic space measurement for convolution reverberation and auralization applications. *Proceeding of the 9th International Conference on Digital Audio Effects (DAFx-06), Montreal: Canada, September 18-20, 2006*. Online.

Naguib, M. and Wiley, R. H. (2001) Estimating the distance to a source of sound: mechanisms and adaptations for long-range communication. *Animal behaviour*. 62, p. 825-837.

Ouzman, S. (2001) Seeing is deceiving: rock art and the non-visual. *World Archaeology*. 33, p. 237-256.

Pager, H. (1971) *Ndedema: A Documentation of the Rock Paintings of the Ndedema Gorge,* Graz:

Akademische Druck.

Rainio, R., Lahelma, A., Äikäs, T., Lassfolk, K. And Okkonen, J. (2014) Acoustic Measurements at the Rock Painting of Várikallio, Northern Finland. In Eneix, L. C. (Ed.) *Archaeoacoustics: The Archaeology of Sound. Publication of Proceedings from the 2014 Conference in Malta.* Myakka City, Florida: The OTS Foundation.

Reed, S. E., Boggs, J. L. And Mann, J. P. (2012) A GIS tool for modelling anthropogenic noise propagation in natural ecosystems. *Environmental Modelling & Software.* 37, p. 1-5.

Reznikoff, I. (1995) On the sound dimension of prehistoric painted caves and rocks. IN TARATSI, E. (Ed.) *Musical Signification.* Berlin: Mouton de Gruyter.

Reznikoff, I. and Dauvois, M. (1988) La dimension sonore des grottes ornées. *Bulletin de la Société Préhistorique Française.* 85, p. 238-46.

Rifkin, R. F. (2009) Engraved art and acoustic resonance: exploring ritual and sound in north-western South Africa. *Antiquity.* 83, p. 585-601.

Rossing, T. D. (Ed.) (2007) *Springer handbook of acoustics,* New York, Springer.

Scarre, C. and Lawson, G. (Eds.) (2006) *Archaeoacoustics. Acoustics, space and intentionality: identifying intentionality in the ancient use of acoustic spaces and structures,* Cambridge: McDonald Institute for Archaeological Research.

Sognnes, K. (1994) Ritual landscapes: towards a reinterpretation of Stone Age rock art at Trønderlag, Norway. *Norwegian Archaeological Review.* 27, p. 29-50.

Till, R., Wyatt, S., Fazenda, B., Sheaffer, J. And Scarre, C. (2013) Songs of the Caves: Sound and Prehistoric Art in Caves. Initial report on a study in the Cave of Tito Bustillo, Asturias, Spain. Available from: URL songsofthecaves. wordpress.com/ [Accessed: July 2015].

Till, R. (2014) Sound archaeology: terminology, Palaeolithic cave art and the soundscape. *World Archaeology [Special issue: Music & Sound]* 46: 292-304.

Trehub, S. E., Becker, J. and Morley, I. (2015) Cross-cultural perspectives on music and musicality. *Philosophical Transactions of The Royal Society B Biological.* 370, p. 20140096. http://dx.doi.org/.

Ulbrich, H.J. (2003), Frequenzanalyse eines Lithophons auf Lanzarote (Kanarische Inseln), *Almogaren,* XXXIV, p. 25-36.

Waller, S. J. (2002) Rock Art Acoustics in the Past, Present and Future. *American Indian Rock Art (special issue Whitehead, P., Whitehead, W., Loendorf, L. 1999 IRAC Proceedings, Volume 2),* 26, p. 11-20. Tucson: American Rock Art Research Association.

Waller, S. J. and Arsenault, D. (2008) Echo spirits who paint rocks: Memegwashio dwell within echoing rock art site EiGf-2. *American Indian Rock Art.* 34, p. 191-201.

Waller, S. J., Lubman, D. and KISER, B. (1999) Digital Acoustic Recording Techniques Applied to Rock Art Sites. *American Indian Rock Art.* 25, p. 179-190.

Watson, A. (2006) (Un)intentional Sound? Acoustics and Neolithic Monuments. In Scarre, C. and Lawson, G. (Eds.) *Acoustics, space and intentionality: identifying intentionality in the ancient use of acoustic spaces and structures.* Cambridge: McDonald Institute for Archaeological Research, University of Cambridge.

Watson, A. and Keating, D. (1999) Architecture and sound: an acoustic analysis of megalithic monuments in prehistoric Britain. *Antiquity.* 73, p. 325-336.

Photometric Stereo 3D Visualizations of Rock-Art Panels, Bas-Reliefs, and Graffiti

Massimo Vanzi[(1)]

Paolo Emilio Bagnoli[(2)]

p.bagnoli@iet.unipi.it

Carla Mannu[(1)]

Giuseppe Rodriguez[(3)]

[1] Department of Electrical and Electronic Engineering, University of Cagliari, Italy
[2] Information Engineering Department, University of Pisa, Pisa, Italy
[3] Department of Mathematics, University of Cagliari, Italy.

Abstract: For small-scale cultural subjects, such as rock engravings, graffiti and bas-reliefs, 3D rendering may be realized by applying the photometric stereo consolidate method, instead of complex and expensive laser-scanning equipments. It is a cheap, portable, and easily implementable technique generally used in quality controls within manufacturing industrial environments or in robotic vision. Its main advantage is the use of common digital photography with portable flash lighting and dedicated software for data elaboration. Furthermore, it provides as output data, in addition to the morphological information of the objects, the map of brightness and surface colours (albedo), which allows the user correctly to identify the frescoes and paintings without distortions caused by shadows or other morphological detail. This paper deals with the theoretical fundamentals of the photometric stereo method for 3D rendering of surfaces, its practical implementation, and the mathematical strategies to obtain both the morphological data and the albedo functions. Some examples of applications on rock-art and other artefacts are presented and discussed.

Keywords: Photometric Stereo, 3D reconstruction, rock art, graffiti, bas-reliefs

Introduction

Photometric Stereo is a fundamental part of the entire process concerning computer vision. This issue is very important in industrial applications, artificial intelligence research, and so on. It is based on an image processing procedure that analyses the scene and tries to recover its two-dimensional surface in the three dimensional space. There are many techniques to 3D map a single object or an entire scene and each of them has different features concerning the approach to the problem.

The most commonly used is the laser-scanning technique. It is able to build up the 3D morphology of the sample by measuring the distances of a grid of points in which each measurement is independent on those of the surrounding points. By contrast, almost all other methods need to analyse a pixel cluster or even all pixels in N images to recover surface heights. This clearly represents a drawback, since the height value of one point (whose data is supposed to be noiseless) will be biased by the noise in the adjacent pixels. For this reason all of these methods are carefully used and, in most cases, merged with other more accurate methods (Nehab *et al*. 2005). Depending on the nature of the samples, however, — rock engravings, for instance — laser scanning seems to be unsuitable because of equipment cost, operational complexity requiring distance resolution within a few millimetres, and the long acquisition time.

Photometric Stereo, conceived by Woodham (1980), takes the theory of shape from shading, which reconstructs the heights using only one image, and extends it to a number $N > 2$ images. Furthermore, it provides as output data, in addition to the morphological information of the objects, the map of brightness and surface colours (albedo). This technique uses a reflectance map as a mathematical model or a lookup table, which decreases the computational time in some simple applications. On the other hand, the algorithms that reconstruct also albedo parameters do not need this constraint.

Note that, if there is no need to find albedo it is better to acquire only grey-scaled images, to minimize used memory, while colour images are obviously necessary if chromatic information is needed. For the Lambertian surface, as discussed in the next section, photometric equations are linear and only three images are sufficient to reconstruct both gradient and albedo. With more than three images some papers use the 'surplus' information to find other object parts as outliers (Woodham 1994), or to recover unknown illumination directions and strengths (Woodham *et al*. 1991).

In this paper we try to demonstrate that the Photometric Stereo method may be successfully applied to cultural heritage artefacts because it is accurate, low-cost, and easily implementable. This method cannot replace more sophisticated technologies for 3D mapping in all cases, however, because of their particular characteristics. Indeed, it is unsuitable for mapping three-dimensional objects, as it is not capable of elaborating full shadows; it is used to map almost flat objects such as rock engravings, graffiti, and bas-reliefs. Furthermore, making use

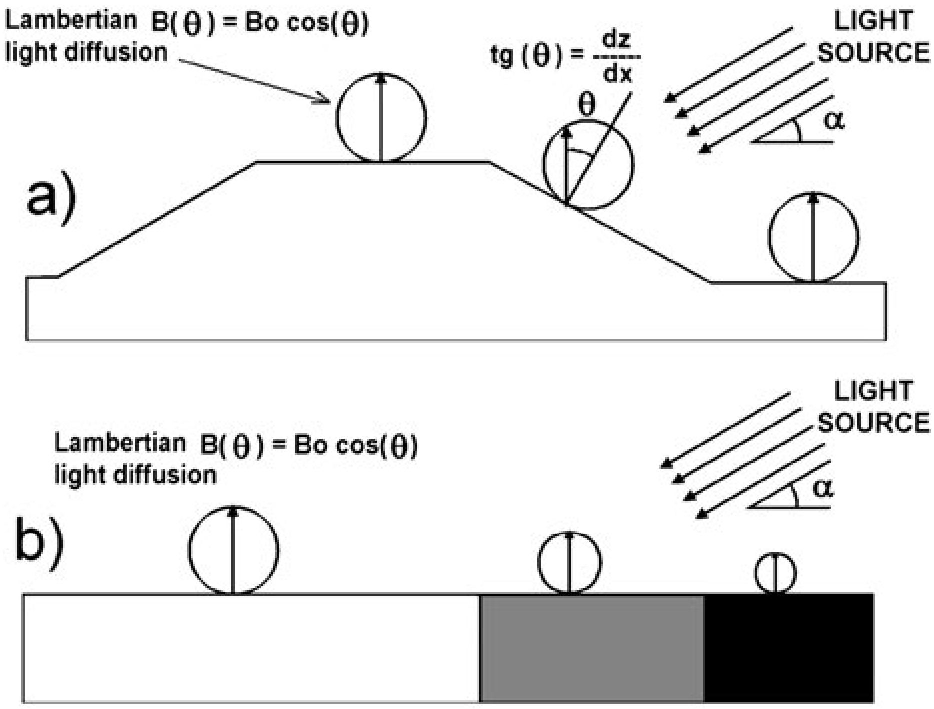


Fig. 1. Lambertian polar reflectivity diagrams as a function of the local morphology (a) and the surface brightness (b).

of multiple photographic images with artificial light sources to create an illuminating field that must be as uniform and parallel as possible, the Photometric Stereo method may be applied preferably to objects of relatively small size. This unsuitable property can be overcome, however, by sewing together more maps to obtain 3D renderings of larger-size panels.

1 Mathematical fundamentals

The basic theory of the Photometric Stereo and its technical implementations are reported in Woodham (1980) and Horn (1989). It is based on the assumption that the shading on a surface depends on the direction of the light source and on the shape of the surface itself through mathematical relationships and independent of the colour.

In the present work, the use of more than three photos was preferred, making the method more 'robust' because of the lack of ideal conditions in the recording set-up.

The theory is based on the assumption that the surface follows the Lambert law for the diffusion of light. The Lambert's cosine law is a property of a rough surface illuminated by a parallel light field source with a given angle α from the horizon, by which all the points reflect the light in the same way. The back-scattered light intensity follows the relationship

$$B(\theta) = Bo * \cos(\theta) \quad (1)$$

where θ is the angle measured with respect to the normal (orthogonal) direction) to the local surface plane and Bo is the maximum intensity along the local normal to the surface. This implies that the diffused light intensity contains information about both the surface slope in that point and its reflectivity.

This behaviour is graphically depicted in Figure 1. In this figure the photo camera is supposed to be positioned in the vertical direction. The small spheres represent the Lambertian polar reflectivity diagrams in the various points whose diameter represents the *Bo* parameter. As can be seen the value of reflected light intensity *B(θ)* is affected by the θ angle and hence by the local surface slope, while the colour or the surface reflectivity (albedo) affect the parameter *Bo*.

From a practical point of view, the experimental procedure consists of the acquisition of three or more digital photographs keeping the camera in the same zenith position and moving the flash light source around the subject, keeping the source at a given angle with respect to the horizon. In the present case the number of digital images is four, positioned at the four cardinals as illustrated in Figure 2.

If we address I_W, I_N, I_S, and I_E the two-dimensional intensity matrices of the four digital photos taken with the light source along the west, north, south, and east directions respectively, *Z(x,y)* the altitude of the surface with respect to the horizon plane, we can calculate the morphological gradients *p(x,y)* along the x axis (W-E axis), that *q(x,y)* along the y axis (N-S axis), and the albedo function *A(x,y)* by means of the following relationships (Woodham 1980):

$$p(x,y) = \frac{dZ}{dx} = -2\cot(\alpha)\frac{I_W - I_E}{I_N + I_W + I_S + I_E} \quad (2)$$

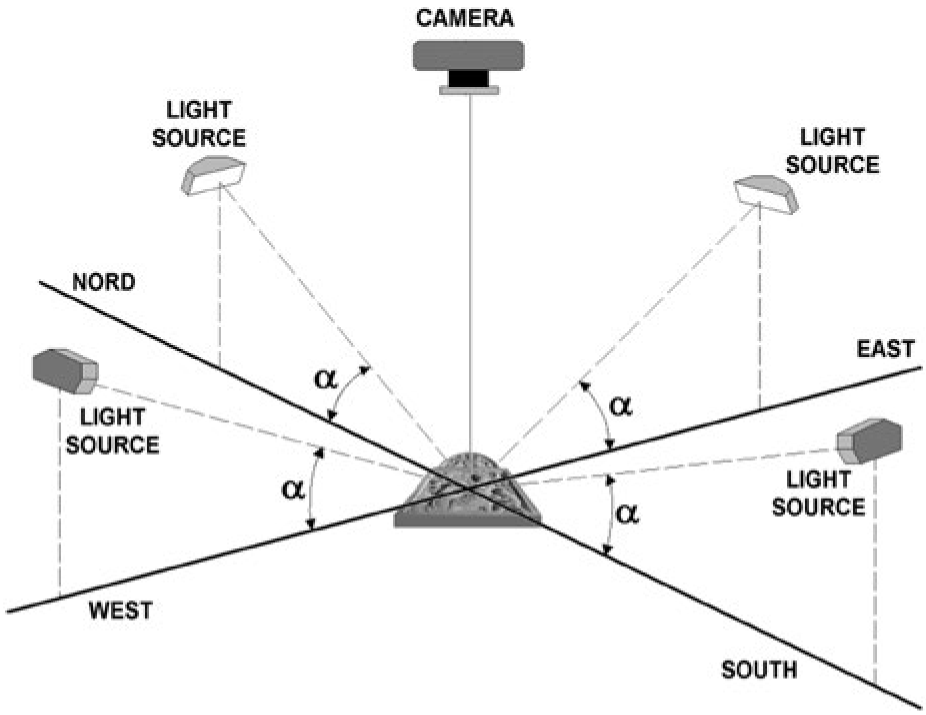


FIG. 2. POSITION OF THE ILLUMINATING LIGHT SOURCE OF THE SAMPLE AND THE PHOTO CAMERA.

$$q(x,y)=\frac{dZ}{dy}=-2\cot(\alpha)\frac{I_N-I_S}{I_N+I_W+I_S+I_E} \quad (3)$$

$$A(x,y)=\frac{1}{4}\sec(\alpha)(I_N+I_W+I_S+I_E)\sqrt{1+p^2(x,y)+q^2(x,y)} \quad (4)$$

Note that the above equations are valid in the case of grey-scaled images. If the colour information has to be maintained, the four digital photographs must be left in their original RGB format. All the intensity matrices are therefore replaced by three others, each representing the reflecting intensity of the image pixels for the red, green, and blue colours (for instance for the north image we have I_{NR}, I_{NG}, I_{NB}). Therefore, while the equations (2) and (3) remain the same since the gradient fields are not affected by the surface colour, in the colour maintaining procedure the albedo function of equation (4) is replaced by three equations, each one describing the albedo function for one of the three main colours ($A_R(x,y)$, $A_G(x,y)$, $A_B(x,y)$) and containing the corresponding reflecting intensity matrices for the given colour.

The 3D map of the surface, *Z(x,y)*, containing the morphological data only, may be obtained from the two-dimensional numeric integration of the two gradient fields given by equations (2) and (3). This type of problem, well known in electrostatic science since the 19th century, consists of the electrical potential generated by the presence of some electrical charges within the space. The starting relationship to be integrated is known as the Poisson equation containing the sum of the second derivatives of *Z(x,y)* along the x and y coordinates.

This may be a first strategy, which can be applied to obtain the selected results, but here there is a serious problem. Since the first derivatives are available, the second derivatives must be obtained by applying a further derivative (differentiating) to the two gradient fields, but this procedure is known to increase the noise superimposed to the numerical functions, leading to a worsening of the final image quality, while the integrating operation generally produces a noise smoothing. Therefore the direct integration of the two original gradient fields must be preferred to the above first strategy.

$$\frac{dZ(x,y)}{dx}+\frac{dZ(x,y)}{dy}=p(x,y)+q(x,y) \quad (5)$$

Recently Harker and O'Leary (2015) published a set a careful studies about the integration of the equation (5), specifically devoted to the Photometric Stereo technique, applying several types of boundary conditions, and also providing several tests on the effects of various filtering strategies in order to reduce the presence of numerical noise. In addition the authors provided, as open-source data, the MATLAB routines implemented to apply their mathematical studies.

The final product of the integrating procedure is a three-dimensional numerical matrix: the first layer contains all the x coordinates of the pixels in the original photos, the second one all the y coordinates, and the third one all the heights in the z direction. This matrix is also referred to as a 'points cloud', which may be visualized using specialized programs such as MESHLAB, available on the Internet as a free-ware. This program allows the performance of all the operations needed to modify the 3D map in different ways for the best visualization

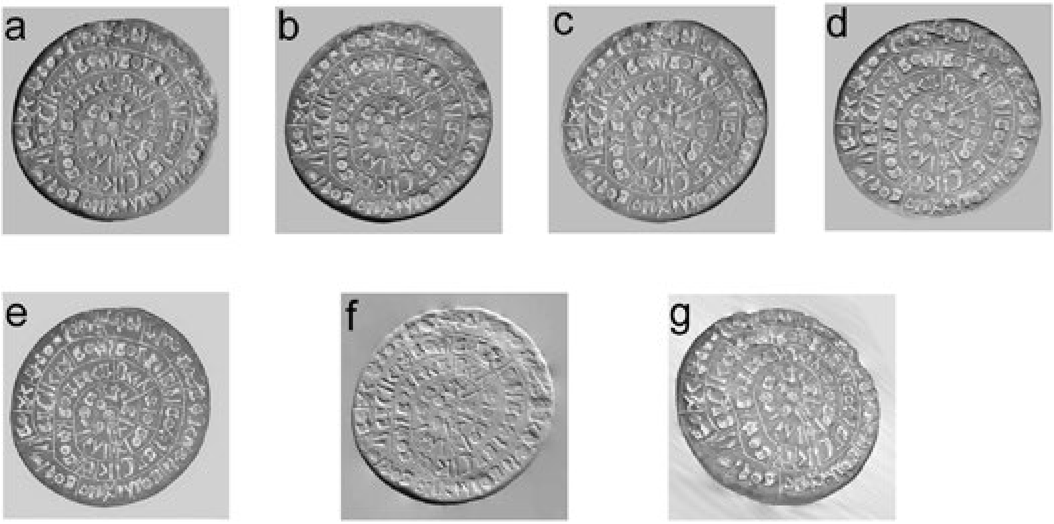


Fig. 3. Verso of the Festo disk. Original photographs with the light source in the east (a), north (b), west (c), and south (d), Albedo map (e), Reconstructed 3D morphology map (f), Morphology plus albedo map (g).

and analysis of the artefact. The overlapping of the original albedo function on the morphology is also available.

2 Practical implementation of the method

The practical application of the method is quite simple and low-cost, but some precautions must be adopted in order to minimize the distortion of the final 3D map of the sample.

The four photographs must be taken using an easel photo device in order to prevent any pixel mismatching among the photos, also using a remote starting device if possible.

For each light direction many poses must be taken because of the presence of possible noise: averaging (summing the pixel values and dividing by the number of poses) is a common technique to decrease random noise (with zero mean value) superimposed on the photographs. In the case of rock engravings the latter procedure must be preferred to the mathematical filtering of the *Z(x,y)* function. This latter procedure corresponds to the application of a spectral low-pass filter, which produces a plus or minus intense smoothing of the surface able to decrease the unwanted noise, but it also produces distortions of particularly sharp details and eliminates the surface natural roughness. Indeed, roughness is in general an important structural detail to be rendered in the 3D maps of rock engravings.

Furthermore the configuration (timing and aperture) of the photo camera must be set in order to eliminate the effect of diffused ambient light as much as possible.

The flash light source should be achieved with multiple power led devices and, whatever the case, it must provide a uniform illumination field on the sample. This feature clearly depends on the source and the specimen sizes and on their relative distance. The effect of lack of uniformity in the illumination field is briefly discussed in the next section.

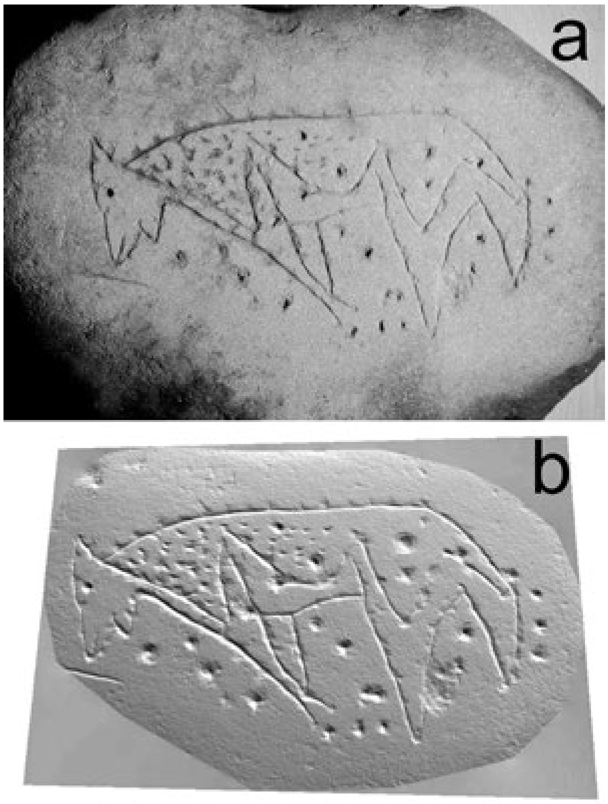


Fig. 4. Copy of the 'Polesini wolf': (a) original photograph; (b) reconstructed 3D morphology map.

Finally, if the specimen is a bas-relief, particular attention must be paid to the choice of the declination angle α of the light source in order to prevent shadows on the samples, which generate distortions on the final 3D reconstruction. Examples of this last detail are also given in the next section.

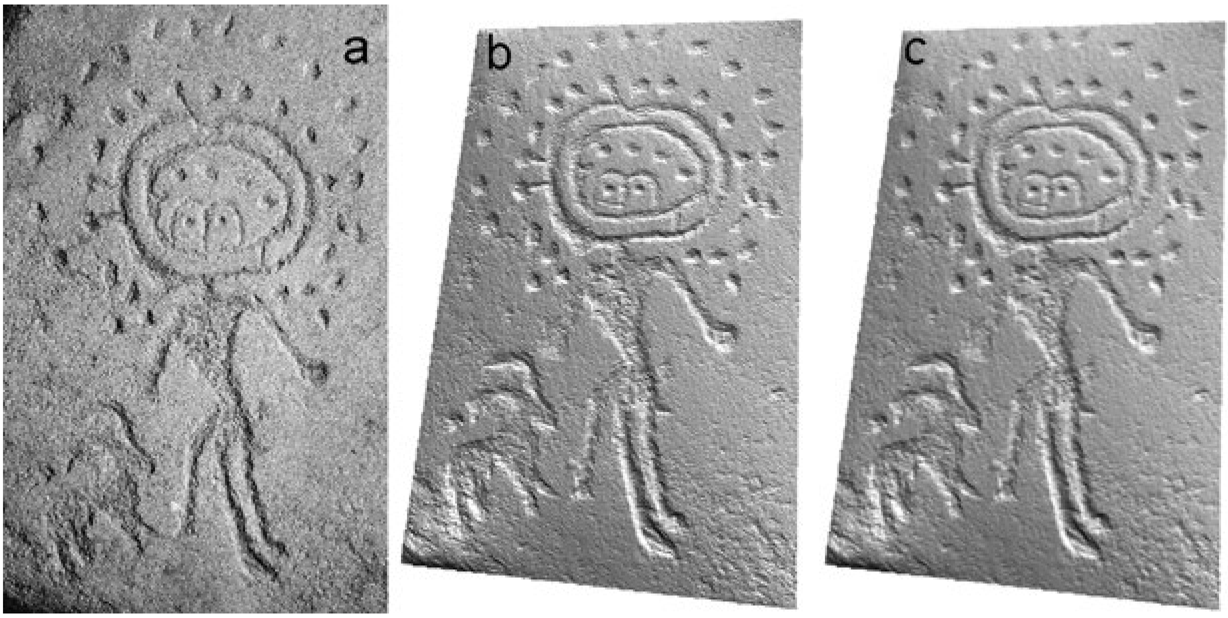


FIG. 5. COPY OF ROCK ENGRAVING FROM TAMGALI, KAZAKHSTAN: (A) ORIGINAL PHOTOGRAPH; (B) UNFILTERED RECONSTRUCTED 3D MORPHOLOGY MAP; (C) RECONSTRUCTED 3D MORPHOLOGY MAP WITH LOW-PASS FILTERING FOR NOISE REMOVAL.

3 Experimental tests

The following application tests were performed to demonstrate the resulting quality of the 3D maps obtained by means of the present method applied to rock-art panels, graffiti, and bas-reliefs. The specimens are faithful portable reproductions of rock engravings, fine graffiti, and artefacts chosen for their particular morphological properties. The resolution of all the photographs was 3200 x 2400 pixels.

Figure 3 shows the application to the recto of a reproduction of the famous Festos clay disk covered with Cretan hieroglyphs organized in a spiral. The actual diameter of the specimen is 12 cm and all the glyphs are painted in white colour. Figures 3/a, 3/b, 3/c, and 3/d show the starting photographs taken with the white led light source placed with a declination α angle of 30° in the east, north, west, and south directions respectively, as can be seen by observing the shadows of the images. The other sub-figures of Figure 3 represent the albedo map (Fig. 3/e), the 3D grey-scaled map (Fig. 3/f), and the re-joining of the albedo and 3D morphological maps (Fig. 3/g).

Figures 4 and 5 show the application on rock engravings. Both specimens were achieved by pecking on flat sandstone rocks using a paper mask. Figure 4 represents the so-called 'Polesini wolf', a Palaeolithic small graffito from the Polesini cave (Tivoli, Italy), originally made on a small chopper but here reproduced in an augmented scale by pecking on sandstone. The photograph of the sample is shown in Figure 4/a; the lateral size is about 26 cm, while the 3D morphological map is shown in Figure 4/b.

There are two details to note about this figure. Firstly, in the corners where there are no engravings and where the 3D map is flat, the starting photographs were painted with a uniform black colour. This detail is the effect of the integration procedure using the Dirichlet boundary conditions which consist of setting to zero all the contour pixels of the $Z(x,y)$ function. Secondly, the 3D surface of the sample seems to be slightly curved instead of being perfectly flat. This distortion is caused by an illumination field that is not perfectly uniform (the flash lamp is probably too close to the sample). This is to show that these less than ideal experimental conditions affect the whole surface but not the engraved details in the centre of the specimen.

Figure 5 represents the copy of an engraving from Tamgali (Kazakhstan), depicting a tailed shaman with its own totem (animal spirit) without a tail (Anati 1994). Furthermore, in this case Figure 5 shows the original photograph (Fig. 5/a), the obtained 3D morphological maps; in Figure 5/b the un-filtered image is depicted while Figure 5/c shows the low-pass filtered image for noise removal. Note that in Figure 5/b the obtained map was able to reproduce all the details of the image perfectly, including the roughness of the surface. By contrast, the effects of filtering are clearly seen in the last image compared with the previous one: as mentioned above, the filtering produces a general smoothing of the 3D surface and the loss of most of the roughness.

Figure 6 shows the reproduction of a famous graffito from Pompeii (*Rufus est*) made on a travertine marble slab covered by epoxy resin to fill the small holes of the surface. The graffito was made using very thin engravings (Fig. 6/a is the photograph, Fig. 6/b the 3D morphology), which can be perfectly rendered by the present method as can be clearly seen. A small detail is able to demonstrate the effectiveness of the method in detecting the presence of fine morphological items. In the 3D map in Figure 6/b an elliptical sign is clearly evident near the chin of the figure. This is due to a local excess of the epoxy resin coating protecting the marble slab and making the surface hygroscopic. This detail is practically invisible in the original photographs.

The experimental tests on bas-reliefs are shown in the Figure 7 — a small clay Roman mask — and Figure 8 representing the

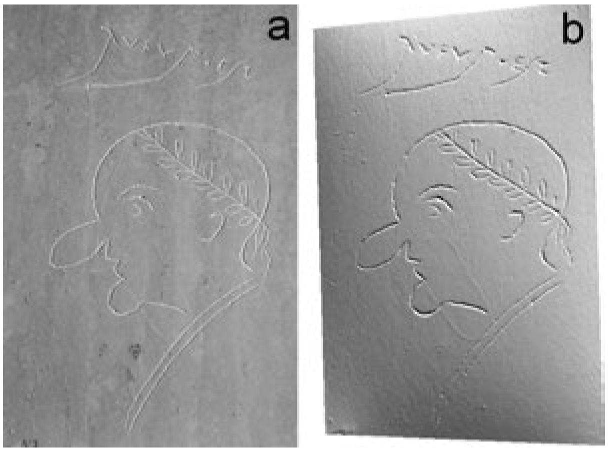


Fig. 6. Copy of a graffito from Pompeii (*Rufus est*) made on a 'travertino' marble slab: (a) original photograph; (b) reconstructed 3D morphology map.

Nativity. In these samples it is possible to observe in the 3D maps the morphological distortion due to the insufficient declination angle α of the illuminating light source. In fact, for the low value of α, such an illumination generates shadowed areas, which cannot be correctly reconstructed during the integration steps, especially in the areas with shaper profiles. This effect can be clearly seen by comparing the 3D morphological maps obtained with α equal to 30° (Figs. 7/b and 8/b) with those obtained using α equal to 60° (Figs. 7/c and 8/c). For example, the parts close to the noose of the mask in Figure 7/b are not rendered in their true depth, while this happens in Figure 7/c obtained using an increased declination angle. The increase of the α angle, however, generally produces a slight flatness of the profile, which is unsuitable for a faithful 3D surface visualization. In the case of Figures 7/c and 8/c, therefore, this defect was compensated by applying an amplification factor (1.6) for the *Z(x,y)* function.

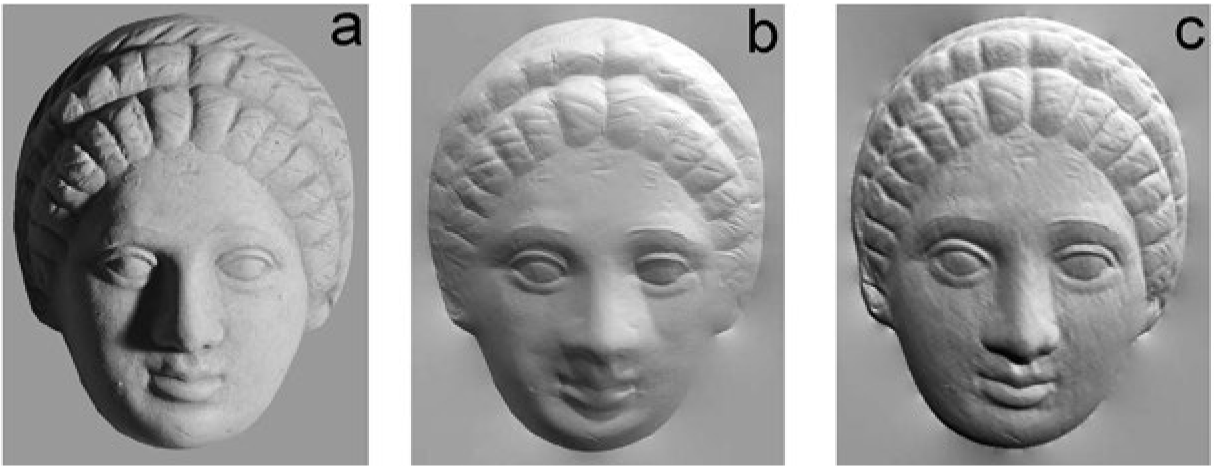


Fig. 7. Small clay Roman mask: (a) original photograph; (b) reconstructed 3D morphology map with α equal to 30°; (c) reconstructed 3D morphology map with α equal to 60°.

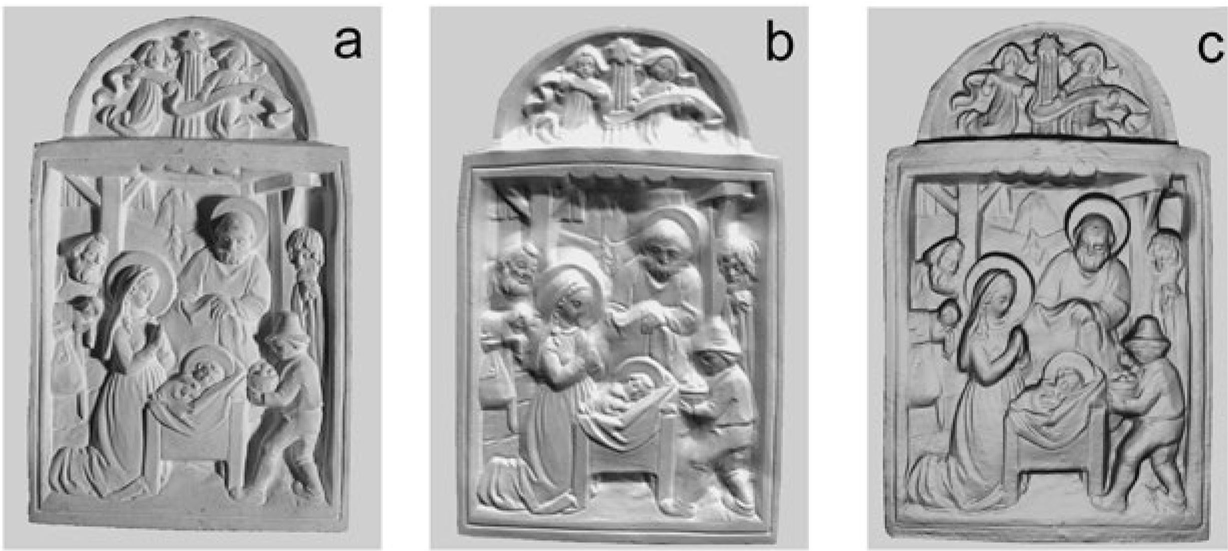


Fig. 8. Small Nativity bas-relief: (a) original photograph; (b) reconstructed 3D morphology map with α equal to 30°; (c) reconstructed 3D morphology map with α equal to 60°.

