



THE THREE DIMENSIONS OF ARCHAEOLOGY

PROCEEDINGS OF THE XVII UISPP WORLD
CONGRESS (1-7 SEPTEMBER 2014, BURGOS, SPAIN)

Volume 7/Sessions A4b and A12

Edited by

Hans Kamermans, Wieke de Neef, Chiara Piccoli,
Axel G. Posluschny and Roberto Scopigno

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the Ojo Guareña Karst complex (Merindad de Sotoscueva, Burgos, Spain)*

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Foreword to the XVII UISPP Congress Proceedings Series Edition

Luiz OOSTERBEEK
Secretary-General

UISPP has a long history, starting with the old International Association of Anthropology and Archaeology, back in 1865, until the foundation of UISPP itself in Bern, in 1931, and its growing relevance after WWII, from the 1950's. We also became members of the International Council of Philosophy and Human Sciences, associate of UNESCO, in 1955.

In its XIVth world congress in 2001, in Liège, UISPP started a reorganization process that was deepened in the congresses of Lisbon (2006) and Florianópolis (2011), leading to its current structure, solidly anchored in more than twenty-five international scientific commissions, each coordinating a major cluster of research within six major chapters: Historiography, methods and theories; Culture, economy and environments; Archaeology of specific environments; Art and culture; Technology and economy; Archaeology and societies.

The XVIIth world congress of 2014, in Burgos, with the strong support of Fundación Atapuerca and other institutions, involved over 1700 papers from almost 60 countries of all continents. The proceedings, edited in this series but also as special issues of specialized scientific journals, will remain as the most important outcome of the congress.

Research faces growing threats all over the planet, due to lack of funding, repressive behavior and other constraints. UISPP moves ahead in this context with a strictly scientific programme, focused on the origins and evolution of humans, without conceding any room to short term agendas that are not root in the interest of knowledge.

In the long run, which is the terrain of knowledge and science, not much will remain from the contextual political constraints, as severe or dramatic as they may be, but the new advances into understanding the human past and its cultural diversity will last, this being a relevant contribution for contemporary and future societies.

This is what UISPP is for, and this is also why we are currently engaged in contributing for the relaunching of Human Sciences in their relations with social and natural sciences, namely collaborating with the International Year of Global Understanding, in 2016, and with the World Conference of the Humanities, in 2017.

The next two congresses of UISPP, in Melbourn (2017) and in Geneva (2020), will confirm this route.

The Three Dimensions of Archaeology – Introduction

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This volume brings together presentations from two sessions organized for the XVII World UISPP Conference that was held from 1-7 September 2014 in Burgos (Spain). The sessions are: *The scientific value of 3D archaeology*, organised by Hans Kamermans, Chiara Piccoli and Roberto Scopigno, and *Detecting the Landscape(s) – Remote Sensing Techniques from Research to Heritage Management*, organised by Axel Posluschny and Wieke de Neef. The common thread amongst the papers presented here is the application of digital recording techniques to enhance the documentation and analysis of the spatial component intrinsically present in archaeological data. For a long time the capturing of the third dimension, the depth, the height or z-coordinate, was problematic. Traditionally, excavation plans and sections were documented in two dimensions. Objects were also recorded in two dimensions, often from different angles. Remote sensing images like aerial photographs were represented as flat surfaces. Although depth could be visualized with techniques such as stereoscopes, analysis of relief was troublesome. All this changed at the end of the last century with the introduction of computer-based digitization technologies, 3D software, and digital near-surface sampling devices. The spatial properties of the multi-scale archaeological dataset can now be accurately recorded, analysed and presented. Relationships between artefacts can be clarified by visualizing the records in a three-dimensional space, computer-based simulations can be made to test hypotheses on the past use of space, remote sensing techniques help in detecting previously hidden features of landscapes, thus shedding light on bygone land uses.

The methods and techniques that fall under the broad definition of 3D archaeology have now reached a mature state, where the advance in technology is at the service of archaeological research.