6 Conclusions

Photometric Stereo appears to be an efficient and powerful tool for producing 3D reconstructions of almost flat panels of cultural heritage specimens, mostly preferable to more expensive and complex equipment such as laser scanners. Although it can only be applied to relatively small samples, this disadvantage may be overcome by connecting together more point clouds from several analyses to obtain larger size 3D maps of rock art panels and graffiti, therefore enabling in a portable and cheaper way, documentation of rock art figures free from manual or subjective interpretations. This may be useful for a more complete analysis and digital documentation storage. In addition, the software programs to elaborate the photo data with the Photometric Stereo technique are very simple and easily implementable in standard software development systems such as MATLAB.

This technique provides both the morphological map and the chromatic one in terms of brightness and colour. This full chromatic information allows the user to recognize frescoes and paintings correctly, without distortions caused by shadows or other surface morphological details. Furthermore, the 3D visualization of a rock art surface can provide a powerful tool to perform accurate and highly resolved measures of the dimensions (height and depth) of linear engravings used to apply a recently reported method for absolute dating of rock-art artefacts (Bagnoli 2009, 2012). Combining computer simulations of the time evolution of the transversal profile of a linear moat due to natural rock erosion mechanisms with several *in situ* measurements, this method enables the calculation, under a given approximation, of the elapsed time from the execution of the engraving as a real root of a simple third-order algebraic equation. The height and depth measurements are currently manually performed using a mechanical tool. Instead, if a 3D map of the engravings is available, the local cross-sectional profiles along any direction can be easily drawn by interpolating the $Z(x,y)$ map along the desired segment and the geometrical parameters needed for the dating can be calculated with the resolution of the original pixel size.

Bibliography

Nehab, D, Rusinkiewicz, S., Davis, J., Ramamoorthi, R. 2005. Efficiently Combining Positions and Normals for Precise 3D Geometry. In *Proccedings of the SIGGRAPH ACM Transactions on Graphics, August 2005*, 24, 3.

Woodham, R. J. 1980. *Photometric Method for Determining Surface Orientation from Multiple Images*, Optical Eng. 19, I: 1391-7.

Woodham, R. J. 1994. Gradient and Curvature from the Photometric-Stereo Method, Including Local Confidence Estimation. Journal of Optical Soc. Am., 11, 11: 3050-68.

Woodham, R. J., Iwahori, Y., Barman R. A. 1991. *Photometric Stereo: Lambertian Reflectance and Light Sources with Unknown Direction and Strength*, technical report, Dept. of Computing Science, Univ. of British Columbia.

Horn, B.K. P. 1989. *Shape from Shading*, MIT Press Cambridge, MA, USA: 123-71.

Harker, M., O'Leary, P. 2015. Regularized Reconstruction of a Surface from its Measured Gradient Field. *Journal of Mathematical Imaging and Vision* 1, 51: 46-70.

Anati, E. 1994. *Arte Rupestre. Il linguaggio dei Primordi*. Capo di Ponte, Centro Camuno Editor.

Bagnoli, P. E. 2009. Absolute dating of Rock-Art on Flat Marble Surfaces. In *Proceedings of XXIII Valcamonica Symposium*: 1-15. Capo di Ponte, Centro Camuno Ed.

Bagnoli, P. E. 2012. Dating historical Rock Art on marble surfaces by means of a mathematical model for natural erosion processes. *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26-29 March 2012*: 269-78. Amsterdam, Amsterdam University Press.

SIVT – Processing, Viewing, and Analysis of 3D Scans of the Porthole Slab and Slab B2 of Züschen I

Stefanie Wefers
frank.boochs@hs-mainz.de

Tobias Reich
tobias.reich@hs-mainz.de

Burkhard Tietz
burkhard.tietz@hs-mainz.de

Frank Boochs
stefanie.wefers@hs-mainz.de

i3mainz – Institute for Spatial Information and Surveying Technology, University of Applied Sciences Mainz, Germany

Abstract: Petroglyphs are traditionally documented through drawings, photographs, squeezes, and stone rubbings. Apart from squeezes, what all traditional methods have in common is that the archaeologist has to accept a loss of a more or less large amount of information. Recently, non-contact 3D recording techniques such as fringe projection are more and more often used for documentation. They provide a high-resolution 3D-point cloud with a high geometric accuracy. Especially in combination with the traditional records, 3D-data enable a more extensive interpretation by an archaeologist. The paper presents a tool that aims to be a simple interactive viewing and analysis tool tailored to the needs of cultural heritage experts not familiar with conventional 3D analysis software. The various interactive viewing functionalities, which can be combined through a layer structure, are presented, documenting its advantages by selected datasets of the gallery grave Züschen.

Keywords: 2.5D data, Visualization, Interactive analysis, Petroglyph

1 Introduction and motivation

Petroglyphs are a widespread cultural heritage which are of archaeological interest as their interpretation and analysis can give insights into common practice and usage of the depicted artefacts, religious notions when they are located, for example, inside megalithic tombs, and regional or even supra-regional contacts in prehistoric times (e.g. Marstrander 1983; Arcá and Fossati 2006; Loerper, Jockenhövel and Dirksen 2008; Schierhold 2012: 118–21). The study of petroglyph decorations encompasses the identification of motifs itself and of different engraving techniques, the determination of the extent of the motifs, and the investigation of superimposed motifs providing evidence for a relative chronology of their creation (e.g. Loerper, Jockenhövel and Dirksen 2008; Moitinho 2013; Cassen *et al*. 2014). All in all, the documentation, interpretation, dissemination, and preservation of these rock arts are tasks that have a long tradition in archaeology (e.g. Boehlau and von Gilsa 1898; She Twohig 1981). Especially long and well-known petroglyphs are often documented several times with different contemporary methods, and as this rock art is very often exposed to the weather, causing a slow but constant degradation, traditional documentation such as drawings, photographs, tracings, and squeezes have a high value for the study of rock art even today. In the last decades these traditional records were supplemented by digital 3D documentation techniques enabling an enhanced understanding, analysis, and visualization of petroglyphs in respect of humanities research questions (e.g. Moitinho 2013; 3D-Pitoti 2015). Besides these advantages for the archaeological research, a digital copy of the actual state of the petroglyphs is recorded. This enables future comparative analysis and supports the conceptual design of conservation and restoration projects if necessary.

These 3D datasets, however, have huge file sizes that are difficult to share and use. Furthermore, they have to be handled in conventional tools (such as MeshLab or Geomagic) designed for technical experts who actually acquire and process the 3D data for the cultural heritage experts (Domingo *et al*. 2013: 1888–89). Additionally, the interpretation and study — especially of petroglyphs — by an archaeologist often requires the usage of a variety of different records from diverse documentation epochs (e.g. Loerper, Jockenhövel and Dirksen 2008; Cassen *et al*. 2014). All in all, a simple tool is needed, which is adapted to the skills of the cultural heritage expert, allowing the interactive analysis of 3D and 2D data. Furthermore, such a tool should allow an easy retracing of the conclusions obtained any time through the re-study of all various data (e.g. through the storage of metadata and project settings) and, last but not least, it should allow dissemination of the interpretations (e.g. through export of images).

The functionalities of a 3D viewer developed in an interdisciplinary project on the understanding, analysis, and evaluation of 3D digitised Buddhist stone inscriptions (Boochs *et al*. 2006; Schmidt, Boochs and Schütze 2010; Schmidt, Schütze and Boochs 2011) gave rise to the development of the Spatial Image analysis and Viewing Tool (SIVT). SIVT aims to be a simple interactive viewing and analysis tool tailored to the needs of cultural heritage experts not familiar with conventional 3D analysis software. The motivation behind the development of the 3D viewer for Buddhist stone inscriptions is still true today: although a variety of 3D viewers exist, they do not all support the requirements of petroglyph analysis, which needs an accentuation of the only slightly engraved motifs in a more or less planar surface, which in itself can have a turbulent rock structure. Apart from visualization functionalities, efficient interactive interpretation needs a layer structure allowing superimposed display through transparency, mapping with multiple vector layers and metadata storage. This allows a holistic analysis of 3D data and various 2D data. Most appropriate are 3D datasets representing objects with a flat surface containing features of interest, which are either elevated from or recessed into the overall topography.

2 State of the art

Traditional methods used for documenting petroglyphs and inscriptions are drawings, tracings, photographs sometimes combined with raking light, squeezes, and stone rubbings. The latter is presumably the method with the oldest tradition as it was already used in China from the 5th century AD onwards on stone steles inscribed with diplomas, poetry, and historically relevant information (Yan 2015: 115–16). Drawings represent interpretations helping to transmit a specific message and hence are not necessarily drawn to scale. All other traditional methods, however, are metrically recorded and are therefore more easily capable of being integrated into SIVT. Stone rubbings, tracings (She Twohig 1981: 4–5; Arcà 2007), and squeezes (Frohberg 2008) are methods applied directly on cultural heritage objects with the risk of causing damage or alteration, such as oil of the silicon rubber permeating into the stone (Heinz 2010: 138). Additionally, the production of squeezes in particularl demands a high amount of work, not to mention the required equipment for large-scale rock art sites which are often located in remote places (She Twohig 1981: 5). Furthermore, raking light photography, tracing, and stone rubbing are methods that produce an objective representation of the physical cultural heritage object, but in producing these records the archaeologist deliberately discards information, such as the 3D surface context or traces evaluated as non-anthropogenic, in order to highlight those features which are of interest. Apart from squeezes, what all traditional methods have in common is that the archaeologist has to accept a loss of a more or less large amount of information.

Through the application of optical measurement techniques such as structured light scanning, structure from motion (SfM), or terrestrial laser scanning (TLS), three-dimensional digital copies of the cultural heritage asset are produced without direct physical interaction. Generally speaking, if small and detailed features of cultural heritage objects must be analysed, which is the case for all kinds of rock art, a high-resolution scan — generated, for example, by a structured light scanner — is required. They provide a high-resolution 3D point cloud (with or without texture depending on the equipment) with a high geometric accuracy — these point clouds are acquired through the accumulation of up to 1 m^3 per single capture of data (Böhler *et al*. 2004). This kind of data opens up different ways of processing to support interpretation with varying methods of 3D visualization (Hanke and Böhler 2004; Domingo *et al*. 2013). More and more often these 3D recording techniques are applied in the documentation of petroglyphs (e.g. Robson *et al*. 2001; Domingo *et al*. 2013; Moitinho 2013; Cassen *et al*. 2014). Besides the obvious advantage of being a record of the current state enabling further research if and when desired, the virtual copies can also be visualized and analysed in various modes in the future. An advantageous option is the possibility of excluding the interfering colour pattern of the surface and only displaying the object geometry, and of combining it individually with different layers displaying various colour interpretations. Furthermore, interactive visualizations are possible (see below), improving and extending the interpretation of the cultural heritage expert. Additionally, modern 3D recording techniques are not limited by the size of the cultural heritage object; minor adjustments of the equipment allow differing scale and resolution simultaneously and thereby enable the recording of a huge variety of cultural heritage assets (Boochs *et al*. 2006).

Projects using state-of-the-art recording techniques for Stonehenge (Abbott and Anderson-Whymark 2012), Gavrinis (Cassen *et al*. 2014), and various Levantine rock art sites (Domingo *et al*. 2013) could demonstrate the power of a holistic approach using various visualizations of 3D data, 2D data, and drawings for archaeological research, as all the various visualizations have different advantages and disadvantages. All these visualizations, however, were used individually for the analysis of the rock art and petroglyphs to evaluate their limitations. Concluding that a holistic approach is essential, Domingo *et al*. (2013: 1889) and Cassen *et al*. (2014, 136-140) state that archaeologists require a tool enabling them to analyse all different datasets individually.

Classic 3D viewer and analysis tools (MeshLab, 3D-PDF Viewer) use high-resolution and very computer-intensive 3D models. They are designed for experienced users who need to be knowledgeable in IT and 3D processing. Furthermore, several developments in the field of visualization and analyses of flat relief structures are developed, on the one hand for specific cultural heritage applications (e.g. ancient Greek and Latin inscriptions), and on the other are part of a specific solution package (Minidome, PTM/RTI-technologies), but the dedicated hardware is not suitable for the recording of petroglyphs and the various tools do not allow interactive analysis and visualization of a variety of different data by an inexperienced user (Tab. 1).

3 SIVT

To date the interactive visualization and analysis of all existing historical and modern data generated by the above-mentioned traditional and digital recording methods simultaneously is not possible without IT expert knowledge, using a variety of different software tools in pre-processing. For the analysis and interpretation of petroglyphs, however, archaeologists focus on a holistic research using all documentations acquired over time, including documentations through traditional methods and 3D recording techniques (e.g. Arcá 2007; Dirksen *et al*. 2008; Loerper, Jockenhövel and Dirksen 2008; Cassen *et al*. 2014). Hence, based on a 3D-viewer developed for the analysis of inscriptions (Schmidt, Boochs and Schütze 2010; Schmidt, Schütze and Boochs 2011) a tool was designed enabling

- interactive visualization of multi-sensory digital datasets such as 3D data, photos, and maps, which can be manipulated by different functionalities;

Tab. 1. Exemplary software developments for the visualization and analyses of flat-relief structures and 3D datasets.

Viewer/tool	Description	Reference
3D-PDF Viewer	Designed for publishing CAD 3D-models and other 3D-data with limited density. Provides simple tools for measuring, sectioning and visualisation.	Adobe, 2015.
MeshLab	OpenSource tool with analyses and editing functionality for complex 3D-data.	MeshLab, 2014.
Digital Epigraphy Toolbox	A scientific tool for the study and dissemination of ancient Greek and Latin inscriptions only.	Barmpoutis, Bozia & Wagman, 2010; Bozia, Barmpoutis & Wagman, 2014.
Canvas Viewer/ Mirador	An image viewer designed for the study of (mediaeval) manuscripts. It enables to display and compare various images of the same page showing different multispectral bands. An RTI (Reflectance Transformation Imaging) viewing function is integrated for demonstration purposes only.	Canvas, 2014; Canvas, 2015.
RTI/ WebRTIViewer	A tool for visualising RTI data and is part of a workflow that includes recording, processing, and visualisation of RTI data.	RTI, 2015.
Minidome/PLD Viewer	It is part of a workflow that includes recording with dedicated hardware, processing, and visualization of RTI data.	Minidome, 2014.

- interactive analysis of individual and arbitrarily combined datasets;
- capture of archaeologist's interpretations through mapping and storage of features, descriptions, and settings of all used layers for the analysis (metadata);
- export of these mapped interpretations for archiving, data-sharing, and discussion.

The interactive analysis and visualization tool handles petroglyphs as existing on a planar surface. If this is not met through a real surface, pre-processing steps can be applied by experts allowing to unroll or flatten the non-planar surface by means of other software packages (e.g. cylindrical unroll in CloudCompare).

SIVT has been developed as a Microsoft Windows® stand-alone application that can make use of two kinds of data: 1) spatial models in the form of raster-based 2.5D images (DEM) generated from 3D datasets recorded by varying 3D techniques (TLS, SfM, structured light scanner); 2) georeferenced RGB or grey-scale images which are metrically rectified and aligned by appropriate pre-processing (i.e. differential rectification). Such images could represent scale drawings, photos, or rubbings of earlier documentations in digital form. The tool handles different images as a type-specific layer; the images have individual functions for visualization depending on the image type. Four functions are actually implemented for 2.5D images and DEM (water-filling, colour mapping, interactive moveable virtual light source, and edge filter; the latter can also be applied to RGB and grey-scale images). Furthermore, the combination of different visualizations is possible through the layer logic. This improves the readability of petroglyphs using different combinations including different levels of transparency.

A vector-based mapping functionality has been implemented to document and store the interpretation results. This helps to compare features with other data or exchange and discuss interpretations with other experts. Mapping includes the storage of metadata such as author, notes, date, and current parameter settings. This is important to make visualizations reproducible and simplifies the discussion of interpretations between experts.

Furthermore, a printable export of vector, raster, and text data in SVG format will enable printing and layout in a third-party tool such as Inkscape or Adobe Illustrator.

4 Case study: gallery grave Züschen I

The Neolithic gallery grave Züschen I near Lohne-Engelshecke (Hesse, Germany) was chosen as a case study as a variety of 2D and 3D datasets from different epochs of documentation were available (Fig. 1). The collective tomb of the so-called Hessian-Westphalian Megaliths was excavated in 1894 and exposed to the weather until the beginning of the 21st century. It is 19 m long and 3.5 m wide and is dated to the beginning of the second half of the 4th millennium BC, although various finds point to the fact that it was reused during the late Neolithic, late Bronze Age, and Iron Age. It consists of 25 vertical sandstone slabs of which at least 14 display petroglyphs. Besides a few zigzag lines and herringbone patterns, bovines are the predominant motif, which are sometimes accompanied by waggon-like structures *c.*20 x 20 cm. The tomb is particularly famous for its depiction of the eye goddess. The latter links it to western European megalithic tombs whereas the former motifs link it to Central and Eastern European Neolithic cultures (Boehlau and von Gilsa 1898; Raetsel-Fabian 2001: 109; Dirksen *et al*. 2008: 3–14; Loerper, Jockenhövel and Dirksen 2008: 1-5; Schierhold 2012: 19, 45, 80, 118–22).

In 2005 all slabs were recorded with a self-made structured light scanner (Dirksen *et al*. 2008; Loerper, Jockenhövel and Dirksen 2008). Additionally, in 2015 the entire tomb was recorded using a TLS, selected slabs were recorded using an

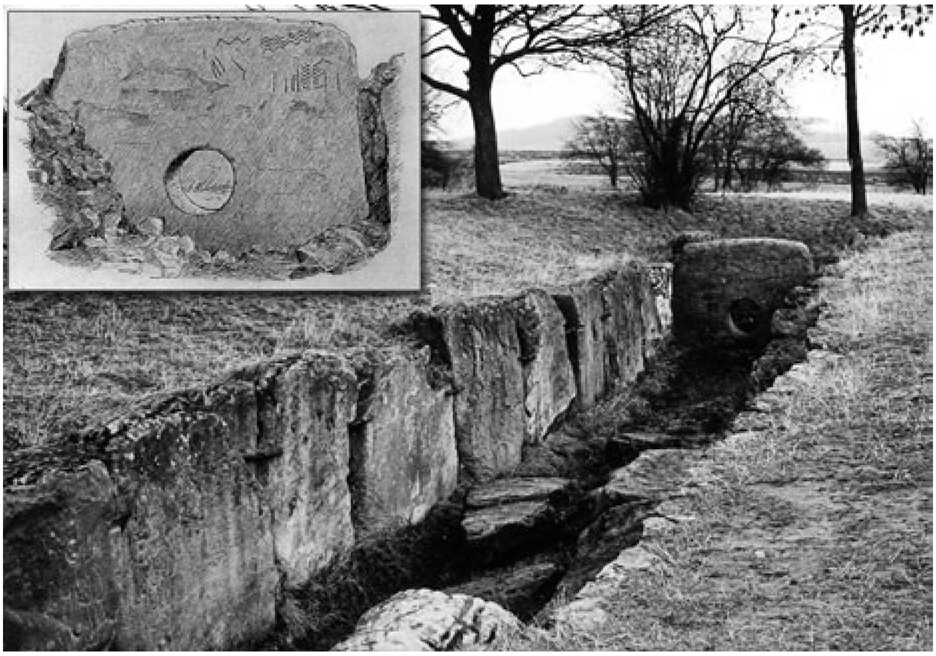


Fig. 1. Photo of the gallery grave Züschen I and drawing (photo Wojtowitsch, 1973; drawing: Boehlau and von Gilsa 1898; tab. 7).

industrial structured light scanner, and high-resolution photos were taken for panoramic views and photogrammetry. All newly generated data were georeferenced and prepared for further archaeological analysis within SIVT (Bies 2015). The lateral resolution of the 3D data generated in 2015 amounts to *c*.0.25 mm. This means that an area of 1 cm² yields 1600 3D points. For this kind of petroglyph the resolution and geometric accuracy is sufficient for the archaeological application. A more detailed recording is possible, however, with the drawback of a drastic increase in expenditure and an enormous amount of data to be processed and handled. Through the TLS data of the entire tomb and a combination of the different datasets, all stone slabs recorded in detail are visualized in a global context (Fig. 2). Apart from these 3D datasets, historical photographs taken in the 1970s, as well as drawings or interpretations of the petroglyphs prepared at the end of the 19th century and between 2005 and 2008, were available.

5 Processing Workflow – SIVT

The general workflow, beginning with the data acquisition through data processing up to visualization and mapping, is illustrated by the slab b2 data of Züschen I (Figs. 3 & 4).

5.1 Data Acquisition

All analogue content of the cultural heritage object has to be digitized if it is to be integrated into the analysis. For example, traditional data such as photographs, sketches, or rubbings can be digitized using a high-resolution flat-bed scanner. For the metric 2D and 3D digitization of the petroglyphs themselves, an appropriate measurement method (3D scanning, 2D photography, etc.) and equipment must be chosen according to the requirements: level of detail, size of the petroglyphs (see above for the case study Züschen I; for generalized recommendations see Boochs *et al*. 2006; Domingo *et al*. 2013).

5.2 Pre-processing (using typical external software-packages)

5.2.1 Geo-referencing of all input data (via external tools)

As the data can originate from different sources these differing pieces of information have to be registered into a common space. Traditional data such as analogue photographs, scanned drawings, and rubbings need geometrical corrections because of distortions or a wrong scale (see Domingo *et al*. 2013). They must be corrected and transformed into a common coordinate system to be used in SIVT for analyses and combined visualization. One approach is to use classical geo-referencing methods such as affine or Helmert-transformation for maps, drawings and rubbings, or projective or differential rectification for photographs which are available in many tools, like QuantumGIS, for example. The Züschen I data collection was corrected through a differential rectification process (Krämer and Reich 2011: 51–61).

5.2.2 Transformation of 3D data into 2.5D raster data (via external tools)

Because of the high resolution of the data recorded by a structured light scanner, several million points for a few square meters are generated. For the recording of the porthole slab covering an area of 1.8 x 1.3 m^2, with a spatial density of 0.25 mm, a point cloud of 40 million points (~4Gbyte as a mesh) is produced. The same spatial density applies for the point cloud of 34 million points (~3.5Gbyte as a mesh) of slab b2 (1.5 by 1.4 m^2). Accordingly, a data reduction process is necessary to enable the use of a traditional image-viewing tool. For this process the CH objects should be of limited global spatial complexity and without self-occluding structures. This allows the performance of a 3D to 2.5D transformation without loss of information, as the object surface can be expressed as a function Z=F(X,Y). Only a 2D image with Z as attribute needs

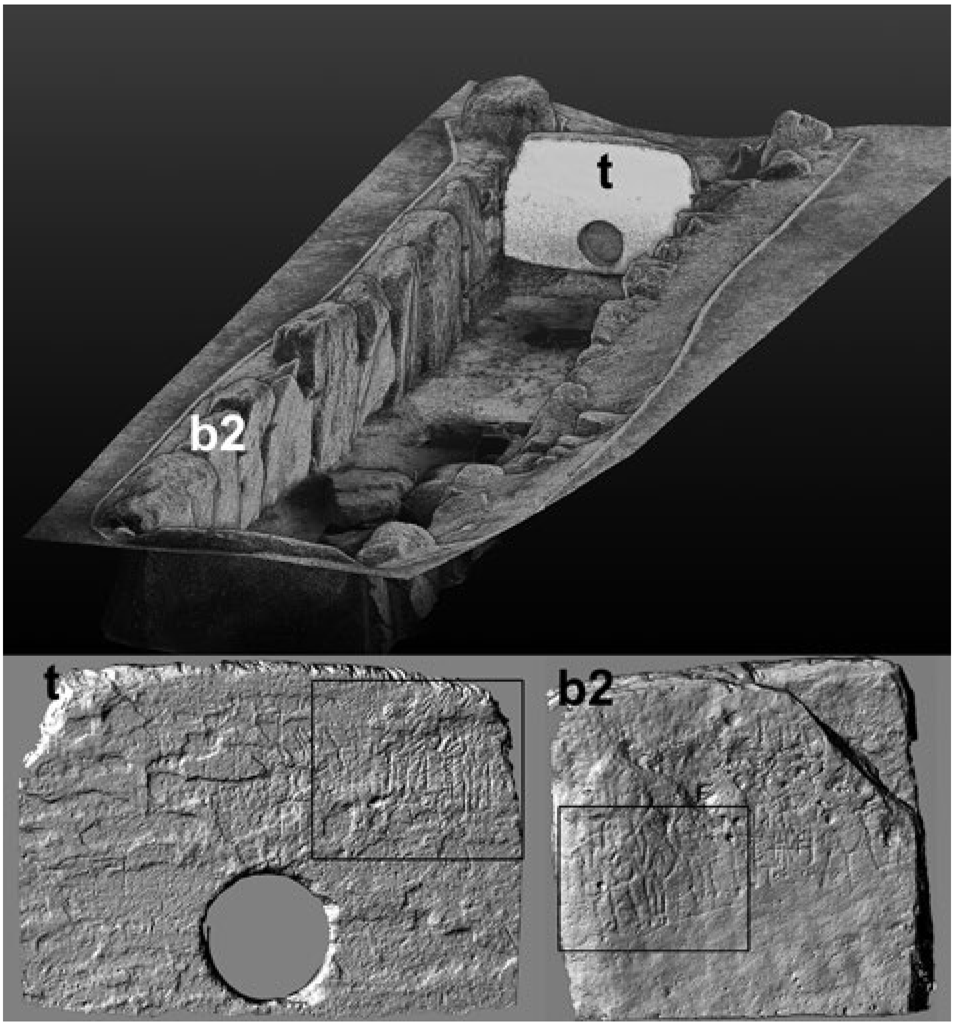


Fig. 2. Top: visualization of the gallery grave Züschen I in a global context based on TLS data. The porthole slab (t, highlighted in light grey) is used in the discussion; slab b2 is used for the explanations of the different functionalities. Bottom: high-resolution 3D mesh generated by a structured light scanner of the entire porthole slab t (left) and slab b2 (right); the framed areas are used for explanations (graphics: T. Reich based on data acquired by M. Bies).

to be stored; this saves a lot of space compared to conventional P(X,Y,Z) representations, which are normally used in flexible 3D viewing tools.

The transformation into 2.5D space is performed by fitting a plane into the 3D model and projecting the model points onto this plane. This produces 2D points on a plane each with a height value expressing the difference from the original 3D point. The DEM is produced through triangulation of irregularly distributed 3D points. This may be processed with any algorithm from the image processing toolbox with the heights of the raster treated as grey values. Avoiding the handling of complex 3D data, it simplifies further processing steps as well. The transformation from 3D to raster-based 2.5D achieves a reduction of data volume by a factor of 8 (from 4Gbyte to 500Mbyte). Pietroni *et al.* (2011) propose a similar approach, which does a local fitting of a parametric surface. This strategy requires interactive support and divides the overall surface in many individually defined pieces. As our approach assumes a less complex 3D model we are able to do a global fitting (plane, cylinder) and put the whole transformation into a pre-processing step.

5.3 Processing (internal viewer)

In order to be used by SIVT, 2.5D datasets have to be transformed into both a normal map image and a difference image. The normal map image encodes one surface normal direction per raster point of the original 2.5D raster. The surface normal direction and its curvature can be calculated by simple vector maths between any raster point and its direct neighbours (Corripio 2002: 3–5). A normal vector contains three coordinates. These coordinates are encoded as an RGB colour. Normal coordinates range from -1.0 to 1.0. These x, y, z coordinates are mapped to a range of 0 to 255 and stored as RGB values respectively. The normal map image is the basis for the lighting visualization, since the lighting calculation requires both the surface normal and light source directions.

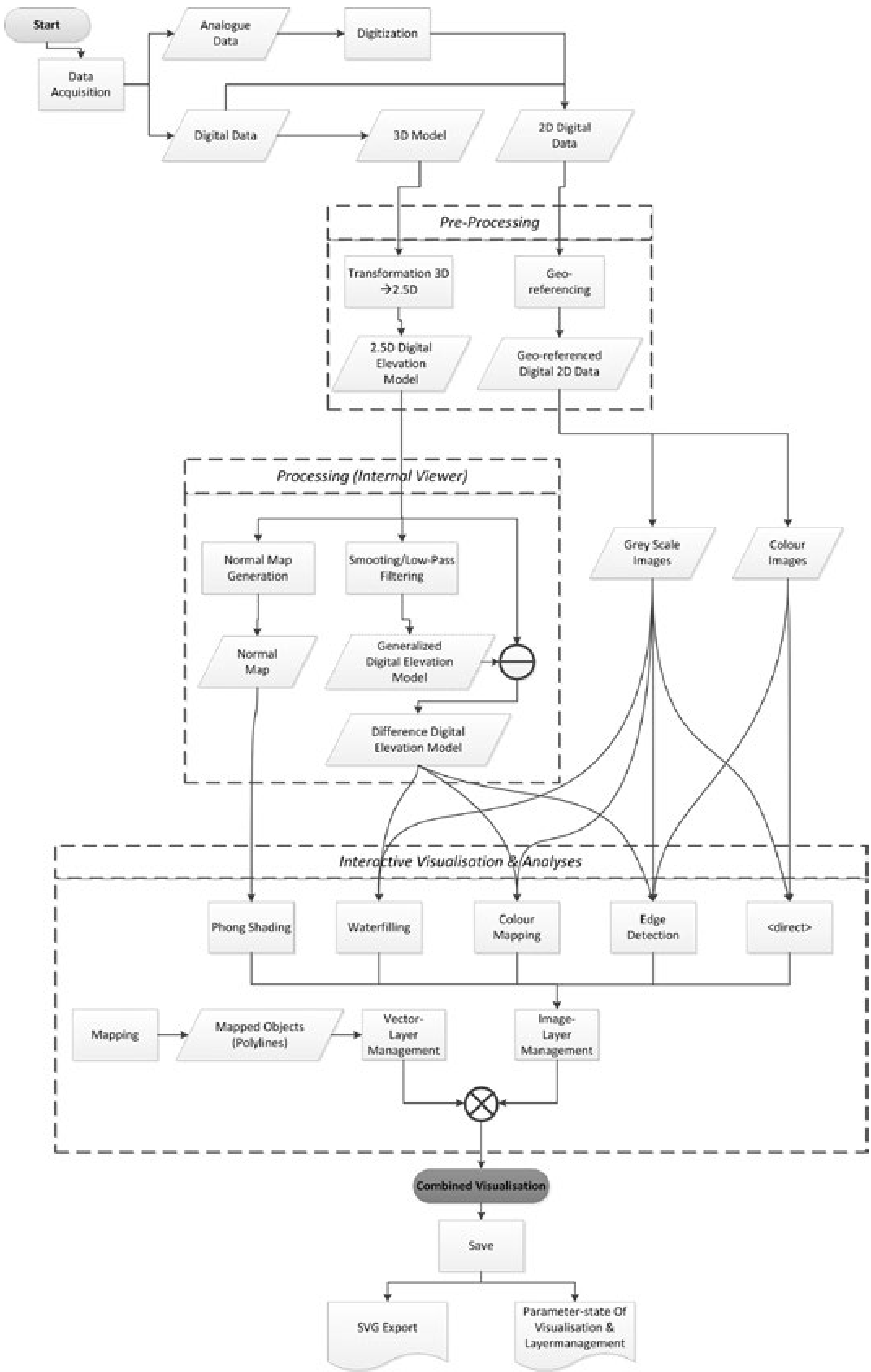


FIG. 3. WORKFLOW DIAGRAM (GRAPHICS: B. TIETZ).

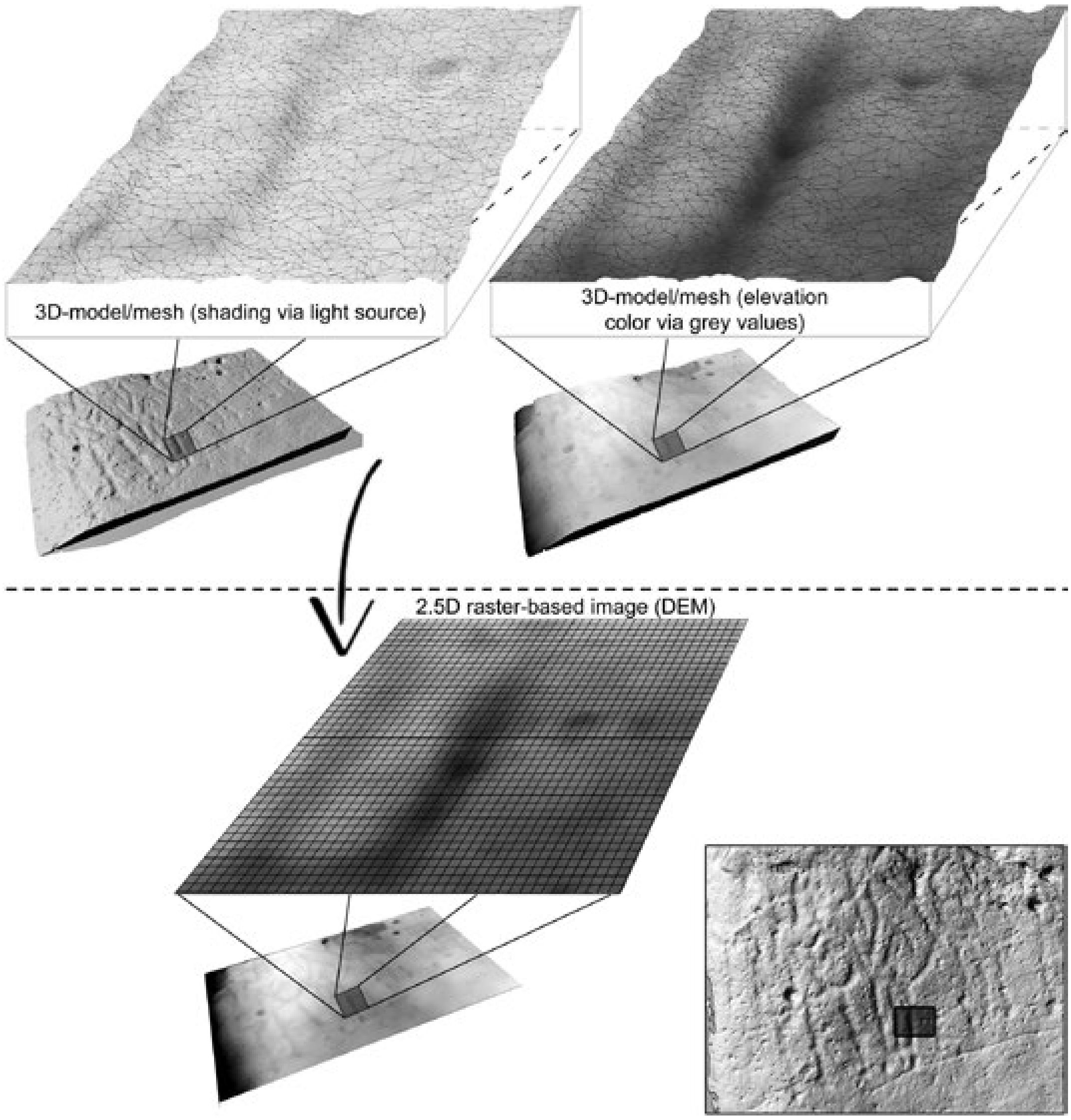


FIG. 4. COMPLEX 3D DATA OF SLAB B2 ARE TRANSFORMED INTO LESS COMPLEX 2.5D SPACE. TOP LEFT: DETAILED VIEW OF THE 3D MODEL/MESH, THE GREY SCALES ARE GENERATED THROUGH A VIRTUAL LIGHT SOURCE. TOP RIGHT: THE DIFFERENT HEIGHTS ARE DISPLAYED IN GREY VALUES AND PROJECTED ONTO THE 3D MODEL/MESH; LOW ELEVATIONS ARE DISPLAYED IN DARK GREY, HIGH ELEVATIONS ARE DISPLAYED IN LIGHT GREY. BOTTOM: THE ELEVATION-RELATED GREY VALUES ARE MAPPED ON A RASTER-BASED IMAGE = 2.5D RASTER-BASED DEM (GRAPHICS: T. REICH).