The session on *The scientific value of 3D archaeology* was dedicated to the presentation of methods, techniques and applications within the broad topic of 3D archaeology, with a specific focus on their scientific relevance. The papers selected for publication give a good overview of the application of digital 3D methodologies in archaeology, discussing how the use of 3D models has helped in the analysis and interpretation of archaeological evidence in a way that could not have been achieved by traditional documentation. The volume opens with the paper by Tjilm Lanjouw, which considers the application of 3D visualizations in archaeology from a theoretical perspective, focussing especially on digital reconstructions and virtual reality applications. Dominic Powlesland discusses the benefits of 3D imaging to accurately document the excavation process and enhance its interpretation, drawing on the experience accumulated by the Landscape Research Centre in Yorkshire. Martijn van Leusen and Serge van Gessel take into consideration the archaeological requirements of a 'true' 3D GIS,

which were discussed in the related session at the 2012 CAA Dutch-German chapter meeting. On the same subject, the paper by Victor Klinkenberg shows the usefulness of a 3D GIS for the interpretation of the 3D distribution of burials and artefacts at the site of Tell Sabi Abyad in Syria. Delphine Lacannette, Catherine Ferrier, Jean-Christophe Mindeguia, Evelyne Debard and Bertrand Kervazo present their research on a three-dimensional fire simulation in the Chauvet-Pont-d'Arc cave (France). Their study aimed to identify the zones that were suitable for occupation within the cave, by simulating temperature, smoke and the distribution of toxic gases of the fires that were lit inside. Next, the paper by Jose L Caro, Víctor Jiménez-Jáimez and José Enrique Márquez-Romero presents the result of digital photogrammetry applied to the prehistoric ditched enclosures of Perdígões (Portugal). Dealing with the application of photogrammetric techniques is also the paper by Lioudmila Iakovieva, François Djindjian and Yves Egels, which focusses on the 3D documentation of the Palaeolithic mammoth bone dwelling at Gontsy (Ukraine). Elias López-Romero, Patricia Mañana-Borrazás, Alejandro Güimil-Fariña and Marie Yvane Daire discuss the benefit of a 3D documentation of coastal heritage sites, which are threatened by erosion, focussing on selected case study areas in Galicia (Spain), Brittany (Western France) and Isles of Scilly (Britain). Finally, Patricia Mañana-Borrazás, Rebeca Blanco-Rotea and José Carlos Sánchez-Pardo present the methodology they have adopted for the 3D documentation of early medieval churches in Galicia (Spain), which enables stratigraphic analysis of the structures and an easy dissemination of their results.

The second part of this volume collects the papers that were selected for publication among those that were presented at the session *Detecting the Landscape(s)*. Techniques such as aerial reconnaissance, Airborne Laser Scanning (LiDAR), Geophysics, UAVs etc. have become major sources of archaeological information, especially for large areas and landscapes as a whole. Each of these techniques adds to the integration of the third dimension in archaeological research. The aim of this session was to highlight the great potential of these techniques for all aspects of landscape archaeology, including but not restricted to site detection, landscape research, heritage management, site and landscape preservation. Speakers were invited to place special focus on national and regional survey strategies and to discuss different research scales, from broad-brush to site specific approaches.

The participants in this session highlighted the application of non-invasive or remote sensing techniques, but also the complex interactions between these digital techniques and “traditional” archaeological recording methods such as field walking and excavation. The papers collected in this volume include four very different approaches to remote sensing for archaeology. First of all, Rebeca Blanco-Rotea, João Fonte, Alejandro Güimil-Fariña and Patricia Mañana-Borrazás discuss the use of airborne laser scanning and aerial photography for the detection of Modern Age fortification structures in the poorly accessible landscape of the Minho Valley (Portugal / Spain). On a site-specific scale, Wieke de Neef and Martijn van Leusen focus on the potential of the integration of surface distributions, geophysical data, and subsurface remains for the reconstruction of Late Bronze Age rural settlement in Calabria (Italy). Eduardo Carmona Ballester, Cristina Vega Maeso, Oscar López Jiménez and Victoria Martínez Calvo show how electro-magnetic induction survey can be applied to mitigate archaeological detection biases in the heavily vegetated landscape of Cantabria (Spain). Finally, Lucia Bermejo, A. I. Ortega, R. Guérin, A. Benito-Calvo, J. M. Parés, M. A. Martín, E. Aracil, U. Maruri and J. A. Porres discuss the application of electric resistivity surveys for the identification of possibly anthropogenic deposits and natural infill processes in a karstic cave system in the province of Burgos (Spain). These contributions show that remote sensing techniques have a great potential for archaeological research in otherwise poorly investigated areas, which adds a further dimension to our knowledge of land use in the past.