The difference image is an efficient way of extracting the actual data of interest from the background noise and topography (Fig. 5). The remaining data, however, are all elevated or recessed structures, which include both the petroglyphs as well as natural cracks and ridges. Even with 16 million unique colours provided by contemporary RGB display devices, the human observer can only distinguish a smaller number of shades and hues limiting the spectrum of displayed and interpretable information (Green 2001; 2002). The difference image is generated by subtracting a smoothed version from the original DEM raster. The smoothed version will mainly contain the geometry of the slab surface as a whole without detailed structures. Subtracting the general form of the slab from the DEM logically only leaves the detailed structures and flattens the global surface. A succession of blur or low pass filters (Luhmann 2003: 378) is applied to the original DEM to generate the smoothed version. The difference resulting from subtraction of the generalized model from the DEM might yield differing results depending on the strength of the generalization. Subtracting a less generalized image may eliminate important details, but using a more generalized version might leave topological features of the slab surface intact, thereby overshadowing engravings (Fig. 6).

5.4 Functionalities

The repertoire of functionalities can be distinguished into three categories: single layer visualization functions, mapping, and layer-based combination of the former two (Tab. 2).

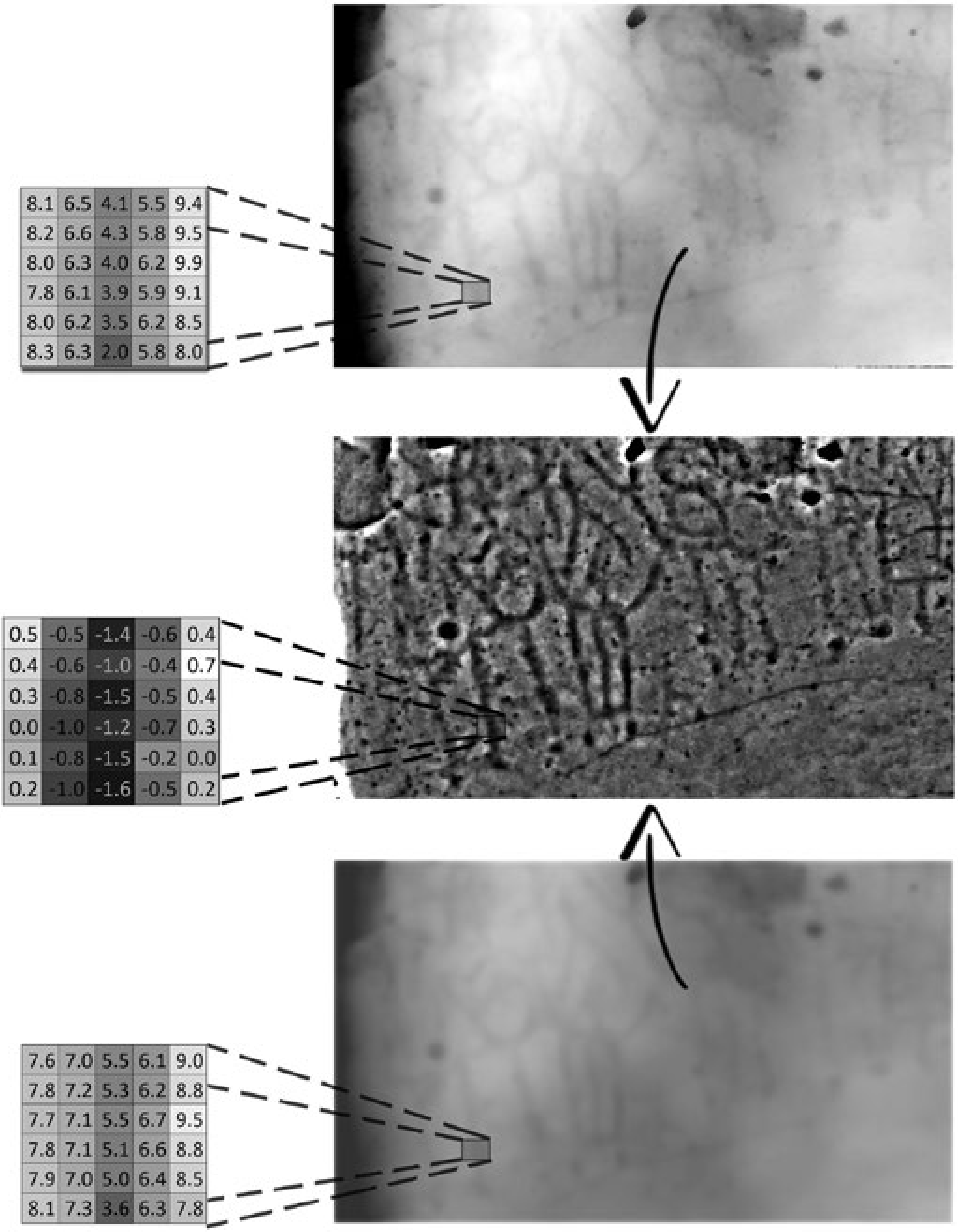


Fig. 5. Generation of a difference image (centre) by subtracting the generalized grey values of the 2.5D raster-based DEM (bottom) from the original 2.5D raster-based DEM (top). Through this calculation the grey values of the entire 2.5D raster-based DEM are stretched (fictive grey-scale values) enhancing the legibility of the petroglyphs (graphics: T. Reich).

5.4.1 Single layer visualization functionalities

The changeable lighting visualization uses the normal map image to calculate diffuse lighting based on the Phong Shading Model (Phong 1975). Depending on the light source position, which the user can change interactively, the surface is shaded giving a good impression of spatiality. In SIVT the lighting calculation is optimized allowing a real-time update of the displayed shading while the user changes the light source position. This enhances the visibility and legibility for petroglyphs. Depending on the light source direction, vertical or horizontal structures may be emphasized in the shaded image. This is comparable to raking light photography (e.g. Cassen 2014) but has the advantage of producing shadings from any angle anytime. Furthermore, the normal map only contains information about the slab surface structure, not its colour. This can also be an advantage. Smaller structures might be overshadowed by the surface colour pattern but through normal map-based lighting visualization they come to light (see below).

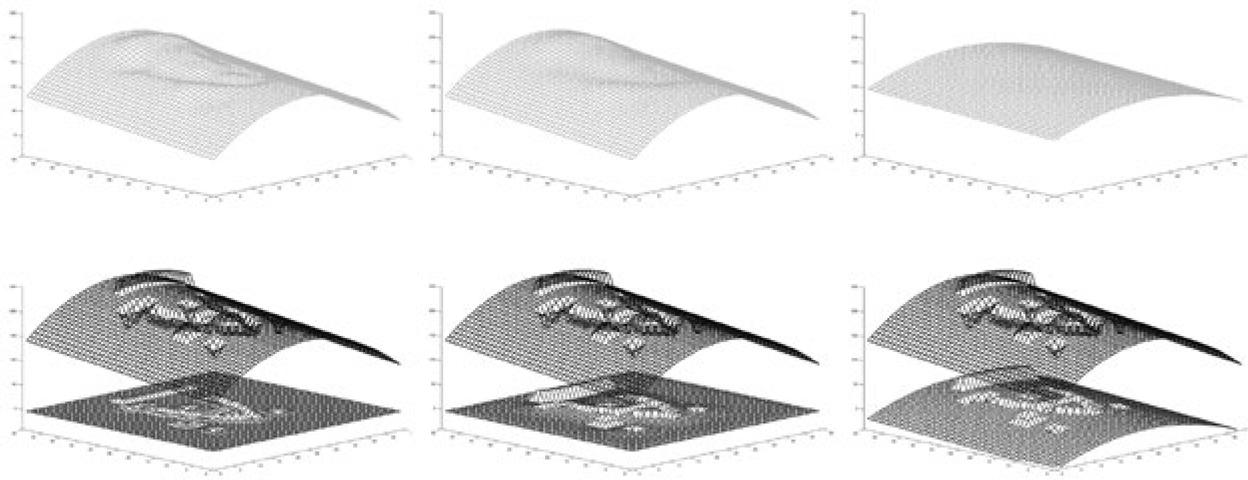


Fig. 6. Effect of the degree of generalization on the calculation of a difference image. Left to right: under-generalized, good, and over-generalized; top to bottom: generalized DEM, original DEM, difference image (graphics: B. Tietz).

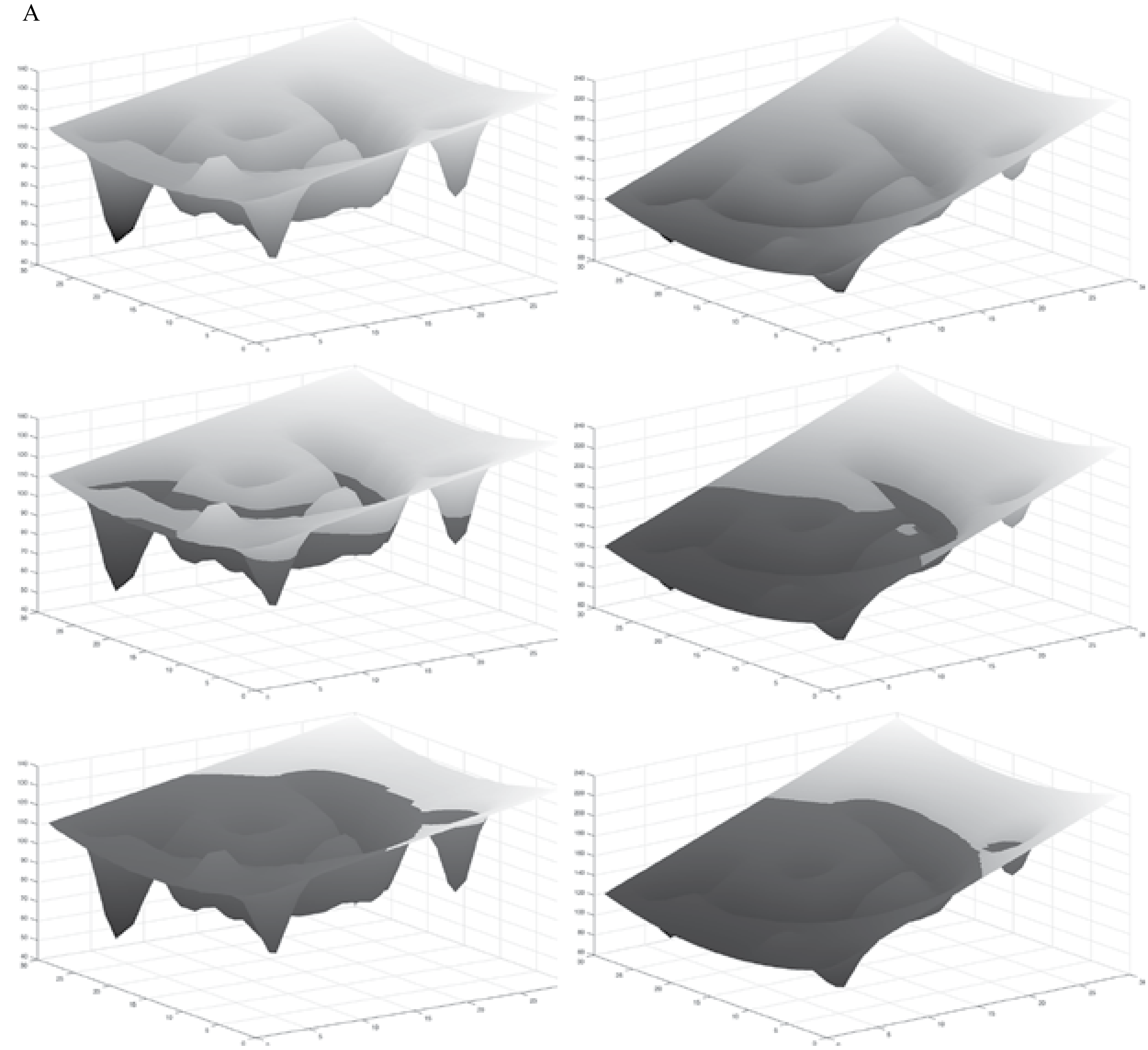
Tab. 2. Currently integrated functionalities in SIVT with their aim and underlying calculation principles.

Functionality	**Aim**	**Data processing methods**
changeable lighting visualisation	simulation of raking light photography	normal map handled with phong-shading method
water filling	visualisation of the overall object topology; enhancing legibility of petroglyphs	thresholding of 2.5D-DEM/greyscale image
colour mapping	enhancing legibility of petroglyphs	mapping of colours to greyscale values of 2.5D-DEM/greyscale image
edge detection filter	enhancing legibility of petroglyphs	differential grey/RGB value operator
vector based mapping	recording of interpretations	interactive tracing of contour lines or features
layer combination	combination of different visualisations complementing each other and thereby enhancing the legibility of petroglyphs	interactive manipulation of layer order and transparency/visibility (alpha blending)

The algorithm for water filling simply replaces the grey values of the difference image below a user-defined threshold with a custom colour. Increasing the threshold makes it similar to water filling the lower elevations of a structure first and then rising up, hence the name. This is a useful functionality to distinguish petroglyphs from the foreground. The usefulness of water filling depends on the overall topology of the cultural heritage object and the quality of the difference image. If the global surface topology (bulge of stone, cylindrical surface) remains in the image, water filling will most likely fail to separate engravings from the surface but instead fills certain areas of the image completely and others not at all (Fig. 7a). Due to the rough topology of the porthole slab, which derives from the characteristics of the Buntsandstein this functionality only suggests an impression of the overall topology but does not enhance the legibility of petroglyphs. As slab b2 has an overall flat topology, however, this functionality enhances the legibility of the petroglyphs (Fig. 7b).

As mentioned earlier, despite the broad colour spectrum provided by modern displays, for practical purposes a handful of good distinguishable hues and shades are more useful for human interpretation. By mapping the grey-scale values of the already greatly compacted elevation model of the difference image to colour values, the subjective contrast is improved. Neighbouring shades of grey, which might have been hard to distinguish, are spread out further over a spectrum of colours. The implemented colour mapping function allows the selection of different pre-defined colour ramps and enables the definition of a custom spectrum of colour. With this the cultural heritage expert may select a range of input values from the difference image or any grey-scale image, a colour ramp, and the number of colour steps. Choosing a smaller number of colour steps has a similar effect as water filling: it helps to distinguish engravings on the surface. Additionally, it functions as the colourization of equipotential lines in the DEM. Applying this functionality

A



B

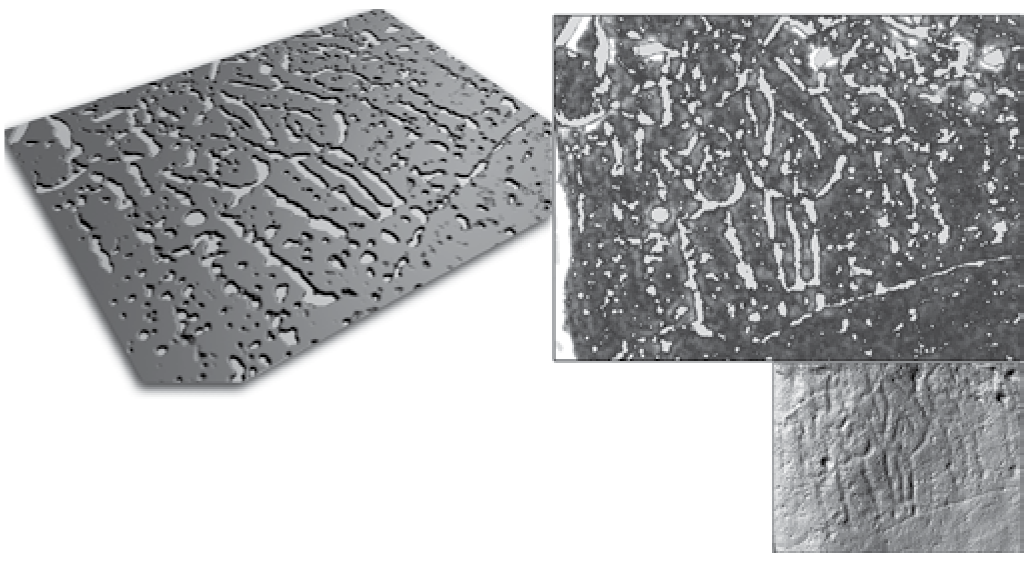


Fig. 7. (a) Top: difference image with good (left) and bad (right) generalization subtraction. Middle: applied water filling threshold I. Bottom: applied water filling threshold II (graphics: B. Tietz). (b) Water filling functionality (light grey) applied to slab b2. Left: applied to the generalized 3D mesh. Right: applied to the difference image (graphics: B. Tietz).

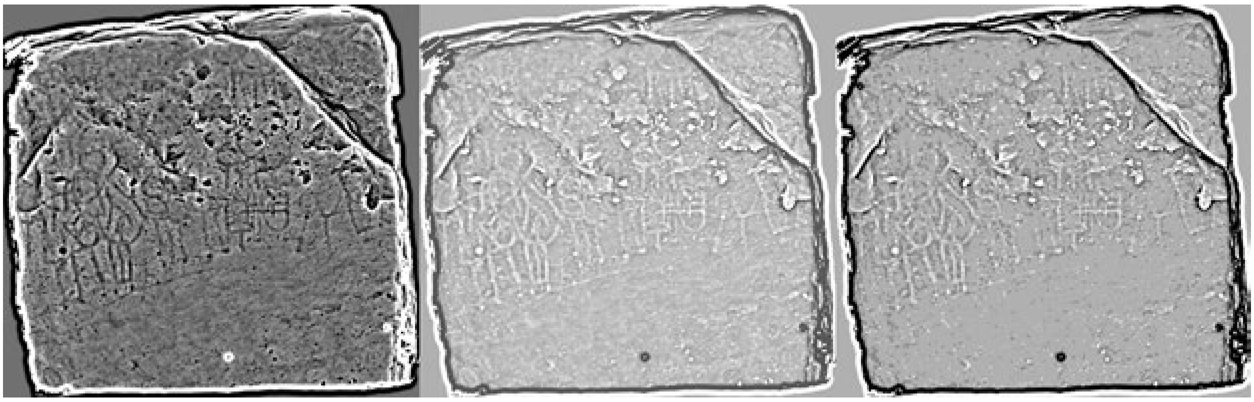


Fig. 8. Three different colourizations of a difference image displaying Züschen slab b2. Left: original in grey-scale; centre: continues [continuous?] grey-scale ramp; right: five grey-scale steps (graphics: T. Reich).

to slab b2's difference map already highlights the petroglyphs (Fig. 8; Cassen *et al*. 2014: 130–31).

An edge detection filter, the so-called Sobel Filter (Duda and Hart 1973), which works on any grey scale or colour image and particularly for the difference image, has been implemented to highlight contours automatically. This filter is a widespread functionality in computer graphics and machine vision (Jain, Kasturi and Schunck 1995). It is called a 'differential operator' as it visualizes changes of grey-scale-/RGB values characterizing edges. To change the clarity of the edges the user may change the range of displayed filtered values. Due to the overall topology of the porthole slab and slab b2 together with the only slightly engraved petroglyphs, this functionality is not as useful for analysis as desired, but for other cultural heritage objects it proved to be powerful (Schmidt, Boochs and Schütze 2010; Schmidt, Schütze and Boochs 2011).

5.4.2 Mapping functionalities

Vector-based mapping was implemented in a similar way to Inkscape and Adobe Illustrator, allowing the archaeologist to draw contours representing his/her interpretation results. For communication and data exchange with other experts, the mapping needs to provide possibilities to distinguish and collate drawings and parts thereof. Through customisable colour and line style the mapping layers can be organized and distinguished, for example, allowing mapping similar petroglyph types on one layer. Since not all petroglyphs can be represented with one continuous polyline, a method for collating parts of the mapping to one item is necessary. Therefore, the mapping is object-based, meaning that the user maps an 'object' which may consist of one or more polylines. It is up to the user to decide which collection of lines constitutes an object. It is also more intuitive to map one petroglyph that the user considers to be one object instead of mapping disconnected lines and grouping them together afterwards, as most vector-based drawing programmes do. For every object metadata may be stored. This metadata may contain textual or date information about the object itself or the interpretation of the user. Up to now the following data fields have been implemented in the metadata structure:

- Author – name of cultural heritage expert
- Creation Date – date of mapping
- Remarks – descriptive remarks
- Type – the cultural heritage expert can add types such as bovine or herringbone pattern individually
- Sub-type – the cultural heritage expert can add sub-types if necessary

5.4.3 Layer combination functionality

The images plus the visualization functions and the mapping are organized in layers. While the mapping layers are fixed, the visualization layers may be changed in order. All layers have an adjustable transparency (alpha channel). With the changeable order and alpha channel settings, visualizations and images can be arranged and mixed to find combinations that complement each other (see discussion below for the advantages).

The arrangement of layers, chosen visualizations, and their parameters as well as the results and settings of the mapping can be stored and restored in file. This not only allows the exchange of visualisation configurations among experts but also the interpretation that was accomplished by the mapping. Even without the visualization functions and the mapping, just having a simple way to arrange and mix different images helps the interpretation (Fig. 9).

6 Discussion

By presenting only a porthole slab of 1.3 m in height and 1.8 m in width, we focus especially on a cluster of decorations overlapping each other in the upper right corner: two bovines with a cart are depicted twice with a herringbone pattern in-between (Fig. 10). For a detailed description see Loerper, Jockenhövel and Dirksen (2008: 3). This decoration cluster was discovered by L. Loerper who analysed only a raster-based DEM calculated from the 3D dataset generated by Dirksen *et al.* (2008) in 2005. Each pixel displayed the elevation values in an individually chosen colour ramp. Displaying a DEM layer on top of a Phong shading layer within SIVT, which enables changing the light direction interactively, it is possible without any problem to retrace the conclusions of Loerper, Jockenhövel

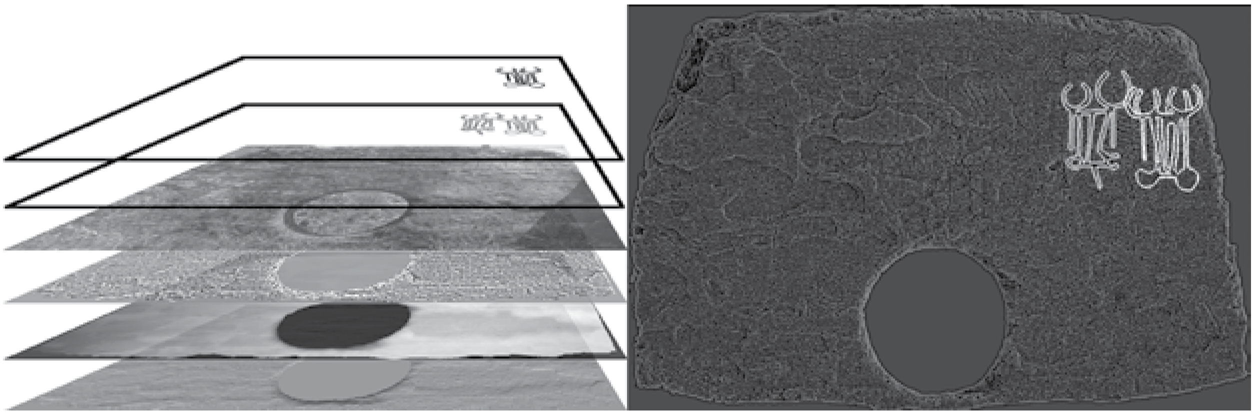


Fig. 9. Combination of four visualization layers and two mapping layers. Left: top mapping layers, bottom visualization layers. Right: combined visualization in SIVT (graphics: B. Tietz).

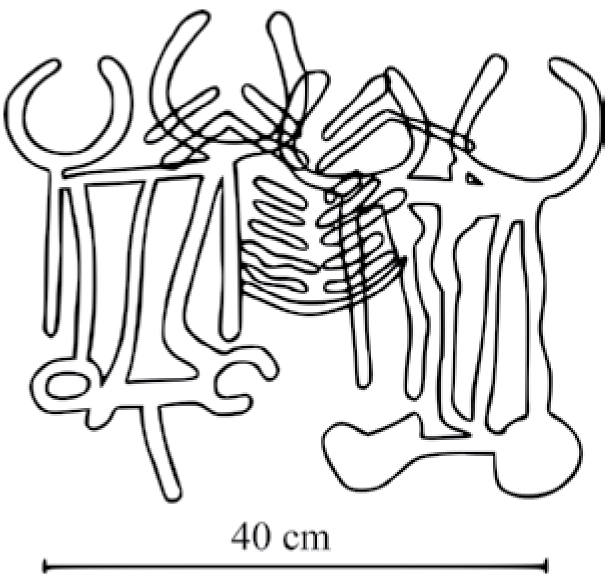


Fig. 10. Decorations in the upper right corner of the porthole slab (t) of Züschen I mapped by L. Loerper in 2005 (Loerper, Jockenhövel and Dirksen 2008: fig. 3).

and Dirksen (2008: 3). Furthermore, by displaying a difference map layer with 80% transparency and colour map function on top of a Phong shading layer it is possible to complete the left of the three vertical lines in-between the bovines. Now both horizontal lines are connected: the first one, which is interpreted as a drawbar connecting the two forked signs at the top, and the second one which connects the so-called cup marks interpreted as wheels (Fig. 11).

Additionally, with the same layer combinations and settings it is possible to point out further possible anthropogenic lines, allowing an additional interpretation of both forked signs (Fig. 11). The forked signs would be less wide, which would be of special interest as the bovine motifs would no longer overlap the right forked sign of the left bovine and cart motif. Based on this, a temporal sequence of the creation of this decoration cluster is hypothesized: on the one hand, the newly discovered forked signs could indicate further motifs superimposed on each other, on the other, it is possible that the bovines of the right cart motif were adapted when the second bovine and cart motif was engraved. These hypotheses need further evidence through additional analysis, for example by comparing profile sequences from the superimposed engravings. Varying depths of the engravings might give further evidence for a relative chronology of the creation of the decoration cluster (Dirksen *et al*. 2008: 14; Moitinho 2013: 159–67).

Using the case study of the porthole slab decorations of Züschen I, the power of a combined layer analysis is demonstrated. Using 2.5D data as the basis for various visualizations with interactive functionalities and in combination with photos, the readability of the strongly weathered petroglyphs could be enhanced enabling to complete the bovine and cart motif discovered in 2005. It is to be expected that further analysis of the entire porthole slab and the other slabs using SIVT will bring forward other decorations, allowing a new interpretation and understanding of this major Neolithic site of European importance.

7 Conclusion and future work

Better usability of SIVT to gain more acceptance within the cultural heritage expert community is prioritized in the future development roadmap of the software: flexible layer management for the mapping functionality, automated calculation of parameter settings for visualization functions, and the adoption of a contemporary look and feel fall under the banner of improved usability. Besides these, further functionalities could be added, and existing ones such as the export function could be enhanced. For instance, if the datasets analysed within SIVT are referenced in the same way as the dataset of the entire site, an export (e.g. in .dxf) of the mapped interpretations for usage in global context analyses is possible. This would enable a usage of these data in 3D-processing software and support further archaeological research addressing the visibility of the petroglyphs or spatial analysis of specific petroglyphs in the context of the entire site. As mentioned above, particularly with regard to the analysis of relative chronological aspects, a functionality creating individual profiles would be useful.

Besides the above described petroglyph case study, the analysis of a variety of 3D datasets can be enhanced using the

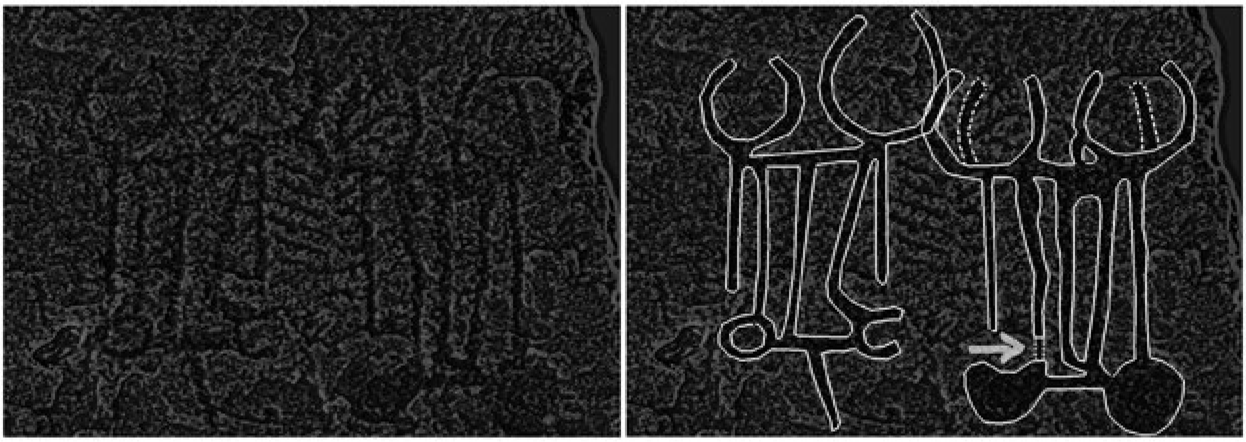


Fig. 11. Decorations in the upper right corner of porthole slab (t) of Züschen I. Left: visualization within SIVT: difference map layer with 80% transparency and colour map function on top of a Phong shading layer. Right: mapped interpretations by L. Loerper 2005 (white continuous line) with completed decoration (grey dotted lines) and with the additional forked sign (white dashed lines) (graphics: T. Reich).

developed SIVT. Cultural heritage objects with suitable spatial characteristics include inscriptions and also small finds such as coins and phalera; sites such as excavations or even complete landscapes are adequate for display and analysis within SIVT.

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Bibliography

3d-Pitoti 2015. *3D-Pitoti – 3D acquisition, processing and presentation of prehistoric European rock-art.* [On-line] Available from: http://3d-pitoti.eu/ [Accessed: 24 June 2015].

Abbott, M. and Anderson-Whymark, H. 2012. Stonehenge Laser Scan: Archaeological Analysis Report. *Research report series* 32. Portsmouth, English Heritage.

Adobe (2015) *Acrobat Help/Adding 3D models to PDFs (Acrobat Pro DC)*. [on-line] Available from: https://helpx.adobe.com/acrobat/using/adding-3d-models-pdfs-acrobat.html#3d_properties_acrobat_pro [Accessed: 30 June 2015].

Arcá, A. 2007. Valcamonica, Dos Cüi, le fasi neolitiche e calcolitiche: cronologia, temi e interpretazioni. In S. Casinin and A. E. Fossati (eds.), *Le Pietre degli Dei. Statue-stele dell'Età del Rame in Europa. Lo stato della ricerca. Atti Congresso Internazionale, Brescia, 16-18 settembre 2004*. Notizie Archeologiche Bergomensi 12, 2004: 279-99. Bergamo, Museo.

Arcá, A. and Fossati, A. 2006. Rupestrian Archaeology. A methodological approach to the rock engravings of Valcamonica. In L. Oosterbeek (ed.), *EuroPreArt II. Prehistoric art research and management in Europe – case studies*. Archeologia storia cultura 4: 51-8. Bari, Edipuglia.

Barmpoutis, A., Bozia, B., Wagman, R. 2010. A novel framework for 3D reconstruction and analysis of ancient inscriptions. *Journal of Maschine Vision and Application* 21: 989-98.

Bies, M. 2015. *Untersuchungen am Galeriengrab in Fritzlar-Lohne mittels Streifenlichtprojektion und Vergleich zu einer Erstmessung von 2005.* Unpublished thesis, Hochschule Mainz, University of Applied Sciences Mainz.

Boehlau, J., Von Gilsa, F. 1898. Neolithische Denkmäler aus Hessen. *Zeitschrift des Vereins für hessische Geschichte und Landeskunde NF*, suppl. 12. Kassel, Verein für Hessische Geschichte und Landeskunde.

Böhler *et al*. 2004. High Quality Scanning and Modelling of Monuments and Artifacts. In *The Olympic Spirit in Surveying. Conference Proceedings of the FIG Working Week 2004. Athens, Greece, 22-27 May 2004*: 1-17. Available from: http://www.Fig.net/resources/proceedings/fig_proceedings/athens/papers/wsa2/WSA2_2_Bohler_et_al.pdf. [Accessed: 25 June 2015].

Boochs, F. *et al*. 2006. Digital Documentation of Cultural Heritage Objects using hyprid recording techniques. In M. Ioannides, D. Arnold, F. Niccolucci, K. Mania (eds.), *The e-volution of information communication technology in cultural heritage: where hi-tech touches the past. Risks and challenges for the 21st century. Joint event CIPA, VAST, EG, EuroMed 2006. Nicosia, Cyprus, 30. October-4 November 2006*. Budapest, Archaeolingua.

Bozia, E., Barmpoutis, A., Wagman, R. S. 2014. Open Access Epigraphy: Electronic Dissemination of 3D-digitized Archaeological Material. In S. Orlandi, R. Santucci, V. Casarosa, P. M. Liuzzo (eds.), *Information Technologies for Epigraphy and Cultural Heritage. Proceedings of the First EAGLE International Conference. Collana Convegni Studi umanistici, Antichistica 26. Paris, France, 29-30 September – 1 October*: 421-435. Rome, Sapienza Università Editrice.

Brecht, B. M., Kessler, B. 2010. *Entwicklung von Verfahren zur automatischen Detektion und strukturellen Analyse von chinesischen Schriftzeichen*. Unpublished master thesis, Fachhochschule, University of Applied Sciences Mainz.

Canvas 2014. Yale Digital Collections Center. Mirador RTI Viewer Demonstration. [Online] Available from: http://ydc2.yale.edu/news/2014/04/25/mirador-rti-viewer-demonstration. [Accessed: 26 June 2015].

Canvas 2015. *Yale Digital Collections Center. Canvas Viewer/Mirador*. [Online] Available from: http://ydc2.yale.edu/canvas-viewermirador. [Accessed: 26 June 2015].

Cassen, S. *et al*. 2014. Complementarity of acquisition techniques for the documentation of Neolithic engravings: lasergrammetric and photographic recording in Gavrinis passage tomb (Brittany, France). *Journal of Archaeological Science* 45: 126-40.

Corripio, J. C. 2003. Vectorial algebra algorithms for calculating terrain parameters from DEMs and solar radiation modelling in mountainous terrain. *International Journal of Geographical Information Science* 17, 1: 1-23.

Duda, R. O. and Hart, P. E. 1973. *Pattern Classification and Scene Analysis*. New York, John Wiley and Sons.

Dirksen, D. *et al*. 2008. Dokumentation des spätneolithischen Galeriegrabes Fritzlar-Lohne „Züschen I' mit Verfahren der optischen 3D-Koordinatenmesstechnik. In F. Verse, B. Knoche, J. Graefe, M. Hohlbein, K. Schierhold, C. Siemann, M. Uckelmann, G. Woltermann (eds.), *Durch die Zeiten… Festschrift für Albrecht Jockenhövel zum 65. Geburtstag. Internationale Archäologie, Studia honoraria* 28: 3-14. Rahden/Westf., VML Verlag Marie Leidorf.

Domingo, I. *et al*. 2013. Latest developments in rock art recording: towards an integral documentation of Levantine rock art sites combining 2D and 3D recording techniques. *Journal of Archaeological Science* 40: 1879-89.

Frohberg, U. 2008. Die Anfertigung einer Kopie des großen Ludovisischen Schlachtensarkophags. *Restaurierung und Archäologie* 1: 69-87.

Green, M. 2001. The Science of Conspicuity. *Brand Packaging* Nov/Dec 2001: 38-42.

Green, M. 2002. Inattentional Blindness. *OHS Canada: occupational health and safety Canada* Jan/Feb 2002: 23-9.

Heinz, G. 2010. Kopien berührungslos erstellen – virtuell und zum Anfassen. *Restaurierung und Archäologie* 3: 137-50.

Jain, R., Kasturi, R., Schunck, B. G. 1995. *Machine Vision. McGraw-Hill Series in Computer Science*. New York: McGraw-Hill, Inc. Available from: http://www.cse.usf.edu/~r1k/MachineVisionBook/MachineVision.htm. [Accessed: 25 June 2015]

Krämer, C., Reich, T. 2011. *Optimierung archäologischer Prozessketten unter Einsatz geodätischer Mess- und Auswertemethoden*. Unpuplished master thesis, Fachhochschule, University of Applied Sciences Mainz.

Loerper, L., Jockenhövel, A., Dirksen, D. 2008. Re-inspection of the Megalithic Art of the Gallery-Grave at Züschen/Lohne, Germany, with Optical 3D Measurement Techniques. In A. Posluschny, K. Lambers, I. Herzog, I. (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, 2–6 April 2007. Kolloquien zur Vor- und Frühgeschichte* 10: 1-5. Bonn, Habelt.

Luhmann, T. 2003. *Nahbereichsphotogrammetrie: Grundlagen, Methoden und Anwendungen.* Heidelberg, Herbert Wichmann Verlag.

Marstrander, S. 1983. Introduction to Section 3: Rock art and religion. In A. Beltran, J. Clegg, C. Colzani, P. Hill, J. Innamorati, M. Singer (eds.), *The Intellectual Expressions of Prehistoric Man: Art and Religion. Valcamonica, Italy, 28 July-3 August 1979. Acts of the Valcamonica Symposium '79*: 319-20. Capo di Ponte, Centro Camuno di Studi Preistorici.

Meshlab 2014. [On-line] Available from: http://meshlab.sourceforge.net/ [Accessed: 30 June 2015].

Minidome 2014. [Online] Available from: http://www.minidome.be/v01/home.php. [Accessed: 26 June 2015].

Moitinho, V. 2013. *Towards Functional Analysis of Archaeological Objects through Reverse Engineering processes*. Unpublished thesis, Universitat Autònoma de Barcelona. Facultat de Filosofia I Lletres. Departament de Prehistòria.

Phong, B. T. 1975. Illumination for Computer Generated Pictures. *Communications of the ACM* 18, 6: 311–7.

Pietroni, N. *et al*. 2011. An Interactive Local Flattening Operator to Support Digital Investigations on Artwork Surfaces. *IEEE Transactions on Visualization and Computer Graphics* 17, 12: 1989-96.

Raetsel-Fabian, D. 2001. Der nordwestliche Nachbar: Neue Aspekte zur Wartbergkultur. In T. H. Gohlisch and L. Reisch (eds.), *Die Stellung der endneolitischen Chamer Kultur in ihrem räumlichen und zeitlichen Kontext. Erlangen 26-28 march 1999. Kolloquien des Institutes für Ur- und Frühgeschichte Erlangen* 1: 107-19. Büchenbach, Verlag Dr. Faustus.

Robson, K. A. *et al*. 2001. An Automated Laser Scan Survey of the Upper Palaeolithic Rock Shelter of Cap Blanc. *Journal of Archaeological Science* 28, 3: 283-9.

Rti 2015. *Reflectance Transformation Imaging (RTI)*. [Online] Available from: http://vcg.isti.cnr.it/rti/index.php. [Accessed: 26 June 2015].

Schierhold, K. 2012. *Studien zur hessisch-westfälischen Megalithik. Forschungsstand und -perspektiven im europäischen Kontext. Münstersche Beiträge zur Ur- und Frühgeschichtlichen Archäologie* 6. Rahden/Westf., VML Verlag Marie Leidorf.

Schmidt, N., Boochs, F., Schütze, R. 2010. Capture and Processing of High Resolution 3D-Data of Sutra Inscriptions in China. In M. Ioannides, D. Fellner, A. Georgopoulos, D. G. Hadjimitsis (eds.), *Digital Heritage. Proceedings of the Third International Conference EuroMed 2010. Lemessos, Cyprus, 8-13 November 2010*: 125-39. Berlin, Springer.

Schmidt, N., Schütze, R., Boochs, F. 2011. 3D-Sutra – Interactive Analysis Tool for a Web Atlas of Scanned Sutra Inscriptions in China. *The Photogrammetric Record* 26 (136/December): 488-505.

Shee Twohig, E. 1981. *The Megalithic Art of Western Europe*. Oxford, Clarendon Press.

Yan, Z. 2015. *Odyssey of Culture. Wenda Gu and His Art*. Berlin, Springer.

Digital Practices for the Study of the Great Rock in the Naquane National Park, Valcamonica, Italy: from Graphic Rendering to Figure Cataloguing

Andrea Arcà
aarca@rupestre.net
University of Pisa University, Dottorato in Scienze dell'Antichità e Archeologia;
IIPP - Italian Institute of Prehistory and Protohistory

Abstract: If we intend rock art studies to be an archaeological science, the greatest possible accuracy should be obtained. In order to do so, computer programs are indispensable; considering the needs of the graphic and analytic workflows, a large set of electronic instruments should be intended as a fundamental toolbox for the careful and up-to-date rock art archaeologist. On the graphic side, the need to obtain a detailed rendering of tracings may greatly benefit from vector drawing software. On the analytical side, the necessity of managing figure classification and relations may lead to the compilation of specific software. This is the case of the study — undertaken by the author — of the Great Rock of Naquane in Valcamonica (Italy). Dedicated software was compiled and from this rankings, statistics, and a catalogue were produced in a few seconds in html format, ready to be published online or printed.

Keywords: Rock art, Valcamonica, Vector tracing, Database, Naquane

Introduction and methodological concerns

If we apply the same rules of archaeological science to rock art documentation, as we should do, including it as 'rupestrian archaeology' (Fossati *et al*. 1990), the study of figured rocks acquires the status of an archaeological excavation: a carved or painted rock panel corresponds to a site, its figures — which are 'real', although non-material, iconic objects — take the role of a collection of archaeological finds and the engraving phases equate to an archaeological stratigraphy. To 'dig out' such iconographic finds and layers, we need to 'extract' all finds, that is, figures, identifying and reproducing them graphically. Moreover, there is the need to 'unearth' the related superimpositions, if any exist and are readable, identifying, rendering, and enlightening them with an appropriate and effective symbolization. In this way, the establishment of an iconic stratigraphy is the key to obtaining the most detailed and correct relative chronological sequence; on the other hand, the comparison of iconic items and real dated objects, if feasible, is the way to establish an absolute chronology. With regard to engraved figures, we may specify that archaeometric measures are not practicable, at least not in the alpine environment;[1] contrary to paintings, during the carving the engraved matter, which might be suitable for quantitative measures and for sampling and radiometric dating, has been removed, not added.

To perform these archaeo-rupestrian tasks, a careful and in-depth recording is required. As with any other scientific archaeological documentation, it should be performed with the greatest possible accuracy. Regarding rock art studies, the long-lasting documentation experience (Anati 1966; 1974; Fossati *et al*. 1990) confirms that a quick and singular autoptic examination is not sufficient to identify figures and superimpositions — a great amount of time is almost always required to identify what is depicted in detail — and photographic recording (both 2D and 3D), although fundamental, may not guarantee clear reproductions, particularly if many figures are bundled together and/or the rock surface is worn out (Loendorf 2001: 65). There is the strong need to enhance contrast, extracting and abstracting figures from their bedrock and from nearby items if a scene is not involved. Above all, we need to reproduce the results by the most exact available and suitable graphic rendering (Fig. 1), appropriately symbolized by the means of flat projection, the selection of relevant traits, complexity reduction, design and visual effectiveness ready for communication and publication. All these characteristics make the production of this archaeological drawing somewhat analogous to the creation of cartographic maps, which are traced and drawn, rather than a simple reproduction of zenith photos. According to these premises, an archaeo-iconographic tracing and its rendering[2] (Fossati and Arcà 2001; Arcà and Fossati 2006) constitute the indispensable base for any further chrono-interpretative study (Anati 1975), data sharing, and knowledge diffusion (Arcà *et al*. 2008).

Some questions arise for surface-contact and objectivity concerns. Contact tracing (Fig. 2) is sometimes questioned, exposing worries about possible damage to rock surfaces and figures. This is surely not a problem where petroglyphs and strong rocks, which are hard and do not crumble, are concerned, provided that permission is granted by the authority in charge. Contact with the original item is largely preferable, being more detailed and assuring the achievement of a greater amount of visual, tactile, and material data. The problem of objectivity is more complex: tracings are often considered to be unreliable and not based on objective data. Regarding this

1 The micro-erosion dating technique, developed by R. Bedanrik and based on the analysis of quartz crystals, was tested in the alpine environment on the Rupe Magna of Grosio (Bednarik 2001). This technique, which has already obtained controversial results in Portugal for the Côa valley Palaeolithic engravings, has not been proposed again nor developed in the alpine area.

2 Methodological considerations and recent technical updating are treated in Maretta 2014 and Marretta *et al.* 2013.

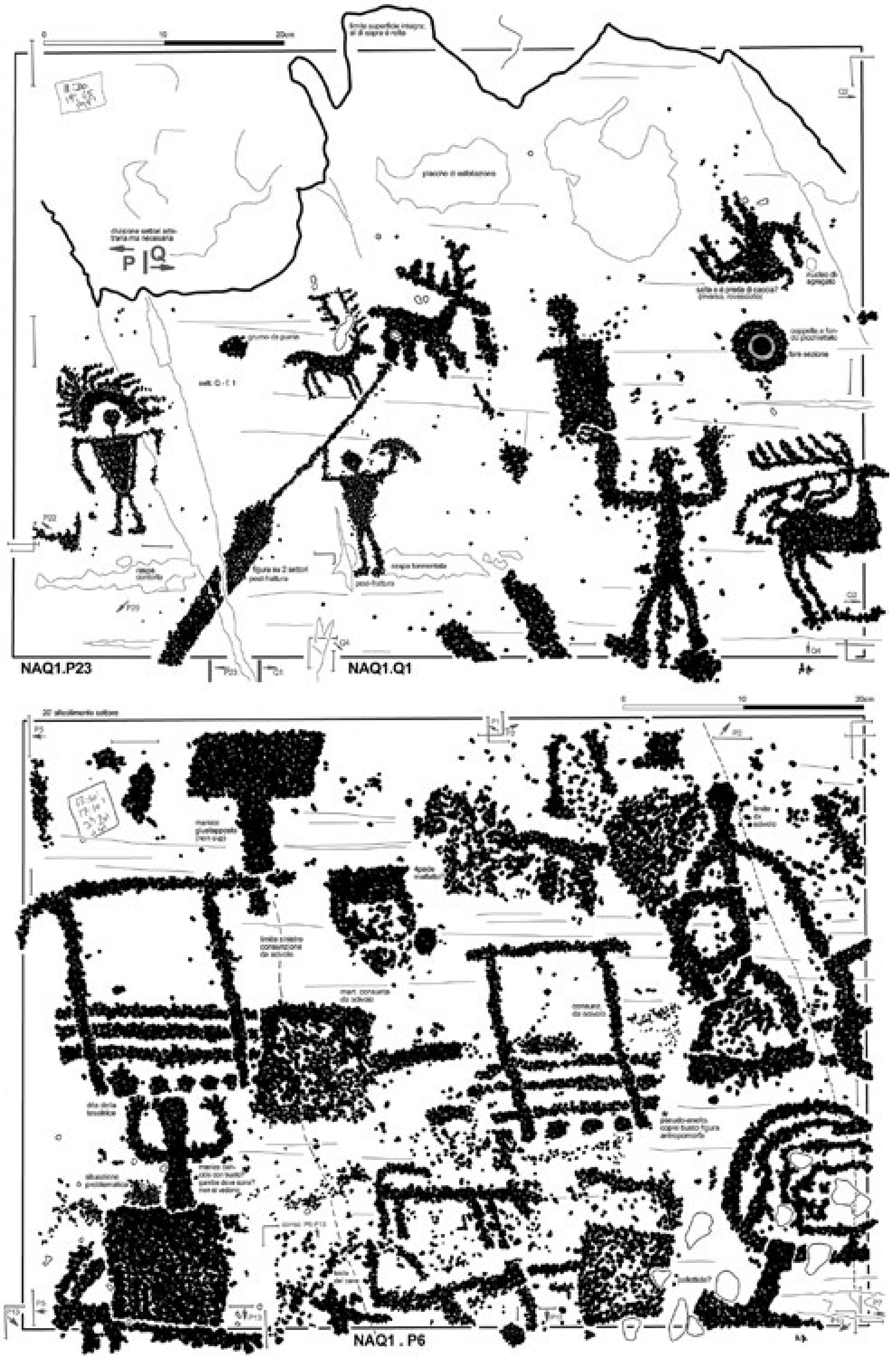

Fig. 1. Contact tracing of the Great Rock of Naquane National Park, Valcamonica; sector P, sheets 23 and 6, fair copy of the raster version (tracing AA).

point, the problem is not related to this specific technique — any technique, manual or digital, even automatic, must comply at some point with human choices — but to the competence and experience of the tracing operator. So we may wonder, while performing this task, if an objective automatic scanner or an auto-recognizing software may (or will) go further than an accurate and experienced archaeologist; or, on the other hand, if and to what extent software tools may facilitate the experience of the archaeologist and improve his/her results. Nevertheless, it should be emphasized that the task of tracing figures and superimpositions is subject to unavoidable human choices in varying degrees; although as objective as possible,

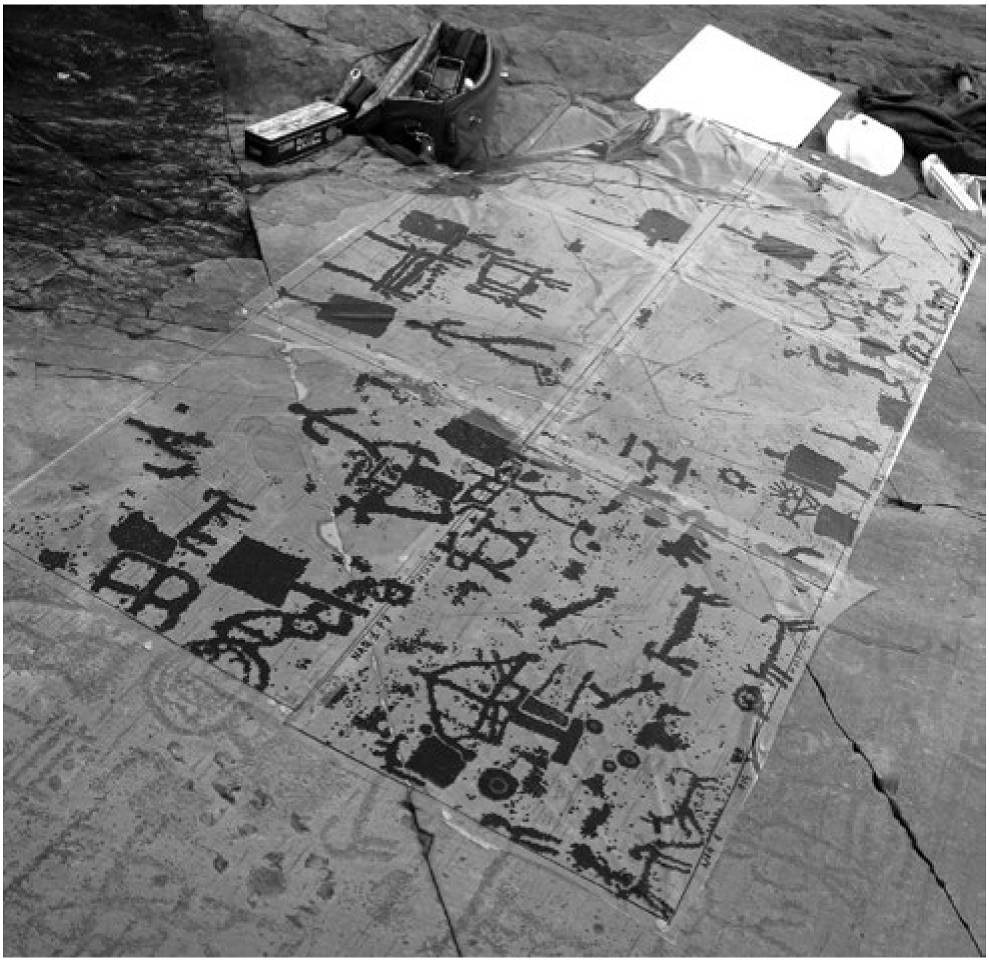

Fig. 2. A moment from the contact tracing of the Great Rock of Naquane National Park, six sheets out of a total of 221, sector P (photo AA).

it takes the nature of an interpretive operation and its results are enriched not only by graphic elements, but also by ideas and solutions.

The third question is related to the third dimension. 3D models, obtained by various methods such as stereo-photogrammetry, laser-scanning, or 3D photo-stitching and modelling, are gaining and will gain more and more importance in rock-art recording. Their capability of avoiding contact and their objectivity are often flaunted as advantageous features. The two questions have already been treated above; the suggested solution would be to search for the appropriate development and reinforcement of such technical 'experiments', avoiding any specious devaluation of traditional and well-grounded methods, if still effective. The core of the problem is obviously the third dimension, that is, the recording of the z-axis, the axis of depth. While inconsistent for paintings, although obtaining the volumetric shaping of a painted rock wall is useful for conservation and exhibition purposes (Scott 2015) and sometimes also relevant for its meaning, it is clearly beneficial for engravings. That said, a distinction should be made between pecked figures and deeper ones such as cup-marks or basins. While a 3D recording of cup-marks and grooves is surely a good choice, the use of these techniques for shallow pecked figures may result in misleading and somewhat oversized recordings. First of all, it should be mentioned that such figures were intended and created by their makers as a series of combined dots. The same goes for their reproduction: the iconic item is the figure made by the texture of its points and by the resulting inner and outer contours. Both may be usefully recorded using a 2D contact tracing, where the point of a felt pen is driven by the eye of the tracer, facilitated by a multi-oriented grazing light over the engraved surface and by the tracer's fingers, by feeling the presence of the pecked shallow dots on the rock through hand pressure, going 'in' and 'after' them. All this supports the points cited above, mainly that symbolization and complexity reduction for the final rendering, which is meant to show the iconic content, are better and more effectively performed by a 2D tracing than by a 3D model, not to mention the cases in which a manual sketch is performed on the monitor over a 3D model, clearly demonstrating the different purposes of the two systems. Clearly, the best choice would be a combination of the two, exactly like using photos to texture cloud points, in other words, simply merging a 2D tracing layer over a textured 3D model of the whole rock surface, as was recently done for the Chenal shelter in the Aosta Valley (Arcà *et al*. 2014). Although 25 years have passed since the first experiments of stereo-photogrammetry were precisely applied to the Great Rock of Naquane, it may be argued that, from the archaeological and iconographic point of view, no

Fig. 3. The richly engraved surface of the Great Rock of Naquane, a monument of the Iron Age and Bronze Age Valcamonica rock art, spectacularly smoothed and shaped by the last glacier; best results achieved with the oblique winter light (photo AA).

publication about alpine engraved rocks with pecked figures (Valcamonica, Mt. Bego, and other areas) has ever gained and shown clearer and more defined iconic data from a 3D model than from a 2D-rendered tracing until now (Arcà *et al.* 2008: 13). 3D modelling, therefore, should be tested for small areas and should attempt to gain more definition, particularly for studying superimpositions where a different depth may show up a more ancient or recent figure and where 3D modelling may enhance such a difference and thereby be useful in reaching the aimed contrast. Another point to be considered is the recording of the conservation status: although a 2D recording is fully effective for the documentation of the various conditions of degradation, displaying their extension along the surface, a 3D model can record better the possible movement or detachment of small rock fragments or clasts.

1 NAQ1, the Great Rock of the Naquane Park

As indicated by its title, the scope of this paper is to present the methods — largely based on contact tracing and its graphic rendering — utilized for the documentation of the Great Rock, also known as Rock 1 (NAQ1; Fig. 3), of the Naquane National Park of Rock Engravings in Valcamonica (I), mainly focusing on software and digital involvement. The description of this archaeological monument shall be limited to stating that NAQ1, 50 m long and 4 m large, is one of the most important prehistoric figurative palimpsest of Valcamonica (De Marinis 1988; Fossati 1991) and of the entire alpine range. On its regular and smoothed rock surface more than 2000 prehistoric figures are stored, written, and archived on a Permian sandstone[3] surface, covering more than a 5 millennia-long chronological frame (from the first Copper Age to 1942). The largest numbers were carved during the final Bronze Age and the first Iron Age (10th–6th cent. BC; Fig. 4). Similar to all the Valcamonica (and Mt. Bego) rock art, figures were engraved by repeatedly hitting the surface with stone tools, most likely sharp quartz

Fig. 4. A dense and very interesting part of sector G of the Great Rock: Bronze Age human figures overlapped by an Iron Age hunting scene (photo AA).

[3] Its petrographic nature — a very finely grained sandstone, pelite tending to siltite, bound by a silica cement — along with the glacial smoothing of its surface, was crucial to enable such easy and dense engraving activity. The same observation is to be extended to the entire Valcamonica and Mt. Bego rock art — in the petroglyphic complex of the Maritime Alps very similar petrographic conditions are present — where by far the largest concentration of alpine engraved signs is present.

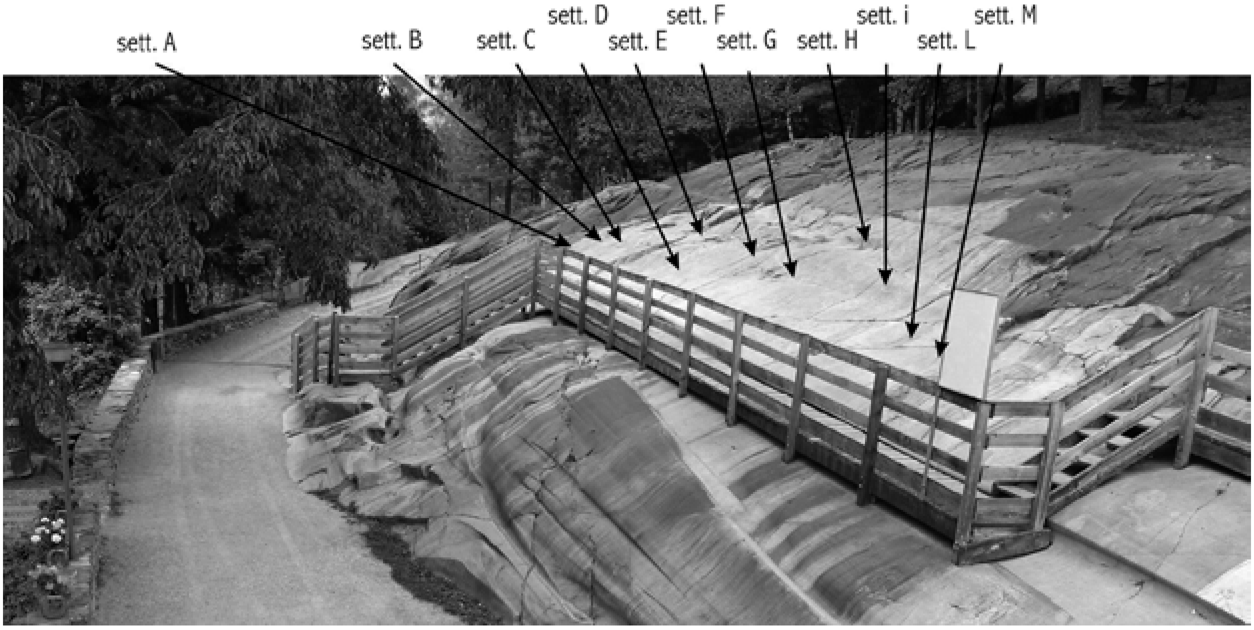

Fig. 5. Great Rock (NAQ1) of Naquane, subdivision in sectors (A–M) of the north part, roughly half of the entire surface (photo AA, reworked).

pebbles, which produced a series of dots, a technique defined as 'pecking'. Among the most important iconic items we only briefly cite here the so-called praying figures, dogs, looms (unique exemplars in the alpine rock art), towels, deer, warriors with important details such as spears, swords, shields, and plumed helmets, hunting scenes, duellists, and footprints.

Similar to many others large engraved rocks of the alps, such as the Rupe Magna in Valtellina (Pace 1972; Arcà *et al*. 1995) — and unlike the Mt. Bego pecked panels, which were apparent — the NAQ1 figures were originally partially hidden under a light layer of lichen and moss. Its discovery, which occurred in the first months of 1932 (at the same time as the disclosure of the larger extent of the Valcamonica rock art) is claimed by two scholars: the archaeologist Raffello Battaglia — helped by his assistant of the archaeological superintendence Antonio Nicolussi and by a local informer Giacomo Bellicini — and the Piedmontese anthropologist and psychiatrist Giovanni Marro, with his local informer Giuseppe Amaracco. Raffaello Battaglia was the first to propose a well-founded archaeological hypothesis (Battaglia 1933), while Giovanni Marro noticed the absence of a unique frame of semantic relations and the presence of superimpositions (Marro 1932).

The only complete study of the Great Rock of Naquane was published by Emmanuel Anati in 1960; thanks to the introduction of the analysis of different chronological layers, it showed a tracing executed in August 1957 over translucent wax paper — fully transparent plastic sheets were not available at the time and figure definition was quite simplified and some perspective distortion is noticeable (Anati 1960). Although the study seems to demonstrate that the published drawing was taken from photographs and not from a scale reduction of the original contact sheets; 876 figures were counted. From 1957 to the present, no updated tracing or a more detailed specific study or monograph has been published.

2 NAQ1, the digital graphic operational chain

A new contact tracing of NAQ1, performed by the author for his PhD research project at Pisa University,[4] was completed by producing 221 plastic sheets of 70 x 50 cm standard measure — along with five minor supplements and 34 connection strips — covering 65 m^2 of engraved surface, subdivided into 21 sectors (Fig. 5). It took 50 inconsecutive days of on-site activity and about 150 days of graphic digital post-processing. As far as digital and software-related features are concerned, two main focus points may be outlined: graphics for the surface's rendering and data analysis for its study. Inexpensive and easily obtainable digital tools were chosen, procured, or even specifically built as a convenience for rock art research, which rarely obtains sufficient, if any, funding — the new NAQ1 study itself has not been funded so far.

Being a multi-phase and multi-tool procedure, digital graphic post-processing may be described as an operational chain. First of all, if large scanning machines (for paper sizes A3 to A0) are not available, original plastic sheets are optically reduced to 50% grey-scale, as colour photocopying is of no use, to fit the size of an A3 paper sheet. A 600 DPI B/W scan is then performed, equivalent to a 300 DPI scan of the unreduced sheet, thereby assuring that quality is not lost. Colours — during the manual contact tracing only red and blue are used, red for rock fractures and blue for collimation marks — are reinserted in the final rendering, as well as different grey or colour layers to symbolize chronological or typological differences. It should be specified that figures were originally traced only in black

[4] At the request of the IIPP (Italian Institute of Prehistory and Protohistory) the study was approved and authorized by the Lombardy Archaeological Superintendence. I gratefully acknowledge Prof. Raffaele De Marinis, Dr Umberto Spigo, Dr Filippo Maria Gambari, Prof. Renata Grifoni, and Prof. Fabio Martini (Milan, Pisa, and Florence Universities, Lombardy Archaeological Superintendence).

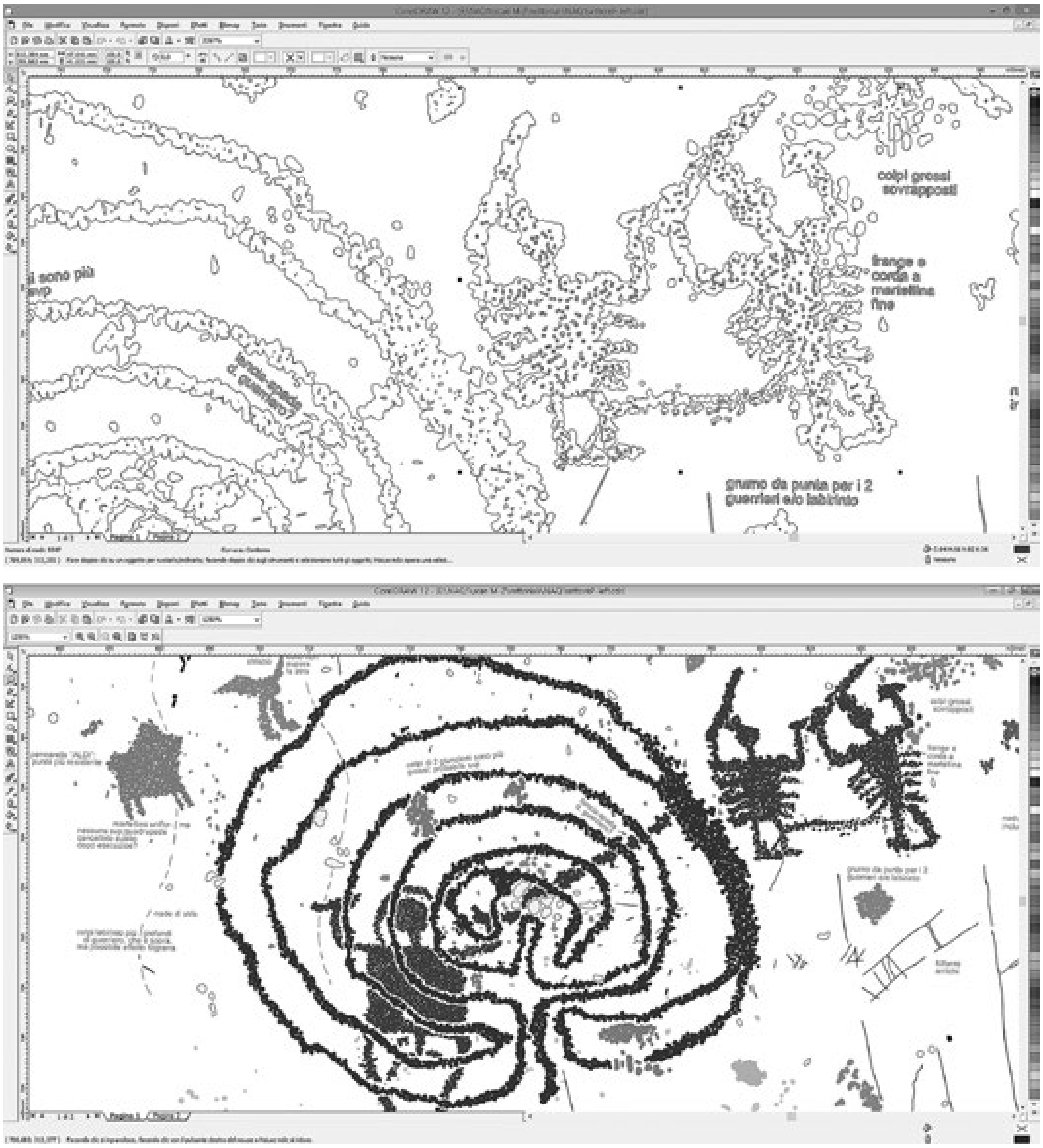

Fig. 6. Phases of the final rendering (vector version) of the NAQ1 contact tracing: inner and outer contours (above) and fake colours (below); to give an idea, the figures of the two warriors duelling with their swords are composed of 5547 curve nodes (graphics AA).

to avoid confusion between phases and problems for the digitalizing process. A great amount of time, more than for the on-site activity, is needed to clean the scans digitally in order to obtain a fair raster copy produced sheet by sheet; these raster files are judged to be indispensable for conservation purposes, as in the computing future it will probably be easier to read pixel-based files than other formats such as vectors. To perform this cleaning task dirty spots are erased, hand-notes rewritten, frames and lines retraced, and figures separated; line retracing and figure detachment is essential to facilitate the subsequent steps of eliminating the occurrences of broken lines and improperly pasted objects. Thereafter, digital sheets for each engraved sector are merged as multiples layers, using the collimation marks to move and rotate them conveniently. Collimation marks and sheet frames are then deleted, thus obtaining a final draft, which is still in raster format with an image described by a dot matrix. Depending on the extension of the reproduced surface, the final raster file is very heavy and awkward to manage, especially if we want to maintain lossless quality. To cite an example, the raster merging of sector P of the Great Rock of Naquane, which, although 50% reduced digital sheets were used, is composed of 30 sheets, exceeding the 36.000 pixel limit and 1 Gb of uncompressed dimension on its largest side. Regarding the software involved, all the steps of this first part are easily performed — depending on CPU and RAM power — by raster photo-editors; since they are very well known worldwide, it is not necessary to cite them here.