Discussing the obvious or defending the contested: why are we still discussing the ‘scientific value’ of 3D applications in archaeology?

Tijm LANJOUW

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Abstract

Archaeologists started to use 3D visualization and virtual reality in the '80s. A discussion about the scientific value of such technology for archaeology commenced and has never stopped since. Many of the key points of this discussion seem already to have been highlighted or addressed during the '90s, and recent theoretical discussion on the topic seems to get somewhat repetitive. At the same time the technological advancements have enabled an ever greater group of archaeologists to experiment with these technologies and learn how to employ them to their advantage. Although theoretical insights of the past remain highly relevant to present generations, to maintain a status of underdog, a contested sub discipline, is not necessary anymore.

Keywords: 3D, virtual archaeology, visualization, historiography

Résumé

Les archéologues ont commencé à utiliser la visualisation 3D et la réalité virtuelle dans les années 80. Une discussion sur la valeur scientifique de cette technologie pour l'archéologie a commencé et n'a jamais cessé depuis. Beaucoup des points clés de cette discussion semble déjà avoir été mis en évidence ou adressés au cours des années 90, et la discussion théorique récente sur le sujet semble avoir un peu répétitif. Dans le même temps, les progrès technologiques ont permis un groupe de plus en plus d'archéologues d'expérimenter ces technologies et apprendre à les employer à leur avantage. Bien idées théoriques du passé demeurent très pertinents aux générations actuelles, de maintenir un statut de outsider, une sous discipline contestée, ne est plus nécessaire.

Mot clés: 3D, l'archéologie virtuelle, la visualisation, l'historiographie

Introduction

Through participating in a conference session entitled ‘The scientific value of 3D’, I started to wonder: why do we still feel the need to talk about this subject? As 3D visualization technology has been utilized for more than 40 years, why does this ‘old’ technology still warrant a separate discussion about its advantages for archaeology? In fact, the scientific value of 3D applications has an intellectual history as long as we’ve been modelling in three dimensions. To examine this history we’ll go back in time to the year 1974.

A sobering journey in time

The creation/use of 3D images is not a new phenomenon. From an archaeological perspective, this technology was only truly ‘novel’ during the late ‘70s until the mid ‘80s when the first 3D reconstructions appeared; these required machines of up to 1,000,000 pounds.¹ Leo Biek (1974; 1976; 1978; 1986; Biek *et al.* 1981; Diment & Biek 1977) is perhaps one of the first in the field of archaeology to publish his thoughts and on such attempts. Biek reported on developing a fully integrated, interactive and visual system to be used for recording and analyzing archaeological data. In his short papers he covered a wide range of subjects such as photogrammetry, animation, ‘video’ digitization and visual learning systems. His ideas were so innovative and forward looking that much

¹ An even earlier example is perhaps the Stonehenge CAD model mentioned by Biek (1978, 53), on display at the CAD centre in Cambridge in those days.