The second part of the digitalization process, far shorter and quicker, is devoted to solving the problems related to the weight of raster files and to their lossless rendering. Vector graphics, where images are not described by a dot matrix but by points, lines, and Béziers curves based on mathematical expressions, represent the best and most current choice. They

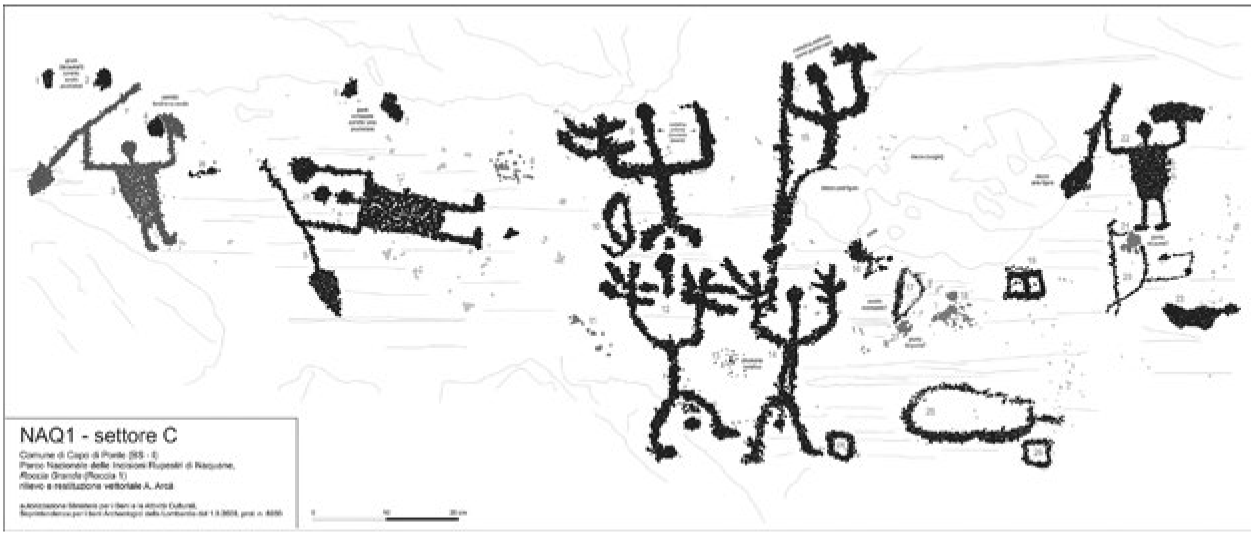

FIG. 7. THE FINAL RENDERING (VECTOR DRAWING) OF THE NAQ1 SECTOR C, 26 BRONZE AND IRON AGE FIGURES; FIELD-NOTES ARE REWRITTEN, FIGURES ARE NUMBERED (TRACING AND GRAPHICS AA).

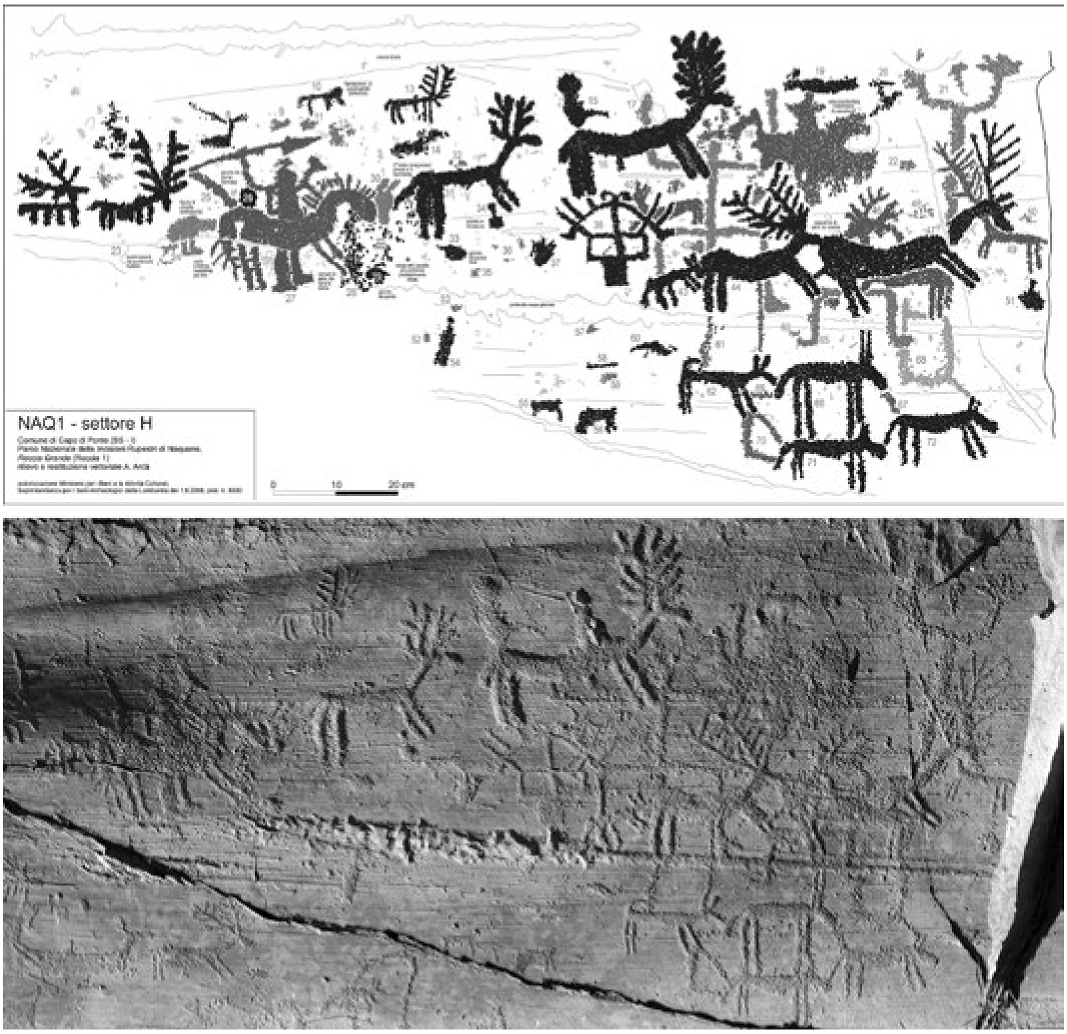

FIG. 8. THE FINAL RENDERING (VECTOR DRAWING, ABOVE) AND A GRAZING LIGHT PHOTOGRAPH (BELOW) OF THE NAQ1 SECTOR H, 72 BRONZE AND IRON AGE FIGURES; GREY-SCALE IS USED TO SHOW THE DIFFERENT SUPERIMPOSITION LEVELS, IN THIS CASE A MAXIMUM OF FOUR (TRACING, GRAPHICS, AND PHOTO AA).

were first applied to rock art tracings by the author in 1992 in the Susa Valley (Arcà 1999; 2000; 2009) and then, in the case of Valcamonica rock art, to the study of the Dos Cùi engraved rock (Arcà 2005). Why vectors? To refer to the case of the NAQ1 tracings, vector rendering (Fig. 6) is essential for reducing file sizes up to 35 times; the sector G of the Great Rock, for example, is reduced from 380 Mb of the raster file to 10 Mb of the vector file. Most importantly, a lossless quality is gained, independently from the size scale, as each figure is a virtual object mathematically described by its outside and inside contour lines, the proportions of which do not vary with its dimensions. The stages of vectorization, provided a clean starting point is available, which is the fair copy cited above, are easily performed by auto-tracing software normally bundled with vector graphics editors, both commercial and freeware. These are illustration-oriented software packages, very useful for producing press-quality final renderings ready for publication or communication: the final outputs of tracings, plates, and tables can be managed in a graphically professional manner. In my opinion, vector graphics editors represent a fundamental tool for archaeologists, mainly for publication functions — for NAQ1, the CorelDraw suite was utilized. The auto-tracing process is performed by the software (CorelTrace) in a few seconds, even for very large tracings; a B/W bitmap file must be provided, as grey-scale or RGB images produce a very large and noisy set of fragmented graphic objects, according to grey or colour levels. In order to avoid the time-consuming necessity of splitting lines, the best choice is to perform a first passage for figures, applying a contour auto-tracing, and a second one for lines, choosing a central line auto-tracing. The vector-based outputs are then merged as different layers in the final rendering. At this point useless parts are deleted, different sections of each figure are joined to produce an individual graphic object, figures are numbered, rock fractures are coloured, and their line-width standardized, while a general frame, headings, and scale measure are added (Fig. 7). Superimpositions, which are outlined by a thin white space among overlapped figures, may be further enlightened by using different colours or grey-scale levels (Fig. 8); grey-scale levels are recommended, since colours can be a problem for press output and for the unavoidable lack of a standard symbolization for different chronological phases or subject categories. At this point the job is completed; the final rendering may be used 'as is', some sections may be isolated, or each figure may be picked as a separate object and reassembled into typological or chronological tables or compared to other similar ones.

All the described steps clearly constitute lengthy on-site and post-processing work. Even if someone claims that it is a time-consuming process (Seidl *et al.* 2015), we need to recall that shortcuts are rarely the best choice in archaeological research and that the essential long time frame is necessary — with the best accuracy— to understand, study, and reproduce iconic palimpsests, which are often very tangled and hard to untie, for chronology and meaning.

3 NAQ1, data analysis software tools

As soon as the graphic 'digging' has been completed and the iconic layers and figures have been extracted from the bedrock, there follows the need to study the collection of archaeological finds. Once more, a workflow is involved. The basis — the first and most important step — is the compilation of the catalogue of iconic objects and their relations. The figure record utilized for NAQ1 is the same as that specifically designed for Valcamonica rock art, which is also suitable for all alpine rock art; for the Great Rock of Naquane, classification opportunities have been enhanced. Its base structure originally derived from the Engraved Rocks Computer Recording Model, which was set up in 1989 by the Lombardy Archaeological Superintendence. Although the figure record is quite detailed and many alpha-numeric and Boolean fields are to be filled — dimensions, engraving technique, conservation level, and description — two main conditions should be outlined: taxonomic classification and identification of the network of relations. As for any archaeological find, a morphological and a chronological position must be assigned to each figure, along with a clear written description. For classification, and considering the need of simultaneously satisfying an overall and detailed analysis, a double taxonomical level is set. The 'general category' coding consists of a one-letter field; this currently includes 15 main figure groups such as anthropomorphs, zoomorphs, tools-weapons, inscriptions, cup-marks, and so on. For the northern part of NAQ1 — roughly half of the entire engraved surface — three categories prevail, of which two are not meaningful: zoomorphic figures (27.27%, coded as 'B'), unclassifiable segments-lines-areas (25.16%) and dot groups or scattered pecking (24.76%). The 'specific category' coding is managed by a three-digit field, currently consisting of 273 specific categories; this more detailed taxonomic level is fully customizable for each particular rock art complex, site, or rock. The specific categories individuated for the Great Rock of Naquane (north sector) total 100; related rankings show the prevailing presence of warriors among the human figures and deer among the animal figures. A similar two-level structure is applied to the chronological classification: the 'style' coding consists of a one-digit field, currently expressed by 10 main archaeological periods such as Palaeolithic, Mesolithic, and so on. The 'specific style' coding is a five-letter field, currently listing 23 detailed archaeological periods such as Copper Age 1, Early Iron Age, and so on. To give an example, an A6 coded figure is an Iron Age anthropomorphic figure, while an A6-VIA-30 coded item (Roman numeral VI) is a warrior of the first Iron Age, with a linear rectangular body, its legs placed as a triangle, and holding an upraised sword. It should be specified that the record compiler needs only to put in the code and not its description, except when modifying the code database. The second main condition, which concerns the relations network, is satisfied by recording, for each figure and if any exists, the associated iconic elements that have a semantic relation — useful for identifying scenes and giving suggestions for real or symbolic meanings — and the superimposed or underimposed elements, which are essential for revealing the sequence of the engraving phases. The current structure allows the inclusion of no more than three figures for each kind of relation, so a maximum of nine. Again for the north sector of NAQ1, 658 related figures, 250 superimposed, and 260 underimposed, have been recorded; 50 superimpositions covering the whole surface, were listed in Anati in 1960.

Apart from descriptive sections, it is evident that a figure record, after being completed, appears as a series of fields filled with alphanumeric codes. That said, it is clear that there is a need to translate, manage, and compute this rather large amount of data, a fortiori if many figures are involved, as in the case of the Great Rock of Naquane. Dedicated software, RAD-Rock Art Database (RAD.exe; Arcà 1997), has been compiled since 1994 by the author of the present paper to perform these

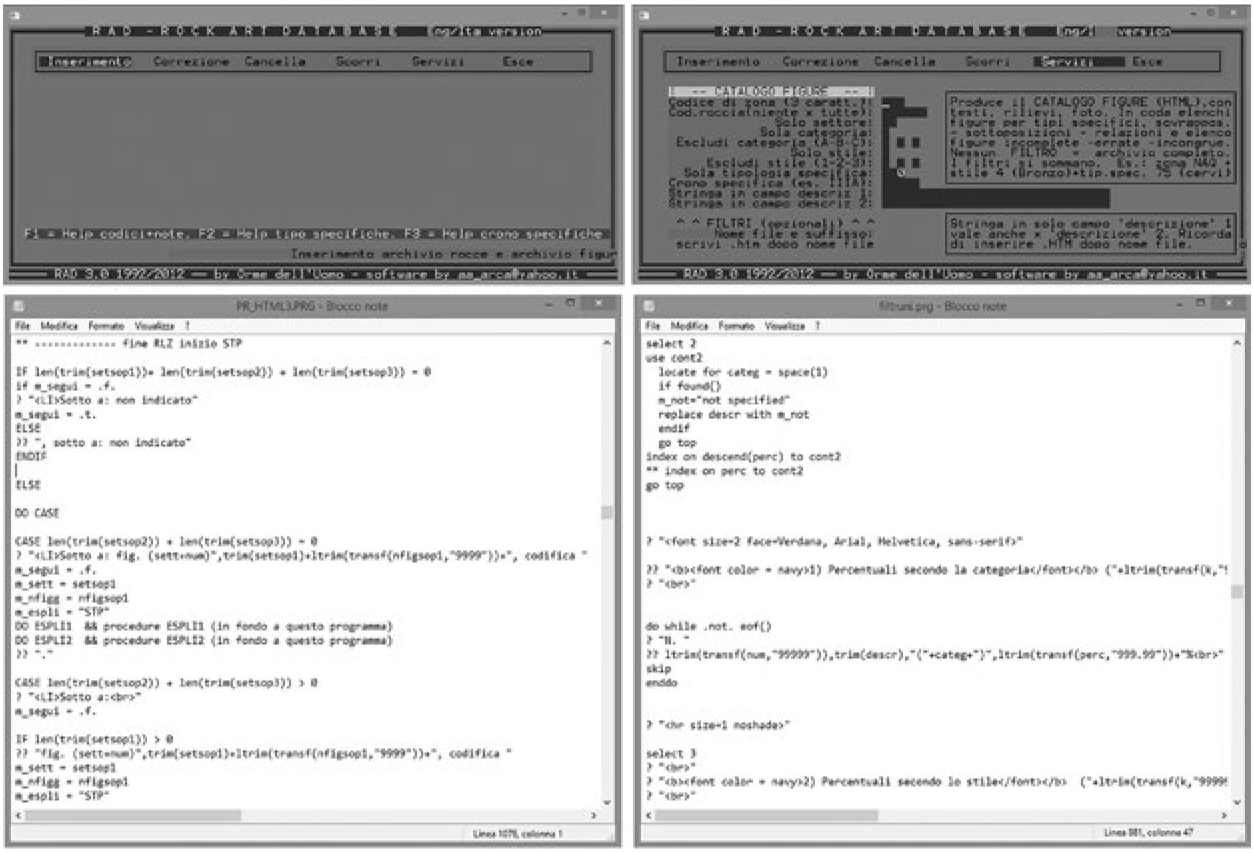

Fig. 9. Screenshots of the RAD-Rock Art Database software, main menu and filtering options for producing the catalogue of the figures (above) and source-code samples, Clipper '87 version (below).

tasks to store and count all these qualitative and quantitative data (Fig. 9). The software took its origin from the executable EUGA.exe, built two years before the RAD to produce the catalogue and the related statistics of the 5454 figures of the Rupe Magna in Valtellina (Arcà *et al.* 1995), the largest prehistoric engraved rock in the Alps. RAD.exe source code was originally written in xBase-Clipper language (Pearson 1997)[5] under a DOS environment and compiled with Clipper Summer '87, following in some way the 'original xBase spirit', intended to be 'powerful, intuitive and easy to use', as reported by the founder and developer of HMG (see below). Clipper was simultaneously a programming language — a superset of Ashton-Tate dBase III+ and xBase products — and a compiler. While as a compiler it definitively has stopped evolving since 1997, as a programming language it is still extant. RAD.exe consists of 41 program files, each written for a specific function such as record editing, database browsing or indexing, and output text-files producing. Its core procedure consists of 3458 rows of code, whose algorithms are mainly structured in IF-ELSEIF-ENDIF or DO CASE-ENDCASE chains and SET FILTER, USE, and SET ALTERNATE TO commands, along with the definition, translation, or calculation of specific variables. RAD.exe has been compiled in 16-bit; it is still very fast when executed in the command shell of Windows operating systems, up to Windows 7. Obviously it does not run on more recent operating systems, such as Windows 8 and 10, unless utilizing DOS emulators like DOSBox, provoking thereby a considerable slowdown in its performance.

In March 2015, taking advantage of the CAA conference and of the presentation of the digital work involved in the study of NAQ1, RAD-Rock Art Database was ported to 32-bit and recompiled for a Win desktop environment (Fig. 10), as well as greatly enriched in its filtering capacities. The job has been completed thanks to freeware tools, all available online, which create a 100% backwards compatibility with the Clipper Language (Esgici 2010). This mean that after installing the software, libraries, and dependencies and completing some rewriting and updating tasks such as main menu building and windows design, not a line of the old xBase-Clipper code is lost during the 32-bit porting procedure. The set of utilized tools is composed by Harbour (Harbour Project 2011), 'a free software cross-platform compiler for the xBase superset language Clipper', MinGW (minimalist GNU for Windows; Mingw 2012), 'a minimalist development environment for native MS Windows applications', and most notably by HMG (Harbour MiniGUI-Graphical User Interface; Hmgforum.Com, 2015),

[5] Briefly detailing some notes on archaeo-computing, the old but indispensable 'Guide to Clipper' (NG.EXE) in Norton Guides by Peter Norton (1987), 'a wonderful on-line reference tool (...) to cover all commands and functions through Clipper's Summer '87 release' (it was simply activated on a DOS screen by keying Shift+F1), describes and gives the syntax of 141 functions (e.g. RECNO() to return the current record number or TRIM() to remove trailing spaces from a string), 121 commands (e.g. DO WHILE to execute loop while condition is true (.T.) or GO TO to move to a specific record), and 22 operators (<, =, >, .NOT.); these are all the 'bricks' of which the Clipper Summer '87 language was composed.

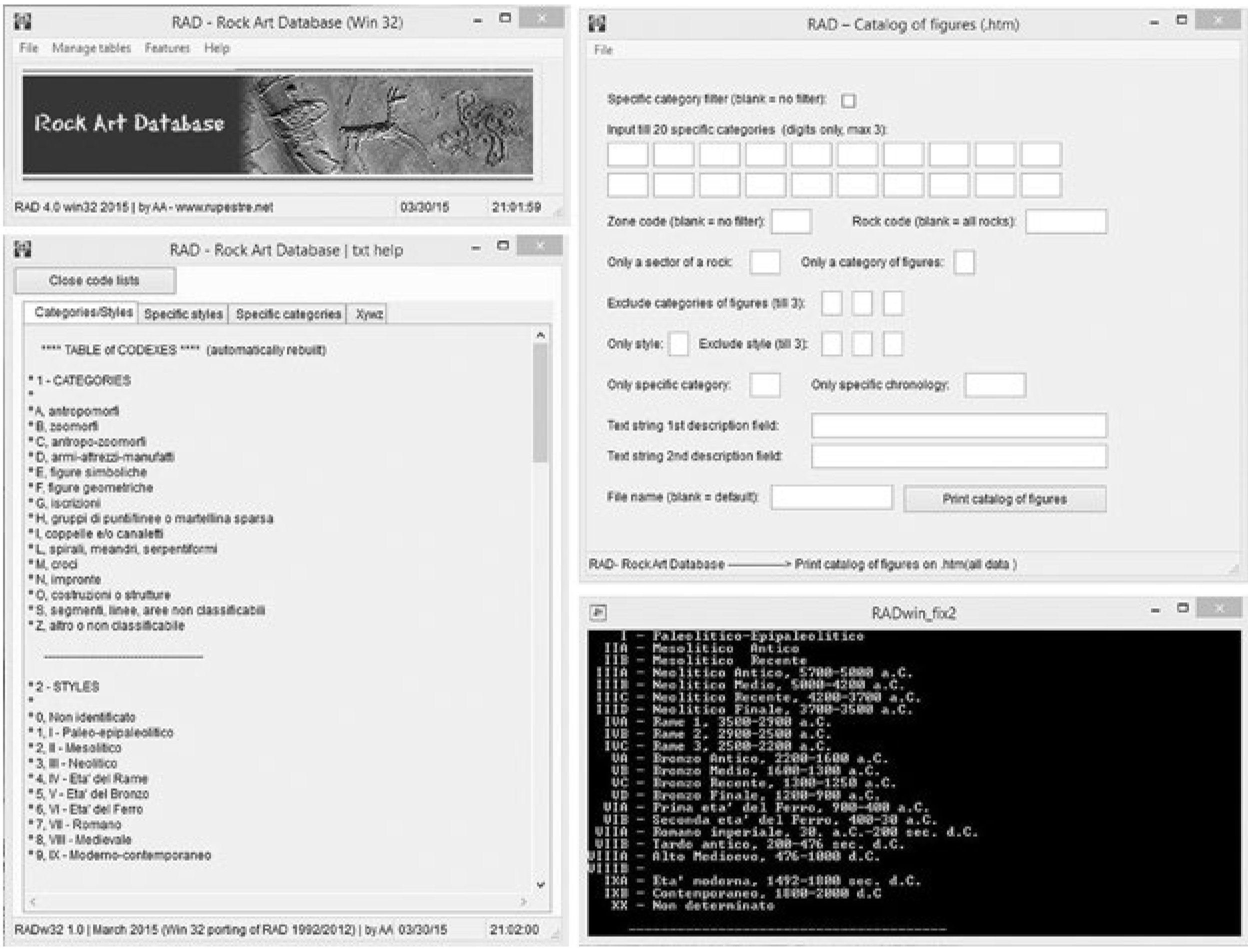

Fig. 10. Screenshots of the RAD-Rock Art Database software (code table and filtering options) ported to 32-bit.

'a free/Open Source xBase WIN32/GUI Development System for Windows platform', written by Roberto Lopez. After being fully updated and tested, the RAD.exe ported to 32-bit becomes RADwin.exe, and will be created and distributed as a freeware, fully customizable for each rock art area and site.

Briefly, the main functions of RAD-Rock Art Database software are related to the management of rock/figure records and to the production of instant outputs, such as the catalogues of rocks/figures and the chrono-typological listings, rankings, and stats. The management of records includes basic functions such as adding, editing, and deleting data, as well as the customization of all classification levels. With this procedure, general or specific categories and styles may be adapted to each particular situation, provided that codes and related descriptions are conveniently translated, added, or rewritten; to justify this need, it is sufficient to cite that, for instance, the European chronology is different and not suitable for a North American rock-art site, and vice versa. The main feature of RAD regarding the file output is the production of the catalogue of figures (Fig. 11). All the data from figure records are copied into a ready-to-use (and to share) html file, where codes — categories, styles, and relations — are translated into words or phrases, paragraphs are formatted, and images (a photo and a tracing/drawing for each figure) are included for the browser visualization, ready to be published and shared online or quickly reworked into a printed book. For the north part of the Great Rock of Naquane, the entire catalogue of its 1232 figures, of which 611 are meaningful, is written by RAD in less than a minute: 280 pages, 145,000 words and 970,000 types. Another instant output is produced by the creation of detailed listings and stats: a list of the specific categories (in descending order based on the presence percentage), a list of relations (associations, superimpositions, and underimpositions), and rankings of categories and styles, both general and specific, with related percentages. For the same sector of the Great Rock we note that Iron Age figures comprise 89.94% of the total, while 82.79% belong to IV2 style, the so-called pre-naturalistic style of the Iron Age from the end of the 7th to the first half of the 5th century BC. For categories, and citing only meaningful figures, we find at the top of the ranking zoomorphic (27.7%, of which 7.32% are male deer and 4.55% are dogs) and anthropomorphic figures (9.90%). One of the most powerful and effective functions is provided by filters: each output html file — the catalogue of figures and their related stats — may be fully personalized by custom filters, for example, limiting the choice to a category/style, or to some specific categories/styles, or to a sector; or excluding categories/styles and not meaningful figures; or simply typing a text-string into description fields, and all related combinations. In this way, it is easy task to produce a convenient set of specific NAQ1 catalogues of figures, for instance footprints, deer, Bronze Age or medieval figures, useful for detailed studies and comparisons.

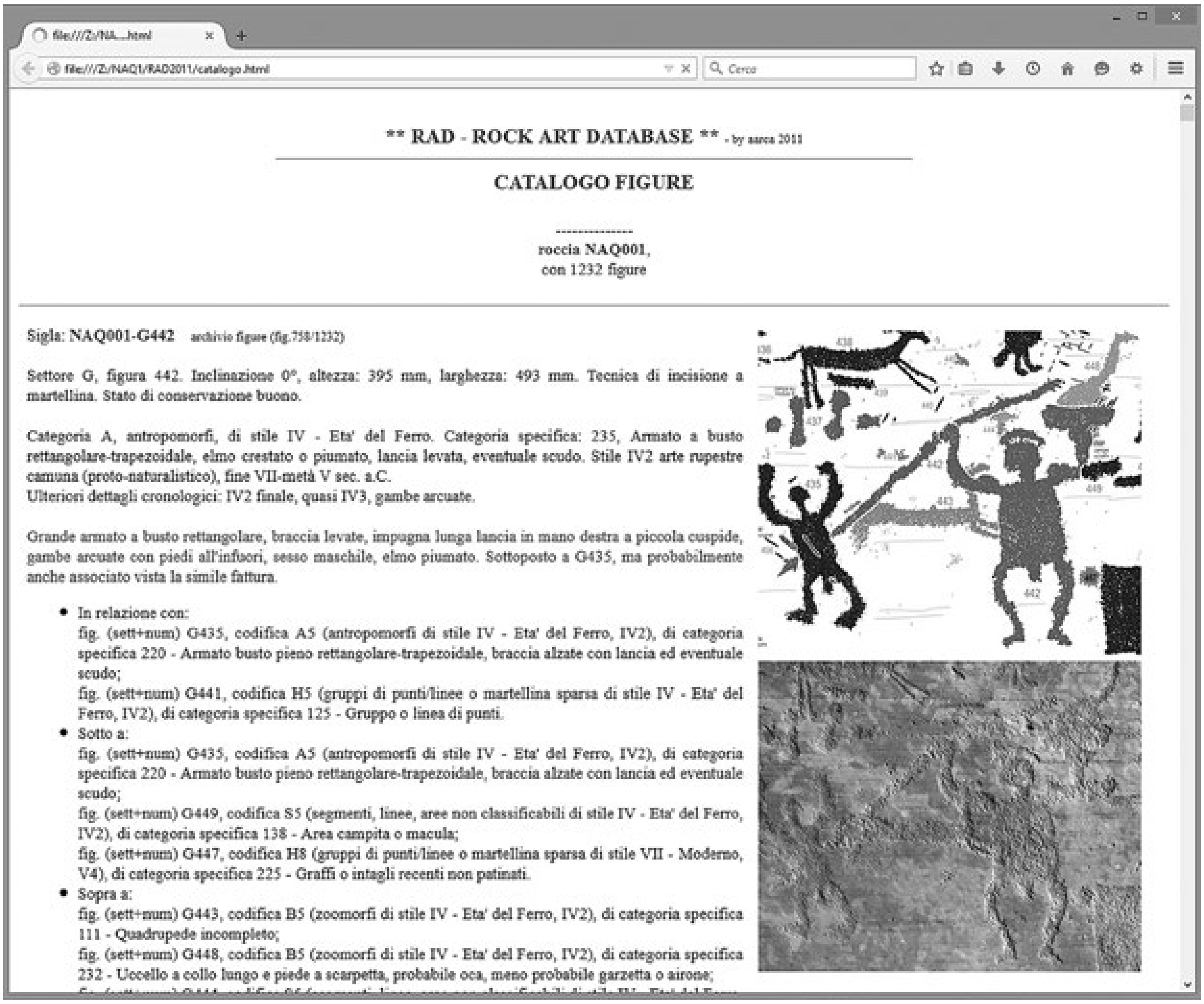

Fig. 11. A screenshot of the NAQ1 catalogue of figures in html format, automatically produced and formatted by RAD; for categories, styles, relations, and superimpositions, input codes are translated by the software into words and phrases.

In reply to the second question posed at the beginning of this paper, about the contribution of software tools to the archaeologist's work, we conclude that the case of the Great Rock of Naquane study shows that a large set of electronic instruments — for graphics and data analysis — are intended as a fundamental toolbox for the careful and up-to-date rock art researcher. On the other hand, the first question, related to the challenge between man and machine, deductions, and algorithms — basically between qualitative and quantitative science — will remain unanswered, waiting for future developments and practical evidence.

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Bibliography

Anati, E. 1960. *La Grande Roche de Naquane.* Paris, Masson.

Anati, E. 1966. Metodi di analisi e di archivio dell'arte rupestre. *Bollettino del Centro Camuno di Studi Preistorici* II: 133-55.

Anati, E. 1974. Metodi di rilevamento e di analisi dell'arte rupestre. *Studi Camuni* VII. Capo di Ponte, Edizioni del Centro.

Anati, E. 1975. Evoluzione e stile nell'arte rupestre camuna. *Archivi* 6. Capo di Ponte: Edizioni del Centro.

Arcà, A. 1997. *RAD - Rock Art Database*. [Online] http://www.rupestre.net/orme/database. [Accessed: 26 June 2015].

Arcà, A. 1999. Digital auto-tracing in Rock Art Recording. Applications of computer vectorial design. *TRACCE - Online Rock Art Bulletin* 11 (February 1999). Available from: http://www.rupestre.net/tracce/?p=1989. [Accessed: 26 June 2015].

Arcà, A. 2000. Computer management of alphanumeric and visual data in the alpine rock art, Valcamonica, Valtellina, western Alps. *Arkeos, perspectivas em dialogo* 7: 55-74.

Arcà, A. 2005. Archeologia rupestre in Valcamonica: *Dos Cüi*, un caso di studio. *Rivista di scienze preistoriche* LV: 323-84. Available from: https://www.academia.edu/7784103. [Accessed: 26 June 2015].

Arcà, A. 2009. Val Susa, rocce coppellate di Chiomonte-La Maddalena, Catalogo delle Schede da Sus-Mad1 a Sus-Mad5 e relazione consuntiva. In A. Arcà (ed.), *La Spada* *sulla Roccia. Danze e duelli tra arte rupestre e tradizioni popolari della Valsusa, Valcenischia e delle valli del Moncenisio*: 239-54. Torino, Gruppo Ricerche Cultura Montana.

Arcà, A., Casini, S., De Marinis, R. C., Fossati A. 2008. Arte rupestre, metodi di documentazione: storia, problematiche e nuove prospettive. *Rivista di scienze preistoriche* LVIII: 351-84. Available from: https://www.academia.edu/7784083/. [Accessed: 26 June 2015].

Arcà, A., Daudry, D., Fossati, A. E., Morello, F., Raiteri, L. 2014. Il riparo inciso di Montjovet-Chenal (AO), seimila anni e più di iconica rupestre. In R. C. De Marinis (ed.), *Le manifestazioni del sacro e nella regione alpina e nella pianura padana, studi in memoria di Angelo Rampinelli Rota, Atti del Convegno, Brescia, Palazzo Broletto, 23-24 maggio 2014*: 27-66. Brescia, Euroteam. Available from: https://www.academia.edu/9449764/. [Accessed: 26 June 2015].

Arcà, A., Fossati, A. 2006. Rupestrian Archaeology: a methodological approach to the rock engravings of Valcamonica. In L. Oosterbeek (ed.), *Europreart II. Prehistoric Art Research and Management in Europe: Case Studies*: 51-8. Bari, Edipuglia.

Arcà, A., Fossati, A., Marchi, E., Tognoni, E. 1995. Rupe Magna: la roccia incisa più grande delle Alpi (2 vol.). *Quaderni del Parco delle Incisioni Rupestri di Grosio* 1. Sondrio, Consorzio per il Parco delle Incisioni Rupestri di Grosio.

Battaglia, R. 1933. Capodiponte: nuove ricerche sulle rocce incise della Valcamonica. *Notizie degli scavi di Antichità comunicate alla R. Accademia dei Lincei per ordine di S. E. il Ministro dell'Educazione Nazionale e pubblicate d'accordo col R. Istituto di Archeologia e Storia dell'Arte* 6, IX, fasc. 7°, 8°e 9°: 201-39.

Bednarik, R. G. 2001. Petroglyphs in Italian Alps dated. *Acta Archaeologica* 72, 2: 109-14.

De Marinis, R. C. 1988. I Camuni. In A. M. Chieco Buanchi *et al*. (eds.), *Italia omnium terrarum alumna: la civiltà dei veneti, reti, liguri, celti, piceni, umbri, latini, campani e iapigi*: 131-54. Milano, Libri Scheiwiller.

Esgici, B. 2010. *Vivaclipper! Notes of a Clipper Language Student*. [Online] https://vivaclipper.wordpress.com. [Accessed 26 June 2015].

Fossati, A. 1991 L'età del Ferro nelle incisioni rupestri della Valcamonica. In La Guardia, R. (ed.), *Immagini una aristocrazia dell'età del Ferro nell'arte rupestre camuna: contributi in occasione della mostra, Castello Sforzesco, aprile 1991-marzo 1992*: 11-71. Milano, Comune di Milano, Settore Cultura e Spettacolo, Raccolte Archeologiche e Numismatiche.

Fossati, A. and Arcà, A. 2001 Tracing the past. Petroglyph reproduction for Rupestrian Archaeology. In R. La Guardia (ed.), *Secondo convegno internazionale di archeologia rupestre. Archeologia e arte rupestre: l'Europa-le Alpi-la Valcamonica. Atti del convegno di studi, 2-5 ottobre 1997, Darfo Boario Terme*: 267-70. Milano.

Fossati, A., Jaffe, L., Simões De Abreu, M. 1990. Rupestrian Archaeology. Techniques and Terminology, a Methodological Approach: Petroglyphs. *Ricerche Archeologiche* 1. Cerveno, Cooperativa Archeologica Le Orme dell'Uomo.

Harbour Project 2011. *A 32/64-bit xBase compiler*. [Online] https://harbour.github.io. [Accessed: 26 June 2015].

Hmgforum.Com 2015. *Exclusive forum for HMG, a Free / Open Source xBase WIN32/64 Bits / GUI Development System*. [Online] http://www.hmgforum.com/index.php. [Accessed: 26 June 2015].

Loendorf, L. 2001. Rock Art Recording. In D. S. Whitley (ed.), *Handbook of Rock Art Research*: 55-79. Walnut Creek, Rowman & Littlefield Publishers.

Marretta, A. 2014. Tecniche di incisione e metodi di documentazione dell'arte rupestre in area centro-alpina: una panoramica aggiornata *Notiziario dell'Istituto Archeologico Valtellinese* 12: 7-20. Available from: https://www.academia.edu/9573735. [Accessed: 26 June 2015].

Marretta, A., Martinotti, A., Colella, M. 2013. Un'esperienza di procedura documentativa e analitica informatizzata di tecniche e sequenze istoriative su due frammenti litici con graffiti protostorici da Piancogno (Valcamonica, BS). *Archeologia Postmedievale* 17: 319-28.

Marro, G. 1932. Il grandioso monumento paletnologico di Valcamonica. *Atti della Reale Accademia delle Scienze di Torino* LXVII, disp. 1ª e 2ª: 413-89.

Mingw 2012. *Minimalist GNU for Windows*. [Online] http://www.mingw.org. [Accessed: 26 June 2015].

Pace, D. 1972. Petroglifi di Grosio. *Tellina Opuscola* 2. Milano, Scuole grafiche pavoniane-Istituti Artigianelli.

Pearson, D. 1997. *The Guide To Clipper Summer 87 - Norton Guide*. [Online] http://www.ousob.com/ng/sum87/index.php. [Accessed: 26 June 2015].

Scott, U. 2015. *Safeguarding Prehistoric Rock Art through Modeling*. [Online] http://blog.pix4d.com/post/122424602526/safeguarding-prehistoric-rock-art-through-modeling. [Accessed 26 June 2015].

Seidl M., Wieser E., Alexander, C. 2015 Automated classification of petroglyphs. *DAACH - Digital Applications in Archaeology and Cultural Heritage*. In Press, Corrected Proof Available online, 14 March 2015. [Online] http://ment.org/DAACH15/DAACH-D-14-00016R1_preprint.pdf. [Accessed: 26th June 2015].

Real-time 3D Modelling of the Cultural Heritage: the Forum of Nerva in Rome

Tommaso Empler
tommaso.empler@uniroma1.it

Barbara Forte
barbaraforte87@gmail.com

Emanuele Fortunati
emanuelefortunati@gmail.com

Department of History, Representation and Restoration in Architecture, Sapienza University of Rome

Abstract: 3D modelling and the ability to view and navigate through reconstructions in real time enables people to gain an understanding of what places actually looked like, recreating their form and spatiality.

The case study is a real-time 3D reconstruction of the Forum of Nerva in the central archaeological area of Rome, which has as yet received little attention of this kind. The reconstruction employed the open-source Blender game engine.

Drawing on input from archaeologists and historians for its content, and the expertise with 3D modelling tools offered by specialists in forms of representation, this is the first time that an attempt has been made to reconstruct and explore the Forum of Nerva as it appeared in Imperial Roman and medieval periods.

Keywords: 3D modelling, Real-time 3D, Open source, Communication view

Introduction

Being able to reconstruct places and buildings from the past that are now considered part of the cultural heritage provides exciting possibilities.

3D modelling and the ability to view and navigate through reconstructions in real time enables both scholars and those without a scientific background to gain an understanding of what places actually looked like, recreating their form and spatiality. This opportunity stems from applications conceived for other sectors, and specifically from the software developed for video games. Thus, procedures that have hitherto been used only in the world of video games are transposed to 3D historical modelling and reconstruction. To ensure fluid navigation, the 3D models developed for this purpose must strike an effective balance between solid and surface modelling, using specific textures for historical reconstruction. It is also important to use appropriate algorithms, which make it easier to calculate shading and shadows.

1 Recent solutions

We have considered three 3D modelling and navigation initiatives for ancient Roman and medieval archaeological sites:

- Rome Reborn (http://romereborn.frischerconsulting.com/about.php);
- Virtual Aquileia (http://www.digitalheritage2013.org/virtual-aquileia/);
- The Sainte-Chapelle in Paris (http://paris.3ds.com/en-sainte-chapelle.html).

1.1 Rome Reborn

Rome Reborn (Dylla 2010) is an international initiative, the goal of which is to create 3D digital models illustrating ancient Rome's urban development for the first settlements in the late Bronze Age (*c.*1000 BC) to the depopulation of the city in the early Middle Ages (*c.*550 AD).

The initiative got under way in 1997, when the Virtual World Heritage Laboratory of the University of Virginia (VWHL) joined forces with the UCLA Experiential Technology Center (ETC), the Reverse Engineering Lab at the Politecnico di Milano, the Ausonius Institute of the CNRS, the University of Bordeaux-3, and the Université de Caen in collaborating on the creation of a digital model of ancient Rome as it appeared in late antiquity. The notional date of the model is 21 June 320 AD. Since 2009, the sponsor and administrative home of the project has been Frischer Consulting, whose mission is to apply 3D technologies to the study and dissemination of cultural heritage throughout the world.

The primary purpose of the project is to spatialize and present information and theories about how the city looked at that time, which was more or less the height of its development as the capital of the Roman Empire. A secondary goal was to create the cyberstructure whereby the model could be updated, corrected, and augmented.

The digital model reflects the sources of our knowledge about ancient Rome, which are of two kinds: archaeological data about specific sites and features ('Class I'); and quantitative data about the distribution of building types throughout the 14 regions (or wards) of the city ('Class II'). Features in Class I are known from archaeological excavations and studies; coins; inscriptions; ancient literary sources; and artists' views from the Renaissance until the nineteenth century. Features in Class II are known from two regionary catalogues (the Curiosum and the Notitia) dating to the fourth century AD.

The digital model as a whole consists of two types of materials: highly detailed models of buildings that can be reconstructed on the basis of reliable archaeological evidence (examples: the buildings in the Roman Forum and the Forum of Julius Caesar, the Flavian Amphitheatre, the Temple of Venus and Rome, etc.); buildings and other features that are known only by type and by frequency in the particular regions of the city. Approximately 200 buildings of the first type and between 7000 and 10,000 in the second category have been modelled.

Around 50 of the 200 Class I buildings that were modelled have been created with the help of scientific advisory committees of experts, while detailing operations are still to be completed for the remaining 150. The Class II buildings have been modelled by a procedure entailing the digitization (Guidi 2005) of the Plastico di Roma Antica created by Italo Gismondi from 1934 to 1974.

As regards dissemination, videos of the digital model have been posted for viewing starting in June 2007. In 2008 the 1.0 version of Rome Reborn was published on the Internet as 'Ancient Rome 3D' in Google Earth. In 2012, this layer was removed. From 2012 to 2013, a number of initiatives surfaced to use Rome Reborn 2.2 as the major asset for educational videos, whether shown in museums or on the Internet. Meanwhile, research was pursued by the leadership of the project on ways of making the model interactively available through a game engine.

1.2 Virtual Aquileia

Aquileia Virtuale is an Augmented Reality Real Time 3D app for Android and iOs tablets and smartphones, designed to provide a better understanding of the city's historical remains.

Aquileia was one of the largest and wealthiest cities of the Early Roman Empire until Attila destroyed it in the mid-5th century. Inscribed in UNESCO's World Heritage List in 1998, it is currently a small town and the ancient Roman buildings, except for the majestic basilica, are mostly unexcavated or buried under more recent buildings. The only way for people to understand what the ancient city looked like is through 3D reconstruction.

Funded by Fondazione Aquileia, the companies Ikon and Nudesign, who specialize in 3D modelling and mobile apps, have created 3D reconstructions and videos of most of the ancient buildings.

The Aquileia Virtuale app, which combines 3D images, videos, and real-time 3D models, allows users to visit Aquileia using their mobile device as a 'time window' and as a multimedia video guide. Walking around town, the visitor receives information on the ancient buildings nearby and, where there is a 3D model available, virtually 'enters' the building to explore it.

The real-time 3D models can be explored both on site (Augmented Reality) and off site (Virtual Tour): the visitor can move the mobile device around him to explore on site, or use the virtual joypads on the side of the screen when off site. This app allows an exploration of the 3D real-time reconstructed buildings using the GPS and the accelerator built in the devices, in an Augmented Reality mode, on the very spot where the original building was. There are also various hotspots inside the 3D models with information about buildings and objects that were present in antiquity.

1.3 The Sainte-Chapelle

With the 3D reconstruction of the Palais de la Cité in medieval times, the Dassault Systèmes Passion for Innovation Institute and the Centre des Monuments Nationaux (CMN) is widening the Paris 3D Saga's collection of monuments. The 3D experience allows credible reconstructions of buildings as they stood in the 14th century, such as the Tour de l'Horloge, the Galerie Mercière, the Trésor des Chartes, etc. With the help of laser digitalization techniques and in addition to the immersive 3D experience, Passion for Innovation Institute teams scanned the Sainte-Chapelle as it is now. The scan was then used as the basis for reconstructing the building in different periods, starting from the Middle Ages.

The model can be navigated in real-time 3D using the link http://paris.3ds.com/en-experience.html?lang=en

The initiative was connected with the *Saint Louis* exhibition, which celebrated eight centuries since Louis IX was born, and ran from 8 October 2014 to 11 January 2015.

2 Proposed solution

The case study is a real-time 3D reconstruction of the Forum of Nerva in the central archaeological area of Rome, which has as yet received little attention of this kind. The reconstruction employed the open-source Blender game engine.

Drawing on input from archaeologists and historians for its content, and the expertise with 3D modelling tools offered by specialists in forms of representation, this is the first time that an attempt has been made to reconstruct and explore the Forum of Nerva as it appeared in Imperial Roman and medieval periods.

2.1 Philology in the reconstruction of the Forum of Nerva

The central area of the Imperial fora in Rome has and continues to be the focus of a number of studies, investigations, and excavation campaigns by the Sovrintendenza di Roma Capitale and the Ministero per i Beni e le Attività Culturali.

The first surveys were carried out by the archaeologist Rodolfo Lanciani, whose investigations in the central portion of the Forum of Nerva in 1882 uncovered portions of the pavement of the plaza and the remains of the perimeter walls at a depth of 5.50 m from street level, enabling him to produce a conjectural layout of the Forum. At that time, the only visible architectural feature was the pair of columns known as the Colonnacce, which protruded from the ground by approximately half their height.

The first excavation campaign took place with the demolition of the Alessandrino district between 1926 and 1934 under the direction of the archaeologist Corrado Ricci. In 1940, the archaeologist Colini began to dig in the area of the Colonnacce and the Temple of Minerva, continuing until 1942 and unearthing the Porticus Absidata and part of the Cloaca Maxima.

Excavations in the Forum of Nerva were resumed in the 1970s, when the German scholar Heinrich Bauer, digging in the area of the west wall, discovered a foundation similar to that of the Temple of Minerva on the opposite side of the Forum, postulating that a temple dedicated to Janus had stood there. It was also suggested that a monument had been located at the centre of the Forum, as the Cloaca Maxima runs off to one side (Meneghini 2007).

Between 1985 and 1988, the Soprintendenza Archaeologica di Roma carried out an excavation campaign in order to understand the topography of the area bounded by the Curia, the Forum of Caesar, and the Forum Transitorium. Although these excavations confirmed Bauer's hypothesis regarding the existence of a second temple, the fact that the foundations were found to be badly cracked suggests that construction of this building was abandoned (Viscogliosi 2000).

The latest excavations were carried out between 1986 and 2008 by the Sovraintendenza ai Beni Culturali del Comune di Roma together with the Soprintendenza Speciale per i Beni Archaeologici di Roma (Meneghini 2009). Remains were found from the protohistoric and Imperial period and the Early Middle Ages. Until the 9th century, there are no signs of major changes and despoliation, as had occurred in the other fora. In this period, two-storied houses rose on both sides of a cobbled road that cut diagonally across the Forum, interspersed with vegetable gardens, fruit trees, and farmyards. They are 'Domus Solarate', houses with an upper floor, presumable aristocratic residences or 'curtes'. This group of 'domus' in the Forum of Nerva was abandoned and buried under about 2 m of soil between the 11th and 13th centuries.

2.2 The background for reconstruction

As excavations have proceeded over the years, our knowledge of the structure of the Forum of Nerva has increased, giving rise to a series of hypotheses for reconstruction.

Creating a three-dimensional model of the Forum of Nerva thus entailed a review of the many hypotheses that have been advanced by scholars, seeking a preliminary definition of the areas to be reconstructed through graphic modelling.

Starting from the latest theories deriving from the excavations carried out from 1986 to 2008, as outlined by the archaeologist Roberto Meneghini in his article 'Gli scavi dei Fori Imperiali. Bilancio di un ventennio d'indagine (1986–2008)', the basic structure of the Forum had already been established from the first excavations by Lanciani in 1882, with the raised structures and the position of the Temple of Minerva and of the Porticus Absidata. Later excavations investigated the west side of the plaza more thoroughly, raising questions about the Forum's termination towards the Basilica Aemilia. Another point that is far from clear is the actual course of the 45 columns making up the engaged colonnade. The only section of this colonnade that is still standing, the Colonnacce, shows an irregular intercolumniation, passing from 6.80 to 5.35 m. In this section, there is also a large and asymmetrically positioned architraved doorway, whose function as a passage towards the Forum of Peace has recently been called into question by the historian Alessandro Viscogliosi.

The irregular intercolumniation can be explained by the need to adapt the rhythm of the columns to a series of pre-existing openings giving access to the adjacent monumental plaza. This irregularity, which can amount to as much as 1 or 2 m is not apparent, however, when walking through the Forum, which is too narrow to afford a view of the entire length of the colonnade.

As it was not possible to reconstruct the Forum of Nerva with any certainty, modelling was necessarily based on an interpretation of the latest available information and thus remained at the level of hypothesis. This was especially true of the western part of the forum, which is still being studied. For this reason, the reconstruction drew on the layout postulated by the archaeologist Lanciani in 1882, with the colonnade running around the entire perimeter of the plaza.

Reconstruction of the remaining portion of the Forum was based on the findings of the most recent surveys, using ground plans drawn up by archaeologists, detail surveys of the elevated parts and, as regards the general appearance of the plaza, the testimony provided by classical authors, combining hypotheses and information with the assessments of scholars in the area.

2.3 Three-dimensional reconstruction methodology

The study involved 3D modelling of the Imperial Roman and early medieval periods. A practical outcome of the research is a real-time navigation of the Forum of Nerva, as it appeared in the two periods described, shifting from one age to the other, comparing site changes during the centuries involved.

The team which provide the reconstruction hypothesis comprises Tommaso Empler, Barbara Forte, Emanuele Fortunati, Riccardo Santangeli Valenzani, and Alessandro Viscogliosi.

The reconstruction of the Forum in the Imperial Roman period used the graphical layout proposed by the archaeologist Roberto Meneghini in his book 'I fori imperiali. Gli scavi del comune di Roma 1991–2007', which hypothesizes a possible configuration of the plaza without advancing theories about the parts that are still uncertain, such as the western termination of the Forum.

For the elevated parts, a dimensioned representation from the survey of the Colonnacce was used, and was entered in scale in a CAD application for subsequent vectorialization.

After entering the Forum's ground plan and section in the three-dimensional modelling program, the structural components of the model were constructed. The first operation was the extrusion of the perimeter walls that constitute the Forum's physical boundaries, using the 2D ground plan imported in the program and the section height. The second step was to extrude the columns, which called for more detailed modelling because of the cornices making up the entablature, which projects from the wall behind the shafts, and the capitals.

The colonnade of the monumental plaza was put together from the detailed model of a single column, its capital, the cornices and the projecting entablature. The single column was duplicated using the modeller's array function, which makes it possible to reproduce an object at precise distances along three Cartesian axes. The replicated objects are identical copies of the original and are linked together so that modifying any one of them will modify them all at the same time. The entablature between each column and the next was produced by creating a connecting band, which was then replicated between all the shafts.

In reconstructing the Temple of Minerva, it is necessary to have a knowledge of certain generic features that commonly recur in Roman temples, such as the type of monumental door, the pavement, the roofing, and the probable, though as yet unascertained, presence of acroteria.

The Temple was modelled on the basis of the historical iconographic sources that have come down to us today, while the portions that have survived were completed using assumptions based on probable similarities and correspondences. This is the case, for example, of the pediment of the Temple of Minerva, the few remaining fragments of which do not permit a definitive reconstruction of the original architecture. The major question in reconstructing the pediment concerned the frieze with the dedicatory inscription and its relationship with the mouldings on the side entablature. After first hypothesizing that the trabeation extended across the entire front of the temple, connecting the two side branches as suggested in a historical document that has come to light, we opted for a 'modus operandi' found in other structures of the same period such as the Temple of Vespasian (De Angelis 1992), where the frieze takes up the entire height, including the trabeated portion, and includes the inscription under a cornice with palmettes. Once this point had been decided, the problem arose of how two resolve the two frontal corners of the side entablature, consisting of several stepped mouldings with the smooth portion bearing the inscription. This issue was clarified by considering the historical representations by Dosio and Palladio (Viscogliosi 2000), which illustrate how the two elements were related, with the trabeation extending to the front of the temple, but only for a small space, thus gracefully connecting the sides without interfering with the inscription.

Interpreting the documentation for the early Middle Ages is more complex because of the lack of urbanistic information in the area of the Imperial Fora. Although the recent excavations brought to light portions of the houses (*domus solarate*) built in the Forum starting in the 9th century, not enough remains to permit us to draw up accurate ground plans which would provide a good overall view.

Combining the information provided by excavations and literary sources makes it possible to interpret structures such as the typical two-storied Domus Solarate, with a lower storey consisting of drafted rectangular blocks — *opus quadratum* — of tuff, and a brick upper storey, but not to establish their real shape and size. Accordingly, three-dimensional modelling was based on a constructional interpretation.

Once again, modelling started from the generic and incomplete ground plans provided in 'I fori imperiali. Gli scavi del comune di Roma 1991–2007' by Roberto Meneghini and Riccardo Santangeli Valenzani, which show the surviving portions belonging to the above-ground structures and offer a hypothesis of how they might have been completed, but do not indicate their precise location in the Forum.

An important reference for modelling the area as it appeared in the early Middle Ages is the reconstructed view produced by Inklink for the Sovrintendenza Capitolina. Another aspect that is of fundamental importance to the 3D model's graphic reconstruction is the presence of vegetation. To achieve an effect that reliably represents the area in the 9th century, it is essential to include natural elements in all parts of the Forum of Nerva, from the packed earth that almost entirely replaced the marble pavement, to the cultivated vegetable gardens and stands of fruit trees, and the invasive plants, such as the ivy clinging to the walls, without forgetting the moss and lichens covering the crumbling stonework. Materials and coverings were checked and evaluated together with scholars specializing in this historical period.

As noted by Felinto (2013) it was also necessary to optimize the modelling techniques to ensure that the application does not slow down during calculation and use. As the intention was to make the application suitable for the widest possible range of users, it was necessary to create a versatile 3D model that does not entail a heavy processing load. Accordingly, the following procedures were used to guarantee a faster program:

- Simplified collision
- Modelling only visible features
- Faked modelling
- Substituting physical models with alpha textures
- Use of power-of-two textures
- Fake reflection

The combined use of these measures at the time of modelling makes it possible to simplify real-time calculation, ensuring the model's fluidity without detracting from the appearance. A low-poly mesh collision model, which can also involve complex objects such as stairways and columns, is created for navigation mesh path finding, and the overly detailed objects in the background are replaced with simplified objects to which high definition textures are applied (Fig. 1).

In the same way, physical objects such as vegetation and the complex details of the architecture are eliminated, replacing them with alpha textures that reproduce their features. Image management during loading was also optimized by using only textures sized in powers of two. Given that it is not possible to recreate the effect of reflection in three-dimensional models intended for navigation, surfaces that were to be reflective were made semi-transparent and a specular model was placed beneath them (Fig. 2).

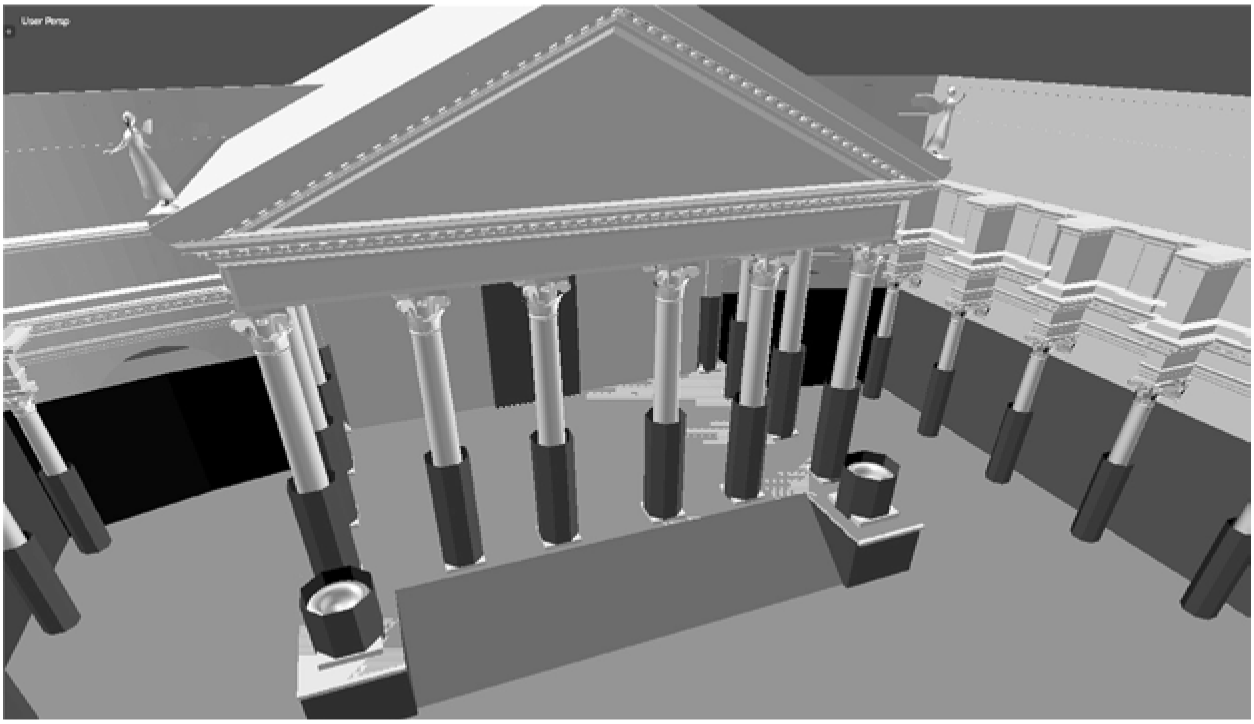

FIG. 1. OBJECTS WITH HIGH DEFINITION TEXTURES APPLIED.

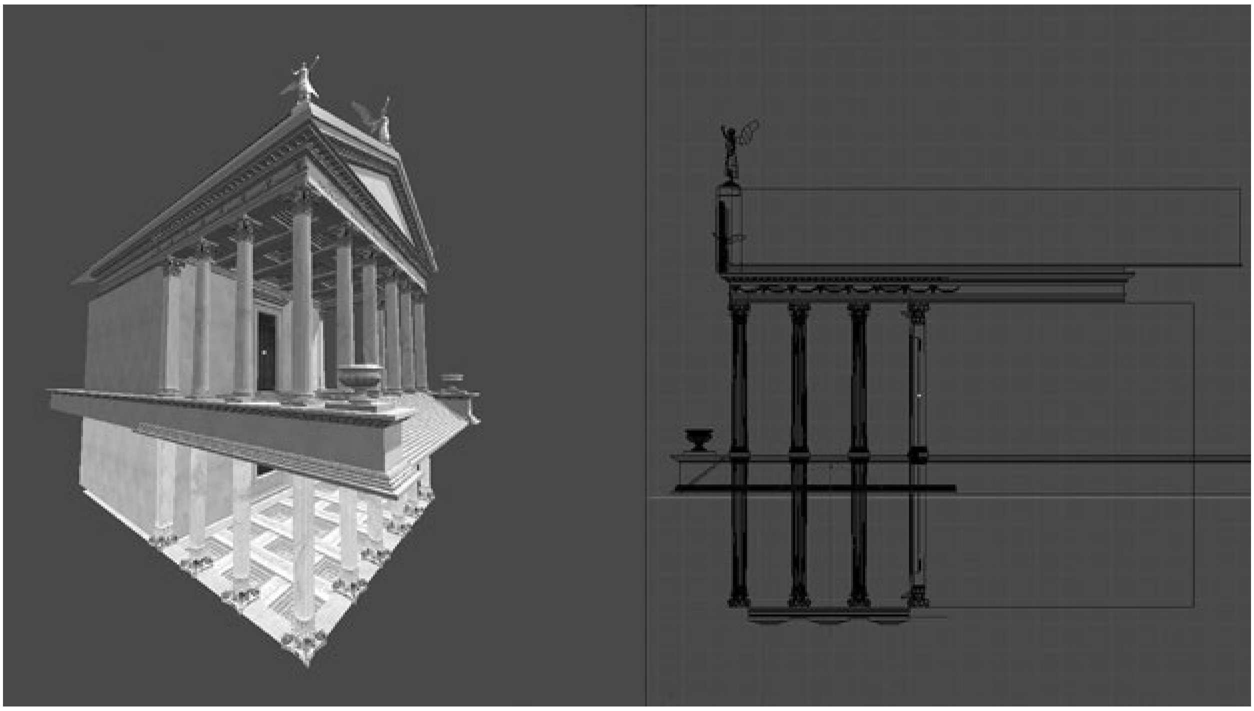

FIG. 2. SURFACES THAT ARE TO BE REFLECTIVE ARE MADE SEMI-TRANSPARENT AND A SPECULAR MODEL IS PLACED BENEATH THEM.

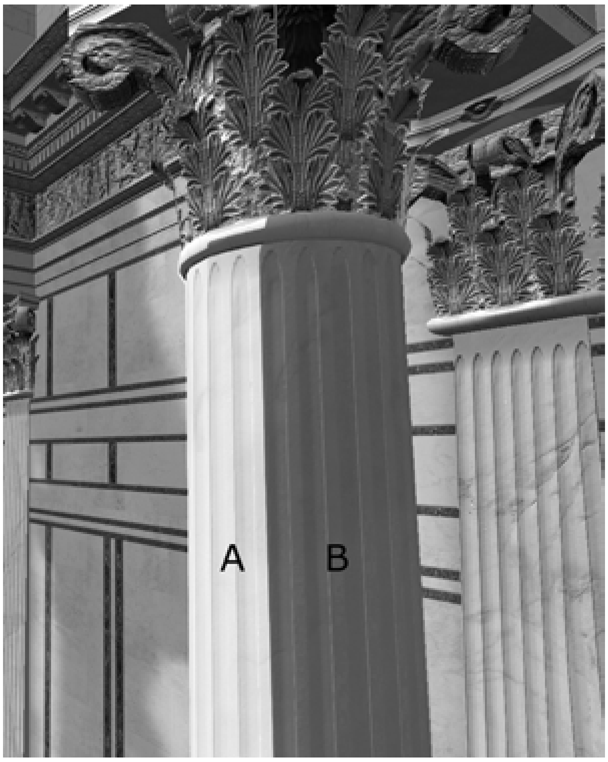

Fig. 3. Texture mapping procedure to simulate fluting on the columns.

Fig. 4. Texture mapping procedure to simulate fluting on the columns.

To ensure that three-dimensional models are complete and realistic, it is essential to apply photorealistic textures which can evoke (in the case of archaeological sites) or present (in the case of architecture) the atmosphere and sensations that the visitor experiences or would have experienced at that particular site. Consequently, it is important that the quality of the applied images is very high, and that the current features — or those that existed in the past — are reproduced as accurately as possible.

Texture mapping used a stack of texture layers, such as Diffuse, Bump, Specular, and Normal Mapping. Layering textures provided a very high level of photorealism while at the same time simplifying the texturing operation and the program's calculation operations. To circumvent some of the specific problems associated with the faked modelling of certain objects, we used nodal materials, which combine different basic materials on the basis of the light striking the object to which the material is assigned. For instance, since in our case the fluting on the columns was simulated with normal maps rather than modelled, this detail was lost in the shaded part but was restored thanks to a nodal material that blended together the specific material for the illuminated part of the column and a specific material for the shaded part, with much more evident fluting (Figs. 3 and 4).

A further texturing technique that was used is Vertex Painting, which is a way to paint meshes manually, directly manipulating the colour of vertices that make them up through a colour gradient. This makes it possible to map a large surface such as the packed earth that serves as the background for the early medieval forum, and add dirt to all the other surfaces, producing a different effect for each feature.

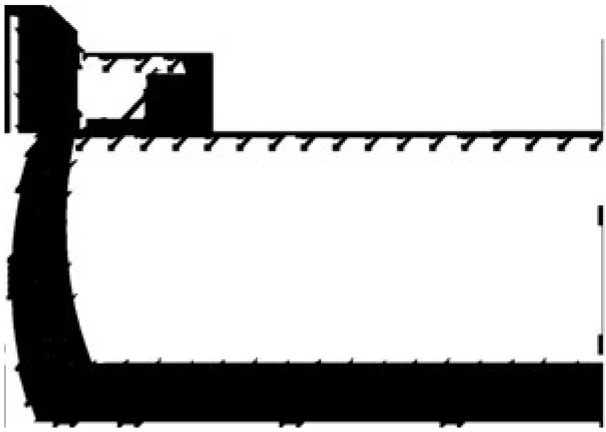

Fig. 5. Pre-calculated shadow mapping in the 3D modelling.

Shadow mapping, which is also called projective shadowing, is a process whereby shadows are pre-calculated in three-dimensional modelling applications (Fig. 5). The technique is not restricted to rendering (static images), but is also used in real-time images, video games, and cinema. Shadows are generated on the basis of whether or not the portion of the surface is visible from the light source: this information is projected to the camera and depth is compared to check whether a given point is illuminated or not, colouring it accordingly. Starting from the principle that the side of an object that is visible from a light source is illuminated and, conversely, the parallel and opposite side is necessarily shadowed, the view from the light source is rendered by deactivating all other

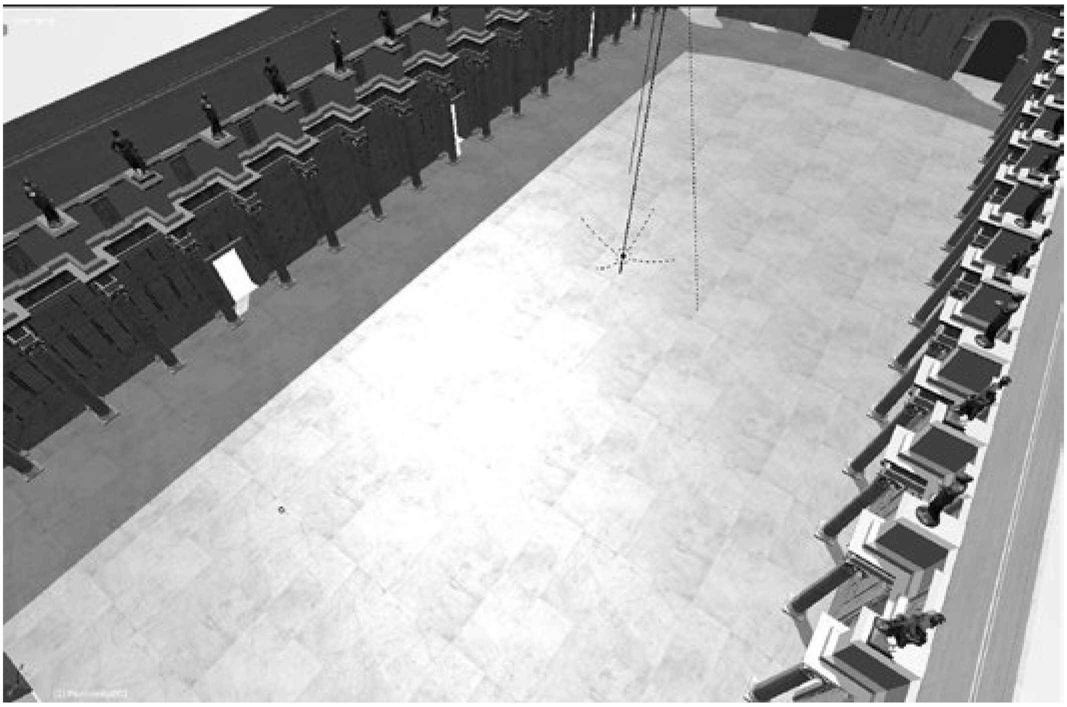

Fig. 6. The shadow mapping technique, especially when working with real-time images, is a valid and significantly faster alternative to computing shadows continuously with the graphic processor.

unnecessary factors, including the texture colour component. That done, all of the parts of the scene are rendered, comparing the depth of each point with the shadow map projection in the camera view space: if a point is behind the shadow map, it is shadowed. The shadow mapping technique (Fig. 6), especially when working with real-time images, is a valid and significantly faster alternative to continuously computing shadows with the graphic processor. In addition, it is not like 'dirtying' the material, in other words a level that darkens the object and cannot be changed, but it reacts to the addition of new light sources and thus produces the effect of a real shadow.

3 Experimental results

3.1 Real-time visualization

Three-dimensional modelling was performed with Blender, an open-source 3D modelling application whose programming structure features a game engine which is capable of managing simultaneous multiple events that permit real-time visualization, including:

- Scene rendering with texturing and light effects
- Physics engine
- Management of sound events
- Management of source code scripts
- Animations

Together, these characteristics permit 'subjective' movement simulation, which is achieved with single images produced in a short periods so as to have between 30 and 60 fps (frames per second), thus providing a smooth visualization.

A navigable model must achieve an effective trade-off between the number of polygons in the 3D model and the processor's ability to run a sufficient number of frames per second to ensure that movement is always smooth. The model must thus be optimized from the viewpoint of the 'virtual camera' located at about 1.70 m above ground level.

After the 3D models for the Imperial Roman and early medieval periods were created and the necessary simplifications were made in terms of polygons and applied textures, the Blender Logic Editor was used to set up and edit the game logic for the objects present on the scene in real-time. The logic for the objects created and selected in the 3D panel consists of logic bricks, which are shown as a table with three columns, indicating sensors, controllers, and actuators. The links joining the logic bricks conduct the pulses between sensor-controller and controller-actuator and permit the physical actions that take place in the scene, indicating the direction of the logical flow between objects. The properties of the game are the variables used to store and access the data associated with each modelled object (Fig. 7). The models for the two historical periods were exported in a standalone .exe player file which allows the models to be run without having to load the program that generated them, in this case Blender.

The structure of the navigation interface was also developed with the Blender Logic Editor. Its objectives are to guarantee smooth navigation mesh movement through the keypad and joypad (such as the Dualshock4 wireless controller for PS4), to make it possible to pass quickly between the Imperial Roman and early medieval models, and to provide interactive

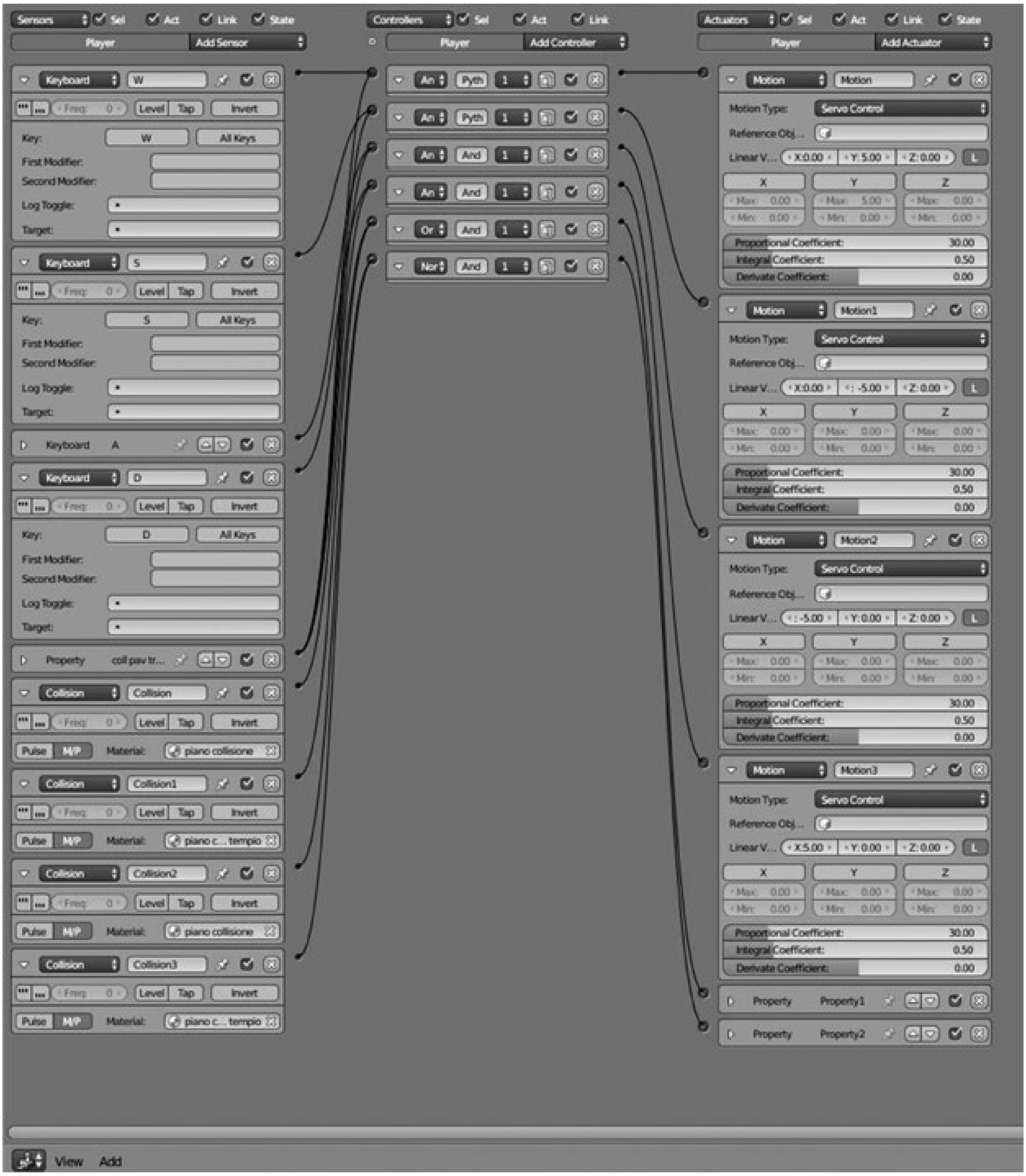

Fig. 7. The logic for the objects created and selected in the 3D panel consists of logic bricks, which are shown as a table with three columns, indicating sensors, controllers, and actuators.

information hotspots that can be accessed for all parts of interest in the 3D models. Hardware controls can be interfaced with input commands with the aid of several logic diagrams and scripts (Fig. 8).

The system with which the end user interfaces with the application includes a main menu, where the user can chose to begin navigating in person in one of the two historical periods, two models in axonometric view with the information hotspots that can be found while navigating through the model, and a screen with a map of the commands that can be used (Figs. 9–11).

4 Conclusion

Being able to use open-source tools to create real-time navigable 3D reconstructions opens up new and interesting prospects for communicating the cultural heritage, thanks to lifelike and photorealistic visualizations of objects and sites from the past. This enables scholars to verify hypotheses

```
        ### Mouselook System ###
        if self.props['mouselook']:
            if not self.features.get('mouselook', None):
                self.addMouselook()

        ### Staticmove System ###
        if self.props['static']:
            if not self.features.get('static', None):
                self.addStatic()

        ### Dynamicmove System ###
        if self.props['dynamic'] and not self.props['static']:
            if not self.features.get('dynamic', None):
                if self.own.parent:
                    self.addDynamic(self.cont)

    def main(self):
        # Refresh properties
        self.props = self.getProperties('mmc')
        self.controls.main()

        cursor = self.props['cursor']
        if cursor in [True, False]:
            render.showMouse(cursor)

        for i in self.features:
            if self.props[i] == True:
                self.features[i].main()
            elif self.features[i].ready == True:
                self.features[i].deactivate()

    def create(self, key, object):
        features = {'mouselook':Mouselook, 'static':StaticMove, 'dynamic':DynamicMove}

        if key in self.features:
            msg('Core Feature "', key, '" already created! Returning None')
            return None

        newFeature = features[key](self, object)
        self.features[key] = newFeature

        return newFeature

    def addMouselook(self, object=None):
        self.setProp('mmc.mouselook', True)
        return self.create('mouselook', object)

    def addStatic(self, object=None):
        self.setProp('mmc.static', True)
        return self.create('static', object)

    def addDynamic(self, object=None):
        self.setProp('mmc.dynamic', True)
```

FIG. 8. HARDWARE CONTROLS CAN BE INTERFACED WITH INPUT COMMANDS WITH THE AID OF SEVERAL LOGIC DIAGRAMS AND SCRIPTS.

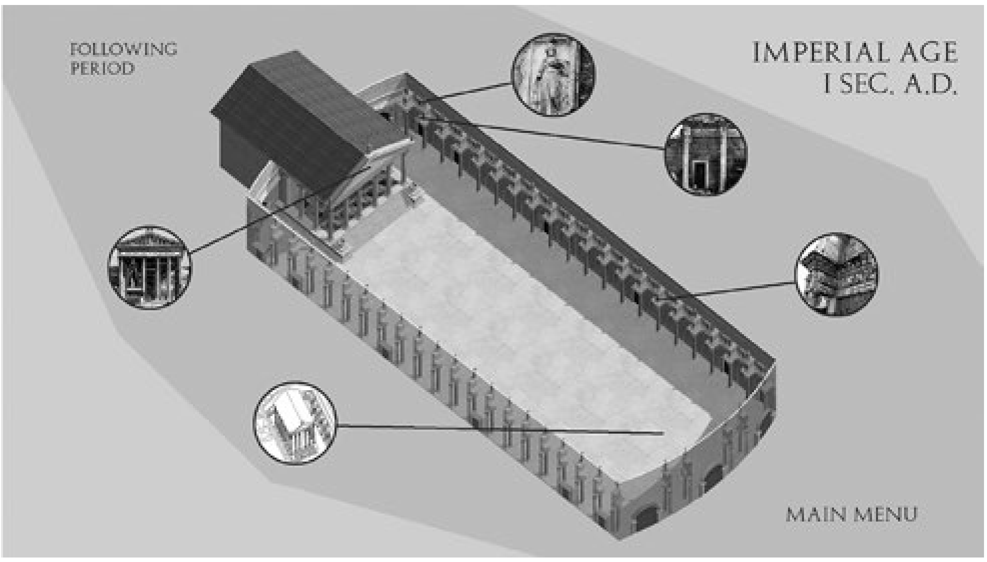

FIG. 9. IMPERIAL AGE MODEL IN AXONOMETRIC VIEW WITH THE INFORMATION HOTSPOTS THAT CAN BE FOUND WHILE NAVIGATING THROUGH THE MODEL.

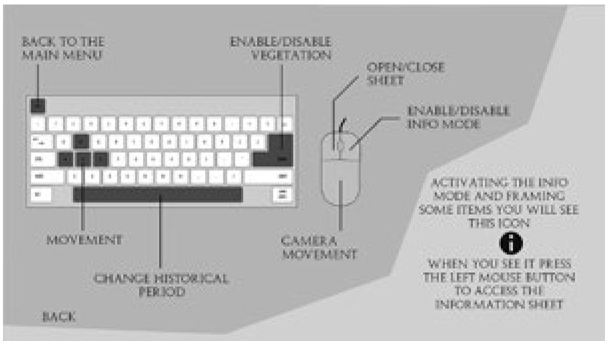

Fig. 10. Screen shot with a map of the keyboard commands.

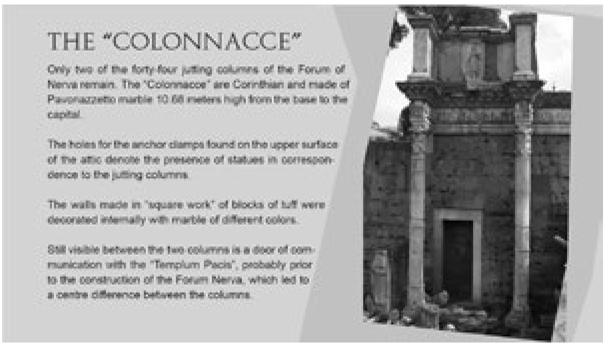

Fig. 11. One of the hotspot fact sheets of the Imperial Rome Age model.

Fig. 12. Real-time image of Imperial Rome Age. View from the west.

Fig. 13. Real-time image of Rome in the Middle Ages. View from the west.

Fig. 14. Real-time image of Imperial Rome Age. View from the south.

Fig. 15. Real-time image of Rome in the Middle Ages. View from the south.

regarding reconstruction and/or modify them in real time, while visitors can gain an understanding of what a site actually looked like in the period of its greatest splendour (Figs. 12–17).

The next stages of the research are in two main directions. The first will contemplate on the reconstructions of the Forum of Nerva in the Baroque period, late 19th century, and before the 1930 demolition. The second plans to extend the 3D reconstruction and the real-time navigation to the entire area of the Imperial Forums and the methodology can be applied to other sites of archaeological interest.

Furthermore, as visualization systems are evolving towards less powerful computing tools, such as smartphones and tablets, while maintaining an effective level of photorealism, the use of tools like blender4web and unity will allow the use of the real-time methodology described, including the shifting procedure from one age to another, directly on portable devices.

Bibliography

De Angelis, S. 1992. *Templum Divi Vespasiani*. Roma, De Luca.

Dylla, K., Frischer, B., Mueller, P., Ulmer A., Haegler, S. 2010. Rome Reborn 2.0: A Case Study of Virtual City Reconstruction Using Procedural Modelling Techniques. In: Frischer, B., Webb, J., Crawford, D. *Making History Interactive. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference*: 62-6. Virginia, Archaeopress.

Empler, T. 2006. *Modellazione 3D & Rendering*. Roma, Officina Edizioni.

Empler, T. 2008. *Software libero per la progettazione*. Roma, Dei.

Forte, M. 2008. *La villa di Livia. Un percorso di ricerca di archaeologia virtuale*. Roma, L'Erma di Bretschneider.

Guidi, G., Frischer, B. 2005. Virtualizing Ancient Rome: 3D Acquisition and Modelling of a Large Plaster-of-Paris Model of Imperial Rome. In A. Beraldin, E. Sabry, A.

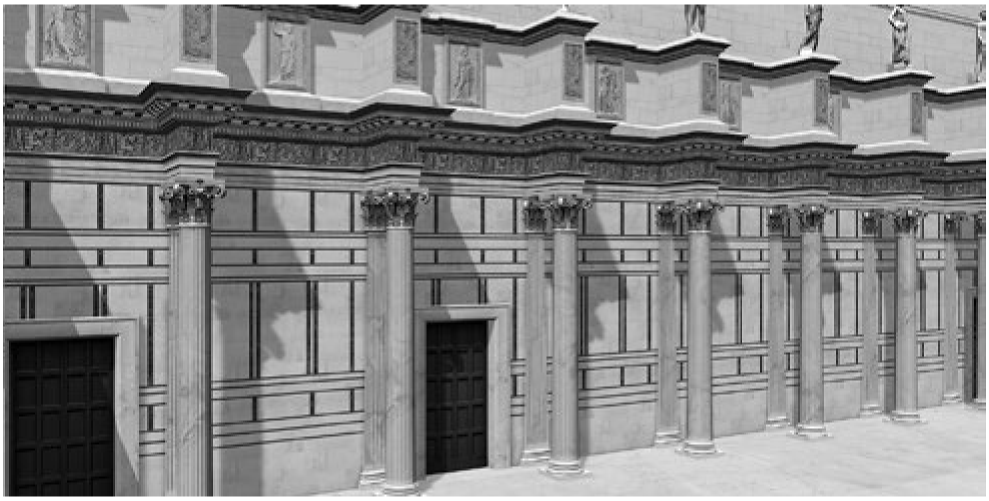

Fig. 16. Real-time image of Imperial Rome Age. View to the north side [looking north?].

Fig. 17. Real-time image of Rome in the Middle Ages. View to the north side [looking north?].

Gruen, J. Walton, *Videometrics VIII*: 119-33. San Jose, SPIE.

Lalle, A. 2005. *Il foro di Nerva e il tempio di Minerva: trasformazioni e utilizzo in epoca medievale.* In F.P. Fiore, *La Roma di Leon Battista Alberti. Umanisti, architetti e artisti alla scoperta dell'antico nella città del Quattrocento*: 230-1. Milano, Electa.

Leone, R. 2009. *Via dell'Impero, demolizioni e scavi: fotografie 1930-1943*. Milano, Electa.

Meneghini, R., Santangeli Valenzani, R. 2006. *Formae urbis Romae: nuovi frammenti di piante marmoree dallo scavo dei Fori Imperiali,* Bullettino della Commissione Archaeologica Comunale di Roma, 4: 28-57.

Meneghini, R. 2008. *Gli scavi dei Fori Imperiali: bilancio di un ventennio di indagini (1986-2008)*, Studi Romani, 56: 64-108.

Meneghini, R. 1991. *Il Foro di Nerva.* Roma, F.lli Palombi.

Meneghini, R. 2009. *I Fori imperiali e i Mercati di Traiano: storia e descrizione dei monumenti alla luce degli studi e degli scavi recenti.* Roma, Libreria dello Stato, Istituto poligrafico e Zecca dello Stato.

Meneghini, R., Santangeli Valenzani, R. 2007. *I Fori imperiali : gli scavi del comune di Roma (1991 – 2007)*. Roma: Viviani.

Meneghini, R., Santangeli Valenzani, R. 1993. *Roma tra antichità e Medioevo, V-VII. secolo*. Roma, F.lli Palombi.

Meneghini, R., Santangeli Valenzani, R. 2004. *Roma nell'altomedioevo: Topografia e urbanistica della città dal V al X sec.* Roma, Libreria dello Stato, Istituto poligrafico e Zecca dello Stato.

Pescarin, S., Fanini, B., Ferdani, D., Lucci Baldassari, G., Calori, L. 2011. Realism, Interactivity and Performance: a pipeline for large scale Virtual Heritage dataset on line. *DisegnareCon* 4, 8: 62-70.

Santangeli Valenzani, R. 2011. *Edilizia residenziale in italia nell'altomedioevo*. Roma, Carrocci.

Tortorici, E., Morselli, C. 1989. C*uria, Forum Iulium, Forum Transitorium*. Roma, De Luca.

Viscogliosi, A. 2000. *I Fori Imperiali nei disegni d'architettura del primo Cinquecento: Ricerche sull'architettura e l'urbanistica di Roma*. Roma, Gangemi.

Mediated Representations After Laser Scanning. The Monastery of Aynalı and the Architectural Role of Red Pictograms

Carlo Inglese
carlo.inglese@uniroma1.it

Marco Carpiceci
marco.carpiceci@uniroma1.it

Fabio Colonnese
f.colonnese@uniroma1.it

Department of History, Drawing and Restoration of Architecture, Sapienza University of Rome

Abstract: In Cappadocian rock-cut architectures, red pictograms painted on rock surfaces were long considered only as abstract decorations of the iconoclastic period to be lately converted into polychromic frescoes, but today other interpretations appear plausible. In the Monastery of Aynalı near Göreme, pictograms both decorate the key elements and describe visual hierarchies with the secondary consequence of transforming the architecture itself into a huge representation: a sort of full-scale model to evoke existing buildings and to design its final configuration. Integrated applications of laser scanning and digital photography today allow the study of these decorations together with the actual shape of rock surfaces supporting them, and may offer innovative contributes to archaeological and historical researches on Cappadocian rupestrian architecture.

Keywords: Monastery of Aynalı, Rock-cut architecture, Rupestrian habitat, Red pictograms

Introduction

The Open Air Museum in Göreme is a large semi-circular rock *cavea* constituting the heart of a singular confederation of ancient monastic communities. It is formed by a huge number of rock-hewn churches, such as St Catherine's Chapel, the Apple Church, the Sandal Church, the Pantocrator Church, and whole monasteries that barely survived the persistent geological erosion. In 1985 UNESCO inserted such a system of rupestrian settlements into the list of World Heritage sites for its unique anthropological, historical, and artistic value.

Since 2007 an Italian National Research on the Rock-cut Architecture has been working in Cappadocia[1] to study the environment and the monuments of the rupestrian habitat in order to support Turkish administrators and cultural operators in the complex actions of preservation, restoration, and transmission of their cultural heritage (Carpiceci 2013). The first achievements of this mission can be appreciated in the Forty Martyrs Church at Sahinefendi, recently restored and open to public.[2]

In the last two years the unit of Sapienza University of Rome has been surveying a number of carved monuments and produced drawings in the area of Göreme. Despite the fact that the executors of the 2013 and 2014 survey campaigns are almost the same and despite the strong analogies between the architectural subjects, deep differences exist between the results. The former campaign focused mainly on the Church of Forty Martyrs at Sahinefendi because the restoration of its significant painting cycle was to be rapidly completed. The 2014 campaign was based on these early results and expanded them to the surrounding areas in order to define the urban context of the Sahinefendi community (Carpiceci and Inglese 2015). The ultimate goal of this latter campaign was to define the church relationships with the urban context by focusing not only on its direct surroundings, but also on other isolated groups of rock-cave rooms. These two distinct phases resulted in a complete survey of the rupestrian village of Sahinefendi, with the Church of the Forty Martyrs at the heart of the whole area.

In the Open Air Museum in Göreme, the two-year survey campaign focused on the main churches located in the semi-circular auditorium, such as St Catherine's Chapel, the Elmali Kilise (Apple Church), the Carakili Kilise (Sandal Church), Azize Barbara Kilisesi (Church of Saint Barbara), and Karanlik Kilise (Dark Church). Finally, the original survey programme has been integrated with additional settlements near Göreme such as the Church of Aynalı with its monastery, which are the main subjects of this paper.

1 Notes on methodology and practice

The data acquisition using old and new technologies and post-production processing involve a necessary critical action that affects both the operative methodology and the specific site. For a decade, the operative unit from Sapienza University has been involved with the systematization of procedures for the architectural survey in the light of emerging technologies such as laser scanning, automated photogrammetry multi-stereo-

[1] Arte e habitat rupestre in Cappadocia (Turchia) e nell'Italia centromeridionale. Roccia, architettura scavata, pittura: fra conoscenza, conservazione, valorizzazione. National coordinator: Maria Crocifissa Andaloro; scientific director of Sapienza University unity: Marco Carpiceci. The research involves three scientific areas (L-ART/01 – History of Medieval Art; ICAR/17 – Drawing; GEO/07 – Petrology and Petrography) and offers a number of different approaches to the Cappadocian environment thanks to geologists, archeologists, historians, architects, engineers, preservers, restorers, chemists, botanists, geographers, and photographers taking part.

[2] See: http://www.operaipogea.it/?p=833 (accessed on 26 June 2015).

matching, and immersive photography. In Cappadocia the goal of this unit was to collect data related to the geometric shapes and colours of both interior and outer surfaces of a number of housing and monastery settlements in the rupestrian community of Göreme, within and outside the precinct of the Open Air Museum. The objective of these surveys was to build digital models of such settlements useful to orient and guide the work of local administrators, scholars, and restorers attending the reconstruction of historical events and the requalification of places and monuments. The lack of either epigraphic or textual sources that could offer information on the life and uses in rock-cut architecture has forced scholars to interpret their function directly from the formal characteristics of the artificial caves as well as from pictographic sources (Jerphanion 1925–42; Thierry 1963; Jolivet-Levy 2006). The quest for the actual form is thus fundamental for Cappadocian heritage where each single step or niche may reveal itself as a clue to uncovering a forgotten world.

Fig. 1. Sapienza Unit working with the laser scanner in the Göreme Open Air Museum (photo F. Colonnese).

1.1 Environmental and procedural problems

The team has faced a number of problems, primarily environmental: the rupestrian settlements are located on a plateau 1500 m above sea level, often dug several metres deep along the steep slopes of tufa and landslides, in some cases beaten by the wind. The campaign phase took place between late August and mid-September, in a warm and dry climate with a generally rarefied dusty air. According to the funds and time available, the team was composed of three members and equipped with a laser scanner. In the last few years laser-scanning technology has been both improving the precision in the acquisition of dimensional data and reducing costs and time taken. At the same time, the procedures of digital visualization offer surveyors a wide range of innovative and easy-to-use tools for both envisioning and navigating three-dimensional models.

The specific spatial characteristics of rupestrian architecture required an instrument that could be easily carried and used both in the difficult orographic conditions and in the dark narrow caves. A FARO laser scanner (Fig. 1) was preferred because of its physical characteristics of a lightweight, easy-to-handle, and powerful tool, compatible with accessibility and investigation problems presented by many sites. This results in a good compromise between the amount of equipment to be carried during the campaign, the time needed, and the quality of the data collected, ensuring a density of dots per inch able to record even the marks of excavation left by the ancient builders on the rock surfaces. The alternate use of two batteries allowed an extensive use of the laser scanner throughout the working day, but it is important to emphasize that on the hottest days, prolonged outside scanning occasionally caused overheating. This has sometimes forced operators to suspend the survey session and to switch off the laser scanner for 20 minutes in the shade of the nearest cave.

Other difficulties were caused by the presence of light, which can distort the results of the colour survey made by the digital camera integrated in the scanner (Carpiceci, Colonnese and Inglese 2015a). This problem affects both the scanning inside the caves, due to the artificial lights placed to show up the monuments and help tourists to appreciate them, and the external scanning because of the strong contrast between sunlit parts and shadows. In the former case it was enough to turn off the electric lights as most of the surveyed rooms are generally lacking doors and windows. Scanning was often performed in the twilight or in complete darkness to minimize environmental electromagnetic interference with the scanner. In the case of rooms with pictograms or painted surfaces, a specific photographic survey was made with an external digital camera and a specific lighting set to give a homogeneous light on surfaces. This procedure is necessary to capture the actual colours of the painted surface and to integrate the numeric model with proper chromatic data.

In the case of external scanning, a first *natural* solution is provided by providential clouds that pass before the sun diffusing its light. Otherwise, a supplementary lighting set should be used to reduce some critical shadows and contribute to a homogeneous aspect and colour of rock surfaces.

The survey of the interiors generally has preceded the survey of their facades or simply of the corresponding exterior rock surfaces. In this way, exterior scans were not only to be connected to the internal ones to evidence the relationship between extrados and intrados of monuments, but to offer a complete, if not exhaustive, digital model of the whole semicircular natural *cavea* of the Open Air Museum.

Complications came from the vegetation growing on the natural surfaces outside the artificial caves. Bushes and little trees block the laser beam and sometimes affect both the morphological continuity between outside and inside and a correct interpretation of the surveyed elements. In any case, apart from bending some plants or keeping them lower with heavy rocks, almost nothing can be done to solve this problem except to work in winter or reconstruct the missing parts in post-production.

A further problem is related to the temporal availability of certain places. During the opening time of the Open Air Museum thousands of tourists visit churches and monasteries every day, but groups also visit the sites outside the museum precinct. Not only their bodies may interrupt the laser scanning but the vibrations caused by people walking are probably amplified by the porosity of the earth support and affect the scanning results negatively. Especially for this reason, in addition to others

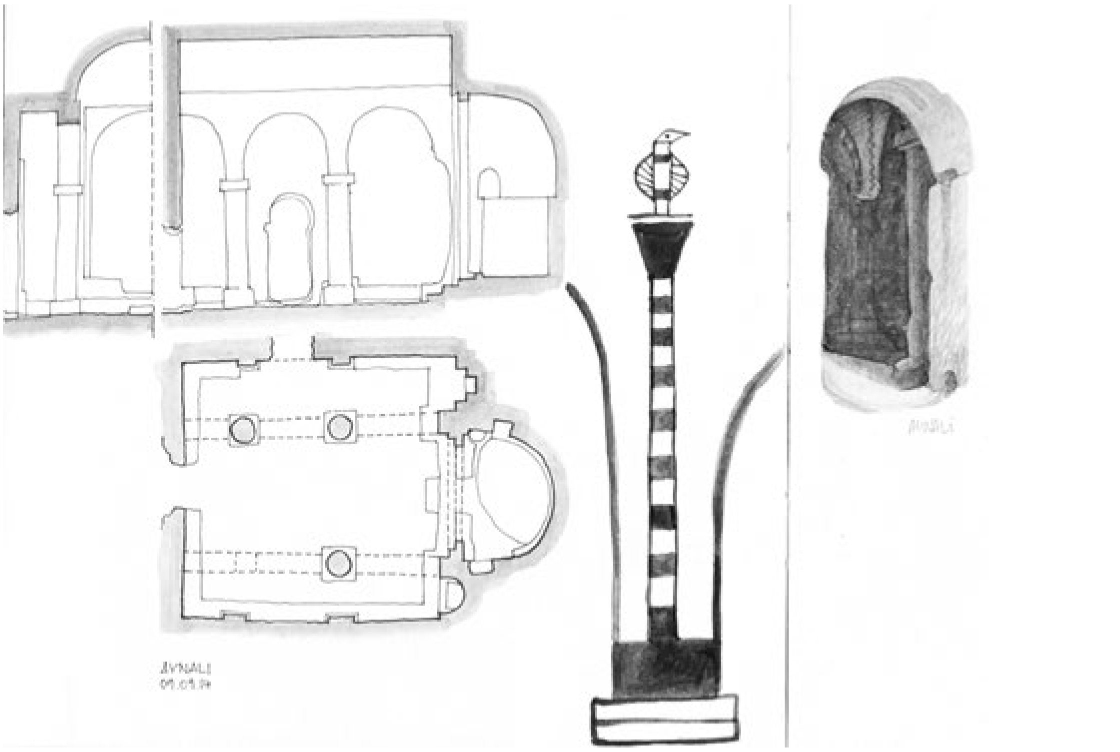

FIG. 2. GÖREME, CHURCH OF AYNALI, SKETCH FROM LIFE OF PLAN AND SECTIONS, DETAIL OF A DECORATION, ENTRANCE TO NARTHEX (WATERCOLOUR F. COLONNESE).

mentioned above, that the monastery of Karanlik Kilise — the Dark Church, *nomen omen* — was surveyed in darkness, during the evening hours from 7 to 10 pm, on three consecutive days (Carpiceci, Colonnese and Inglese 2015b).

1.2 Critical approach and representation after the numeric model

Scanning has been regularly performed through the use of reference spheres: at least three spheres must be detected in two adjacent scans to ensure their effective welding during the production phase of the general points cloud. Before each scan, the operators would search extensively in the neighbouring rooms and zones for the most advantageous point in which to place the spheres. During this operation, they made systematic observations at different heights through openings, rocks, and plants, while their bodies and minds were testing size, alignments, gradients, and spaces. This direct experience of places has been integrated not only with a canonical photographic campaign but also with sketches and watercolours (Figs. 2 & 3) drawn from life on several occasions, and has often fuelled doubts and questions that have later gradually grown to become key elements of investigation. This heterogeneous approach constitutes an antidote against the risk of relegating the knowledge of the site to the machine outcomes and provided the operators with a critical attitude to their own work, which is an essential contribution in the post-production stage.

Unlike the traditional additive architecture, in which a structure can be easily read in advance to establish the most significant and exhaustive representations, rock-cut architecture requires a deeper enquiry. The absence of repetition, symmetry, sharp edges, orthogonal corners, plane or constant dimensions,

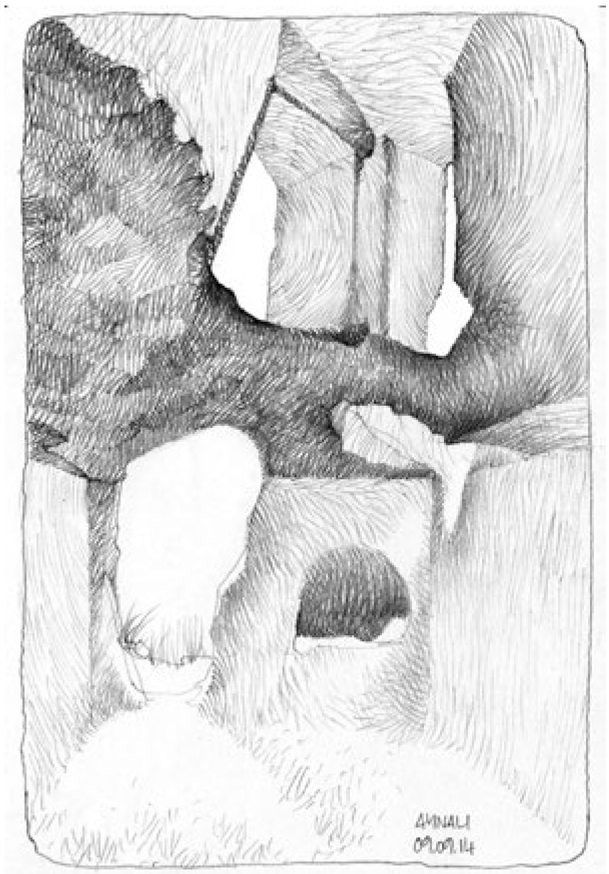

FIG. 3. GÖREME, MONASTERY OF AYNALI, SKETCH FROM LIFE OF A COLLAPSED ROOM ADJACENT TO THE CHURCH (WATERCOLOUR F. COLONNESE).

Fig. 4. Göreme, Monastery of Aynali, view of the tufa cliff in the distance (photo C. Inglese).

prevents operators from applying conventional criteria for applying section and projection planes as there is no guarantee they would be able to represent spaces as well as envision and communicate their properties and qualities. Thus specific procedure and drawings have been conceived to represent these rock-cut architectures.

After registration, the numerical model (per points) was processed and translated into a meshed model (per surfaces) but the sculptural nature of rock-cut architecture makes it impossible to choose and draw lines that describe apparent contours or edges unambiguously. Therefore a contour line representation was elaborated by producing a number of sections driven by the position of the significant section plans adopted at regular intervals. A number of significant section plans have been identified according to their ability to describe the complex morphology of the settlement: horizontal plans for the plans and vertical plans for elevations and sections. In cartographical practice the equidistance (i.e. the constant gap between successive contour lines) is conventionally set at 1/1000 of the denominator of the scale of representation in metres. For a canonical architectural representation 1:50 equidistance is 5 cm, but tests undertaken with this step have not given a readable result due to the excess visual data. Finally an equidistance of 10 cm was achieved in order properly to describe the architectural shapes without it becoming a sort of confusing background noise (Carpiceci 2015).

After pasting the specific photographic shots of the polychrome pictures on the meshed model, the decorative system can be finally studied together with the architecture itself. By navigating the model, a scholar can adopt the point of view of the ancient builders and decorators, even at a height of 4 m. Paintings and pictograms can thus be studied and analysed in their actual size and position; at the same time, their deformations and irregularities can be related to the surface conformation, the hypothetical position of the artist's body as well as their visual effect from below, obtained from photographs, watercolours, and memories.

2 The Church of Aynalı and its monastery

The monastic settlement of Aynalı is about 1 km from the Göreme Open Air Museum. The church and the rooms of the monastery are on two main levels and surround a rectangular courtyard, the southern facade of which is articulated on three levels of openings and arches (Figs. 4–6). Two of the three doors in the exterior wall open into the largest room of the complex, the so-called Sala Maior: its walls, articulated by pilasters, support a barrel vault with arches and are decorated with red geometric patterns (Fig. 7). An opening in the same wall leads to a smaller barrel-vaulted room that can also be entered from the courtyard. Another room lies near this one: it is accessible from outside, but most of it is lost after the cliff partially collapsed. An opening in the internal wall of the main room leads into a cave with a curved stair leading to the upper floor, while an opening in the western wall leads to the church.

The third opening in the south face of courtyard is the main entrance to the church (Fig. 8). A small square narthex with cross-arms welcomes believers and tourists: a dome covers it, just above four primitive pendentives in the corners. A side opening leads into a side square tomb room, with a niche and benches on two sides, while the front opening leads into the approximately square church. Four large columns (with one partially collapsed) divide the church space into three naves covered by barrel vaults and decorated with red symbols: a large central horseshoe-shaped apse and two smaller ones at its sides open in the east wall with their floor as high as the continuous bench running along the base of the walls.

Smaller irregular rooms characterize the upper floor. The stairs leads into a large storey carved over the main room, with niches and shelves on every wall and two more openings. A small tunnel leads into a circular cave in the north-west corner, while the cave zigzags in the east wall leading to a cave protected by a rolling door. A narrow oblique pit connects the latter cave with the lower room, where there is a second rolling door used to protect the passage from the rectangular room with a flat

Fig. 5. Göreme, Monastery of Aynali, view of the courtyard toward the entrance to the narthex (photo C. Inglese).

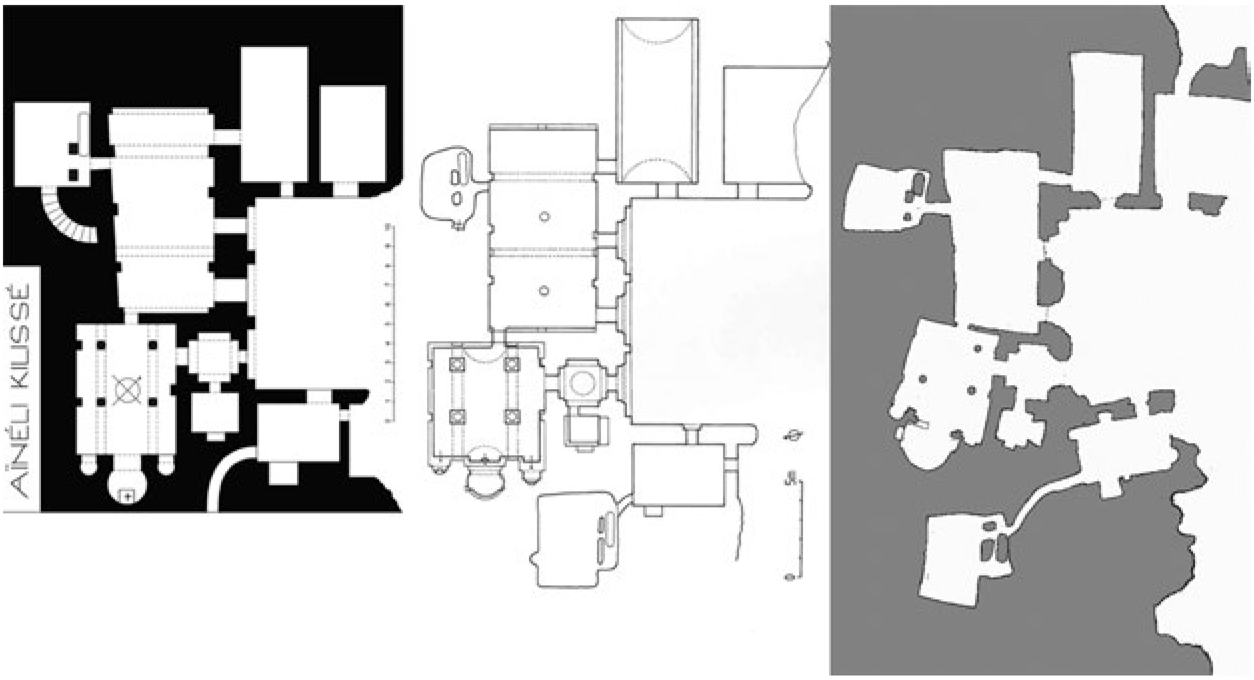

Fig. 6. Göreme, Monastery of Aynali, comparison between the ground floor plans according to Jerphanion (left) and Rodley (centre) with the plan after authors' survey in September 2014.

Fig. 7. Göreme, Monastery of Aynali, view of the Sala Maior toward the entrance to the church (photo C. Inglese).

Fig. 8. Göreme, Church of Aynali, view toward the passage to Sala Maior (photo C. Inglese).

ceiling behind the east face of the courtyard. The missing parts of the ceiling reveal another room above, which is a part of a linked system of rooms with stables and a vinery extending along the north-east cliff, and accessible through many openings in the fallen cliff.

2.1 Functional and morphological considerations

The passage of time and the unstoppable erosive process have made it difficult to distinguish the evolutionary history of the monastery of Aynalı Church. The assemblage of more than 50 scans produced in three different days have revealed the concealed relationships between the architectural volumes carved into the tufa and allow some hypotheses on the general organization.

The general plan embodies a clear and efficient idea of the organization of interior spaces. The external openings seem clearly designed to offer a unitary mutual visibility to ensure control and defence, while the internal openings are not aligned to avoid enfilades and favour a maze-like effect.

The presence of the red decorations identify the rooms on both the ground floor and the upper floor overlooking the courtyard as belonging to an initial core. Among the decorated rooms, the small porch and the church are those whose function can be detected no doubt thanks to their form. The church has the typical *tetrastila* plan with three apses. While most of other churches of the Göreme Open Air Museum present domes arranged crosswise with respect to the centre of the main aisle, clearly showing a centric attitude, the church of Aynalı displays a longitudinal structure with an uninterrupted barrel vault covering the main aisle ending with a deep apse, configuring a kind of Serliana-shape section (Fig. 9).

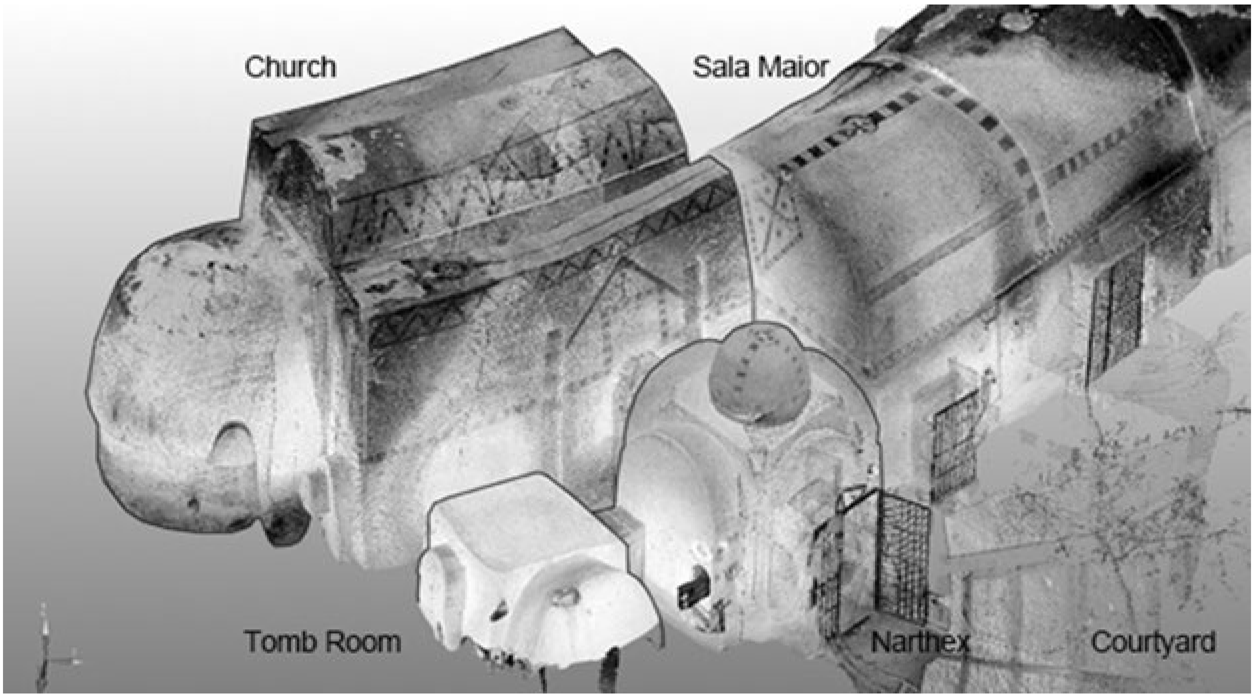

Fig. 9. Göreme, Monastery of Aynali, axonometric view from the numeric model after points cloud (image M. Carpiceci).

The Sala Maior has a large barrel vault divided by three light arches and is directly connected with the church. Its original function is still uncertain but it certainly embodies the heart of the monastery. The general size as well as the openings into the courtyard, towards the last decorated room as well as the interior room with a staircase protected by a door, qualify this room as the most important for access to the monastery. It is possible that it was originally used as a refectory: perhaps the usual carved mensa that can be found in all the other monasteries of this area was later destroyed because the room was destined for different uses. Otherwise, the absence of a traditional refectory in the monastery of Aynalı would raise doubts on its religious function.

The most important contribution of the scan laser survey consists in measuring by subtraction not only the rock envelope surrounding the carved rooms and plan their correct preservation in time, but the actual curved nature of all interior surfaces. The barrel vaults themselves follow lines that correspond neither to a cylindrical geometry, nor a conical one, but to a longitudinal extrusion path that gradually changes direction and angle of deformation. The resulting surfaces are recognizable as similar to cylinders and planes but despite the efforts of many scholars such as Jerphanion (1925–42) and Lyn (1985), they are hardly reducible to any elementary geometric pattern (Fig. 10) and quite correctly, recent historical studies seem to consider deformations as an essential element of plans and sections (Kalas 2009).

The mismatch between the actual carved rooms and the regular geometric scheme behind them cannot be considered simply as a technical inability, but as a specific approach by the builders. Such an efficient organization and distribution could not match an inappropriate but careful material execution of the carving process. We believe that the mismatch between the actual carved rooms and the regular geometric scheme behind them must necessarily also be the result of a precise requirement.

Both structural and aesthetic reasons could lie behind the choice of adopting curved shapes and surfaces. Empirical knowledge possibly convinced those ancient architects that formal resistance of curved shapes contributes to a better structural behaviour in both walls and ceilings. Moreover, the curved shape is the most suitable and natural one for carved architecture: the process of excavation tends to progress, placing the operators at the centre of a theoretical sphere and the movement of their arms follows an arch, too, as can be seen in the furrows on the walls.

3 The dichromatic pictograms in the Aynalı Church

Most of the artificial caves in the area of Göreme do not present painted decoration, only low-relief pseudo-architectural elements that embellish the space, while a number of them show a varied range, from pictograms to complex paintings. According to the use of colour and the level of accuracy, these decorations can be roughly classified in three categories, which sometimes relate to the different periods of the settlement. A first category is constituted by monochrome — generally red ochre — decorations painted directly onto the rock. A second category is formed by polychrome painted decorations, with wide blue and green fields added to red ochre motifs. Historians such as Richard Krautheimer (1986: 432) generally considered these monochrome pictograms as a form of aniconic decoration and used them to date the architecture to the iconoclastic period or immediately after (AD 843).

In the third category are figurative fresco-like decorations that embellish the most important religious buildings, such as the Church of Forty Martyrs and the famous Tokali Kilise — often

Fig. 10. Göreme, Monastery of Aynali, general plan in contour lines (equidistance = 10 cm) after points cloud. In blue, the lower level; in green the middle level; in green the higher level (image M. Carpiceci).

with the secondary consequence of dematerializing the interior surfaces and visually wiping out the architectural fiction of the carved parts.

The red monochrome decorations in the Aynalı church and the Sala Maior belong to the second category and beyond the aesthetic function, contribute to their spatial sense as an architectural semantic tool. The most obvious feature is, for example, the demarcation in light and dark bands of all the intrados of the arches (Fig. 11). In some cases this band also runs through the ridge generatrix, as in the case of the Sala Maior and in the subdivision in four of the intrados of the narthex dome. In the pseudo-refectory chiaroscuro bands run horizontally around the perimeter of the room demarcating the impost line of the barrel vault. In this case an alternation between light and dark fields along the southern wall is duplicated on two overlapping bands creating a chequered cornice. In the Sala Maior the band running along the impost line is formed by a chequer motif with triangular fields in place of rectangles (Fig. 12).

In his *Cave Monasteries of Byzantine Cappadocia*, Rodley (1985: 62–63) gives an accurate description of the red signs decorating the interior space of the Aynalı church. 'The arches

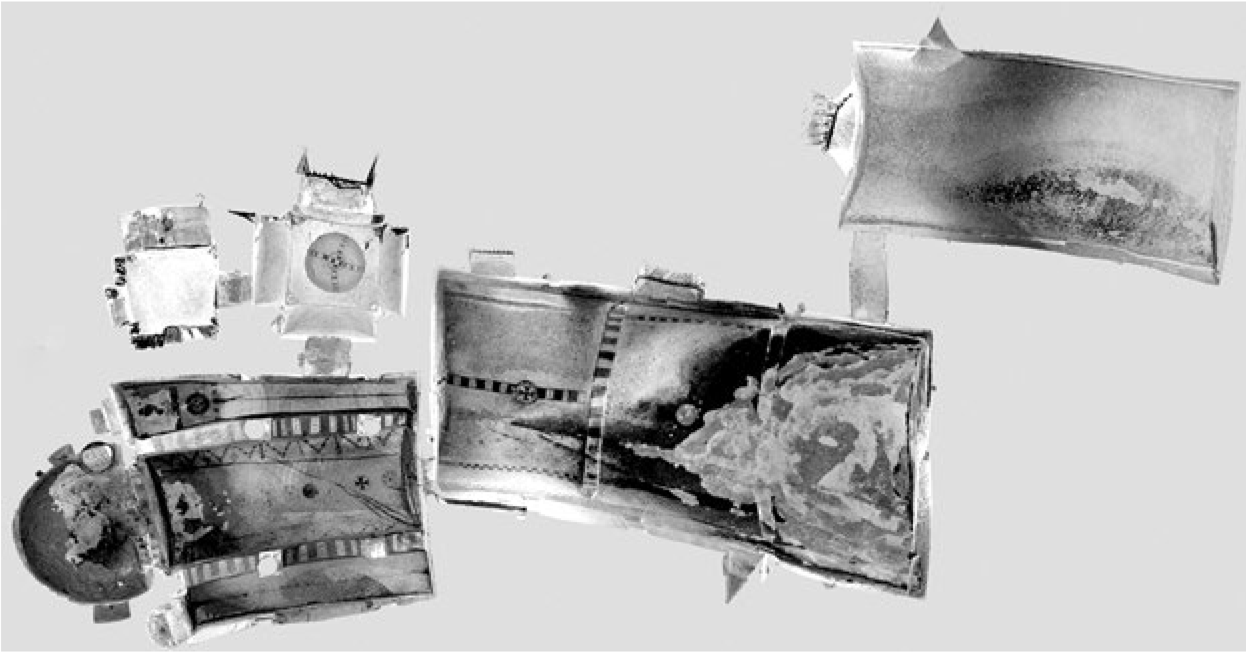

Fig. 11. Göreme, Monastery of Aynali, *ipografia* (bottom-up orthogonal projection) from the numeric model after points cloud (image M. Carpiceci).

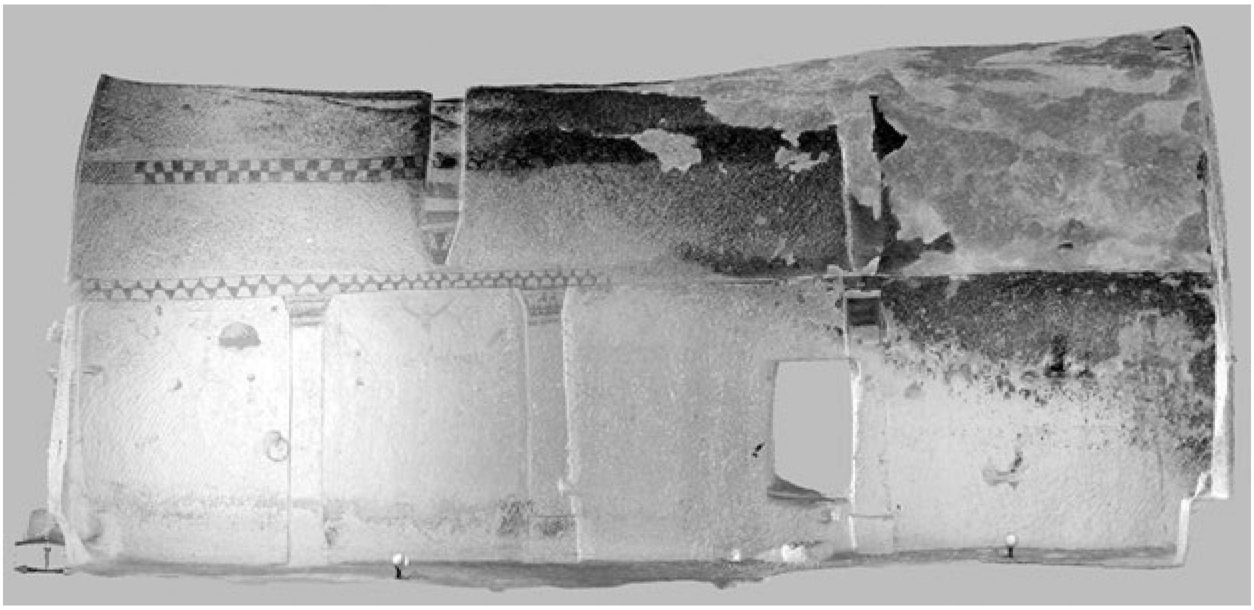

Fig. 12. Göreme, Monastery of Aynali, orthogonal projection of the Sala Maior south-west wall from the numeric model after points cloud (image M. Carpiceci).

of the arcades are rimmed with red and rectangles of "domino" patterns. A line of ten medallions containing various motifs (…) runs along the crest of the barrel vault. The vault is divided into two registers each side by red bands, below which are broad zig-zag bands of red and white chequer pattern (…) [and] painted pillars topped by devices of various forms (…). In the lunette above the apse another cross, enclosed in a kite-shaped border, is surmounted by a medallion containing a vertical eight-lobed pattern, flanked by two quadrupeds (…). A chequer pattern rims the recess in the east wall and the soffit of the apse arch is similarly decorated. In each spandrel flanking the arch is an equal-armed cross. The apse has a cross in a kite-shaped border in the conch and a chequered "cornice" below the conch. North and south walls of the naos have a chequered band painted at the level of the arcade capital and another at the tops of the walls, decorated with a zig-zag pattern, above the painted band

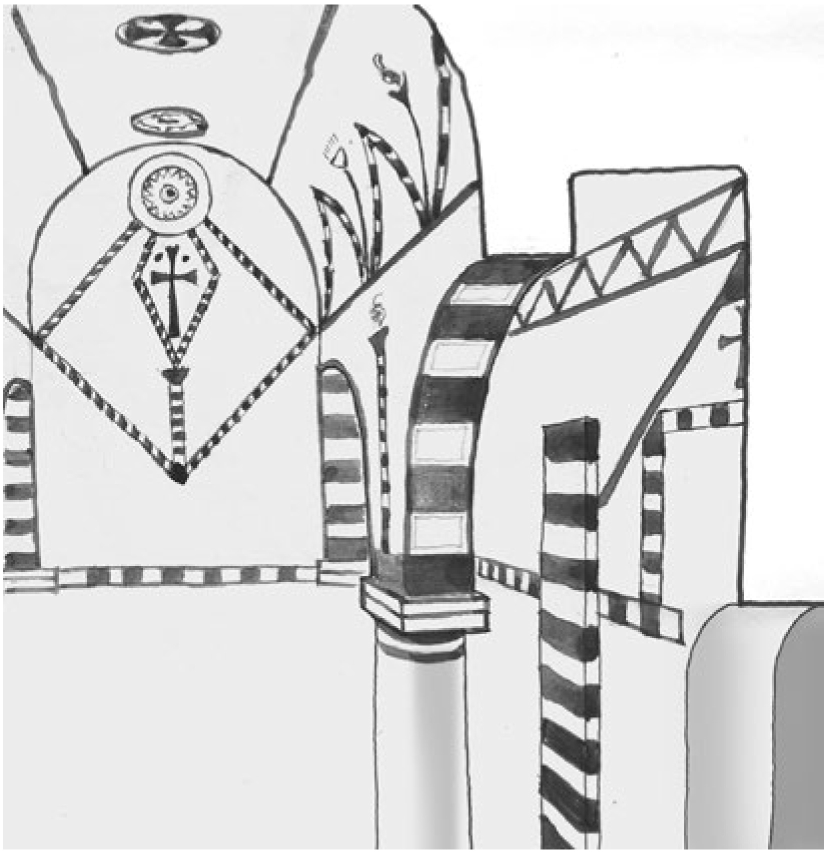

Fig. 13. Göreme, Church of Aynali, sketch looking towards the passage to Sala Maior (watercolour F. Colonnese).

of the north aisle is a painted keyhole shape with a gable above it; there is a further keyhole shape in the equivalent position on the south aisle wall. A red band runs along the ceilings of both aisles and the ceiling of the north aisle also has two medallions in square frames at the east end. The naos entrance in the north wall is flanked by carved pilasters, painted with the domino pattern, which end about 1 metre above the entrance; a painted gable links them. The painted band rises above the entrance to form three sides of a square. A similar arrangement is found in the opposite space on the south wall where, however, there is no entrance'.

Most of these geometric decorations are easily recognized when compared with architectural elements in buildings of the same area and period. As testified by the pictures, most of them show a predominant geometric character and are generally used to describe and highlight the rock-cut surfaces according to those elements, which play the figurative role of architectural components such as columns, pilasters, capitals, architraves, and cornices. A number of examples can be suggested: the red and white '"domino" pattern' on the arches of the arcades evokes a dichromatic masonry arch; the 'broad zig-zag bands of red and white chequer pattern' on the low part of the barrel vault can be easily interpreted as the representation of triangular lunettes opening in the vault itself; the horizontal red lines on the upper part of the columns and the pseudo capitol describe the specific parts of a Doric order such as abacus, echinus, collar, and so on; the 'carved pilasters, painted with the domino pattern' with a 'painted gable' linking them and a 'painted band' forming 'three sides of a square' remind one of the sort of altarpiece or triumphal gateway to the square narthex and the square tomb room, as in a traditional church chapel (Fig. 13).

Other pictograms are quite abstract representations of decorative elements used in Roman and medieval architecture. The 'painted pillars topped by devices of various forms' or the 'medallions containing various motifs' look like a direct transposition of decorations seen elsewhere; even the recurring chequer bands could be interpreted as the visual effect of rotated brick patterns in the wall, as can be seen, for example, in the Byzantine church of St Theodore in Athens (12th century). If confirmed, this aspect could be quite interesting as the pictograms are depicting their visual effect rather than brick edges.

Some pictograms instead represent archetypical symbols like crosses and swastikas as well as animals and natural elements, such as birds and plants. Some of them could be representations of existing icons from either religious or military standards: 'the pillar carrying birds, in particular, may be seen as distant country cousins of roman eagles' (Rodley 1985: 62). But other pictograms, such as the 'two quadrupeds' and some of the birds, could be considered as a picture of something Cappadocian artists had seen and depicted from life.

There is something special in the pictograms of Aynalı church that was generally neglected by scholars: they are not monochrome and light-grey painted signs can often be

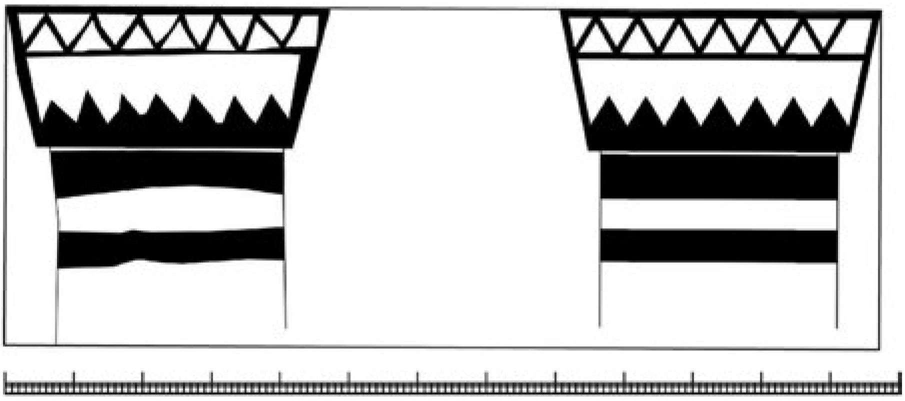

FIG. 14. GÖREME, CHURCH OF AYNALI, SCALE DRAWING OF THE PICTOGRAM ON THE SIDE WALL OF THE SALA MAIOR (DRAWING C. INGLESE).

seen near red ones. The grey signs seem to play at least three contemporary roles in relation to the red ones. Sometimes they are below the red signs, as a construction scheme for the most complex figures. Sometimes they define the role of the blank areas as a semantic complement of the red adjacent fields, like the white tassels of the domino pattern on the arches of the arcades, where grey points and filled circles characterize them according to many different schemes. Finally grey paint is occasionally used as a substitute for red in some decorative patterns, as can be seen in the kite-shaped chequered band around the cross on the wall of the main room, just above the entrance to the church (Figs. 14–17).

3.1 Rock-cut architecture as a 1:1 model

The red decorations of the Aynalı Church, like other churches of the same period and area, must be primarily considered as the very last stage of architectural achievement. Their depiction is to be connected to some sort of apotropaic process of sanctification, which was imposed by the need to use those spaces as soon as possible, only in few cases delaying the moment of the creation of the more articulated decorations. Even if these pictograms appear to be the result of hasty and rough work, their symbolic value and meaning should not be underestimated. First of all, the presence of a second colour on the walls of the church of Aynalı, even if only a light grey, gives the pictograms a sense of permanency as if appositely designed to represent the architectural visual definition elements in a definitive way. Secondly, the form and colour seem to have been conceived to work together to support the architectural fiction: some carved forms can be rough and approximate because the colour gives them an optic contribution to denote their specific role. On the other hand, the pictograms can be monochromatic or dichromatic, as the element is already characterized by its form and position in the architectural envelope. This is an interesting way of economizing efforts and shortening the time of construction without renouncing a correct visual identification of the parts.

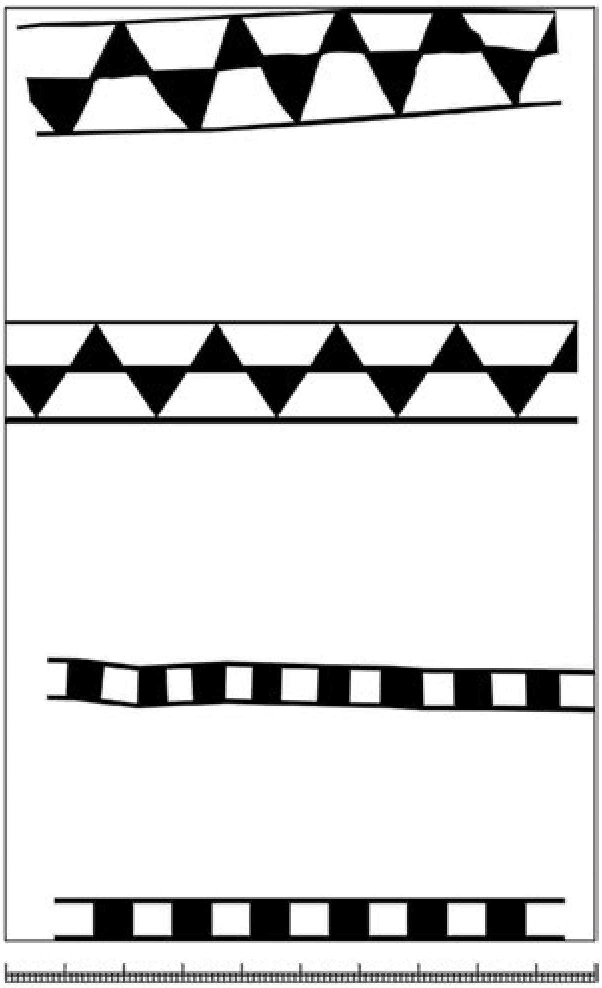

FIG. 15. GÖREME, CHURCH OF AYNALI, SCALE DRAWING OF THE PICTOGRAM ON THE SIDE WALL OF THE SALA MAIOR (DRAWING C. INGLESE).

While in *traditional architecture* the elements of the orders describe the visual hierarchies and structural behaviour of the parts, in Cappadocian rock-cut architecture this function is filled by red pictograms, with the secondary consequence of transforming architecture like that of the Aynalı Church into a huge representation, a sort of full-scale model (Colonnese

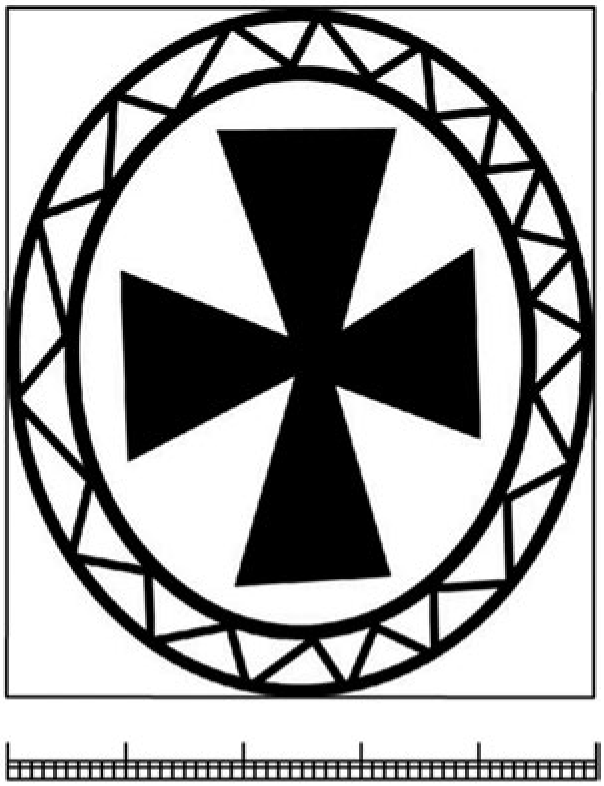

Fig. 16. Göreme, Church of Aynali, scale drawing of the pictogram on the vault of the Sala Maior (drawing C. Inglese).

2015) with two different meanings. Firstly, it is a model through which the church itself is gradually designed and perfected, like in a sort of sculptural *direct forming*, as defined by George Bauer (1981); secondly it is a model referring to existing traditional churches, through both its spatial typology and most of its depicted decorations. It could even be defined as an intertextual work as most of its depicted parts require a ‘cooperative interpretation’ (Eco 1979) by the people looking at them, who should be aware of their representative mission as well as the distant buildings they refer to.

4 Conclusions

Laser scanning technology has proved particularly suitable and effective in the process of the acquisition of metric data from the artificial caves that form the rock-cut settlements in Cappadocia. In a rocky territory subjected to aggressive erosion, such scans have an intrinsic importance both as a three-dimensional mould of places of great historical-documentary and artistic value, and as a tool to screen the erosive process itself. Some expedients have been developed to overcome some of the environmental and functional difficulties. For example, the chromatic survey of the interiors, especially in the case of pictorial surfaces, has required a photographic integration with controlled lighting conditions.

The knowledge developed by operators through both direct experience of places and sketches and pictures, has been useful to lead the post-production and representation after the model that has resulted in the development of orthogonal projections; this is possibly the most affordable way visually to transmit metric information and spatial relationships between the

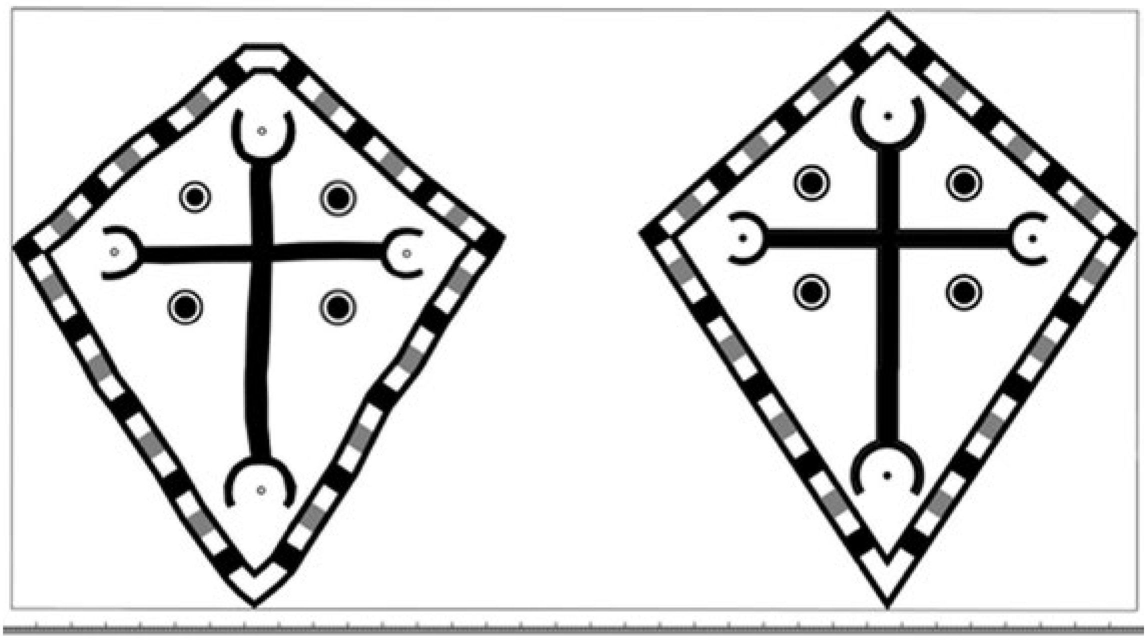

Fig. 17. Göreme, Church of Aynali, scale drawing of the pictogram on the wall of the Sala Maior (drawing C. Inglese).

various environments and between these and the outside. Plans and sections have highlighted the inherently curved geometries that characterize the carved spaces and which cannot be ignored or reduced as a consequence of the technical limits of the manufacturers, but offer themselves as a key to interpreting both uses and construction periods.

The meshed model with the application of the internal photographic maps has allowed the study of decorative elements in their true form and location, according to their execution and visual effect, in order to evaluate their iconographic role in the Aynalı Church and its monastery.

Acknowledgements

This paper is the result of a synergistic collaboration between the three authors, fuelled by suggestions from other participants to the Italian mission, especially Maria Andaloro and Giuseppe Romagnoli. Specifically, Carlo Inglese is responsible for *Introduction* and *The Church of Aynalı*; Marco Carpiceci for *Functional and morphological considerations*; and Fabio Colonnese for *Notes on methodology and practice*, *Environmental problems*, *Critical approach*, *The dichromatic pictograms*, *Rock-cut architecture*, and *Conclusions.*

Bibliography

Bauer, G. 1981. Bernini e i ‘modelli in grande’. In M. Fagiolo and G. Spagnesi (eds.), *Gian Lorenzo Bernini architetto e l’architettura europea del Sei-Settecento*: 279-90. Roma, Istituto della Enciclopedia italiana.

Carpiceci, M. 2013. Cappadocia Laboratorio-Rilievo (2007-2015). In M. Filippa and A. Conte (eds.), *Patrimoni e Siti Unesco, memoria, misura e armonia*: 221-9. Roma, Gangemi.

Carpiceci, M. 2015. Rilievo morfologico e rappresentazione dell’architettura rupestre. In G. Bordi, I. Carlettini, M. L. Fobelli, M.R. Menna, P. Pogliani (eds.), *L’officina dello sguardo. Studi in onore di Maria Andaloro* II: 385-91. Roma, Gangemi.

Carpiceci, M. and Inglese, C. 2015. Laser scanning and Automated Photogrammetry for Knowledge and Representation of the Rupestrian Architecture in Cappadocia: Sahinefendi and the Open Air Museum of Göreme. In F. Giligny, F., Djindjian, L. Costa, P. Moscati, S. Robert (eds.), *CAA2014. 21st Century Archaeology Concepts, methods and tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA)*: 87-94. Oxford, Archaeopress.

Carpiceci, M., Colonnese, F. 2014. Rilievo e documentazione del colore in architettura: un problema attuale e irrisolto / Survey and documentation of color in architecture: a current unsolved problem. In S. Bertocci and S. Van Riel (eds.), *La cultura del restauro e della valorizzazione. Temi e problemi per un percorso internazionale di conoscenza*: 189-96. Firenze, Alinea.

Carpiceci, M., Colonnese, F., Inglese, C. 2015b. La caverna svelata. Il monastero di Karanlik e la rappresentazione digitale del patrimonio rupestre. In *ReUSO 2015. III Congreso Internacional sobre Documentación, Conservación, y Reutilización del Patrimonio Arquitectónico: Paper Book*: 635-42. Valencia, Universitat Politecnica de Valencia.

Carpiceci, M., Colonnese, F., Inglese, C. 2015a. Potential and limitations of new technologies for the survey of morphology and colour of rupestrian habitat. In M. Parise, C. Galeazzi, R. Bixio, C. Germani (eds.), *Opera Ipogea. Suppl. 1/2015. Hypogea 2015. Proceedings of International Congress of Speleology in Artificial Cavities.* Rome, 11-17 march 2015: 399-406.

Colonnese, F. (forthcoming). Die Erfahrung mit lebensgroßen Modellen im Entwurfsprozess. In *Manifestationen im Entwurf in Architektur, Design und Ingenieurwesen*. Aachen.

Eco, U. 1979. *Lector in fabula. La cooperazione interpretativa nei testi narrativi*. Milano, Bompiani.

Jerphanion, G. de 1925-1942. *Une nouvelle province de l’art byzantin: les églises rupestres de Cappadoce*. Paris, P. Geuthner.

Jolivet-Levy, C. 2006. *Sacred Art of Cappadocia: Byzantine murals from the 6th to 13th centuries*. İstanbul, Ertuğ & Kocabıyık.

Kalas, V. 2009. Sacred Boundaries and Protective Borders: Outlying Chapels of Middle Byzantine Settlements in Cappadocia. In: Gates, C., Morin, J., Zimmermann, T. (eds.), *Sacred Landscapes in Anatolia and Neighboring Regions*: 79-91. Oxford, British Archaeological Reports.

Krautheimer, R. 1986. *Architettura paleocristiana e bizantina*. Torino, Einaudi.

Rodley, L. 1985. *Cave Monasteries of Byzantine Cappadocia*. Cambridge and New York, Cambridge University Press.

Thierry, N. 1963. *Nouvelles églises rupestres de Cappadoce: Région du Hasan Dağı.* Paris, C. Klincksieck.