of it comes across as dreamy future thought: “The next step could be holographic?”, Biek (1978, 53) muses. Nevertheless, he presented some very real examples of 3D visualizations. A little later, in 1982, pottery shapes were already being digitally constructed in three dimensions (Angell & Main 1983). But 3D modelling in archaeology seems to have really taken off in the mid ‘80s, when projects like the digital reconstruction of the Roman temple of Bath reached a massive audience through extensive media coverage (Reilly 1991). Following the wave of excitement generated from these initially spectacular results, one of the Roman Bath Team members, Paul Reilly (1991), conceived of a new form of archaeology famously dubbed ‘Virtual Archaeology’ (VA). VA has become a theoretical battleground for discussing ‘scientific value’ ever since. We fast forward to the 21st century, where we hear the lament of Maurizio Forte, one of the first archaeologists to work with Virtual Archaeology: “the balance sheet of 20 years of archaeological research on the application of the 3rd dimension as a research tool was fairly depressing” (Forte 2008). Remarkably, the overarching aim of the volume in which Forte presented this statement was to go ‘beyond’ illustration and “to collect some of the pioneering efforts in this promising field” (Frischer 2008). And in 2014 we can still read Forte stating that VA didn’t bring about the revolution that was hoped for (Forte 2014, 115). Why was there still some years ago talk about ‘pioneering’ this field? And why remains the scientific value of 3D visualization a popular topic for conference sessions such as this one (another example is TAG 2014), and book chapters (e.g. Hermon 2014). On top of that, why did so many papers on the application of 3D modelling technology feel the need to add an extended section expounding the benefits of 3D visualization/VR for archaeology (e.g. Hermon & Fabian 2002; Earl & Wheatley 2001)? Despite years of development, why does this all sound as if a contested position needs to be defended? Clearly, 3D visualization didn’t yet claim its place next to the trowel and GIS in the standard archaeological toolbox.

3DA is not VA

It may be superfluous to do so, but it is perhaps important here to emphasize that 3D archaeology is not equivalent to Virtual Archaeology. A 3D model “is simply any model whose approximation of the real world incorporates the third dimension” (Daniels 1997). A church recorded in photographs and modelled using digital photogrammetry, a laser-scanned flint tool, or a hand model of the excavated foundations of a ruined building: these are all 3D models. Whereas one of the definitions of a virtual model goes: “A virtual model [...] is a representation of some (not necessarily all) features of a concrete or abstract entity. The purpose of the model of an entity is to allow people to understand the structure or behaviour of the entity and to provide a convenient vehicle for “experimentation” with and prediction of the effects of input and changes to the model” (Barceló 2000, 9). Virtual archaeology in these terms means to go beyond constructing a spatial model, and, at least in Barceló’s definition, also implies the intent to dynamically *simulate* the past. In theory therefore, VA is not necessarily three-dimensional but can be any-dimensional in nature (Barceló 2001). Here we will primarily be concerned with the three-dimensional aspects of VA and models otherwise 3D in nature.

Advantages of 3D

As stated above, 3D is not new anymore, nor are the reasons advanced for its application. In order to convince the archaeological community, the early developers naturally felt the urge to emphasize the advantages of the new technology. One of the first things often pointed out (e.g. Forte 1997), is that archaeology is inherently three-dimensional in its methodology and its primary data is often three-dimensional in nature. Information is lost through conventional methods of recording and visualizing (e.g. 2D plans and section drawings) which can be overcome by three-dimensional models. Moreover, because of the three-dimensional nature of human visual perception, it is regularly argued that we are “able to conceptualize our data better and work with it more efficiently and accurately if we can see it in three-dimensions” (Daniels 1997). The inventor of Virtual Archaeology himself advocates that 3D modeling forces the modeler to be spatially explicit, and can therefore help to expose inconsistencies in the interpretation of features while excavating (Reilly 1992, 96). The same spatial explicitness

is invoked in the context of 3D reconstructions when arguing that “the very task of setting up a computer reconstruction obliges the archaeologist to pose the right questions, and to answer them.” (Forte 1997). Robert Daniels (1997) created a method or approach applied to the archaeology of buildings on the tenet that the explicit modelling of the spatial relation *between* structural elements is needed in order to better understand the entire structure. Many contemporary and past research has benefitted from these properties of 3D space: a group of researchers reconstructing a Bronze Age tell site in Greece already stated on the CAA of 1994 that 3D visualizing helped to understand the spatial relations between features and the terraced nature of the site (Kotsakis *et al.* 1995); Murgatroyd (2008) uses 3D modelling to visually ‘test’ different hypotheses about the roof construction of a Pompeian house. On top of all this, Reilly stated that in the future Virtual Archaeology, the 3D recording of excavations would enable an archaeologist to return to the site to look for evidence that escaped the eye (1991, 135). In these days, high resolution recording wasn’t available yet for archaeological excavation, but at the turn of the century, these began to make an appearance. Initially, light or laser based techniques were considered the most practical and efficient to use, as around the turn of the century photogrammetry in its current form was still thought of as too hardware intensive (Avern 2001). However, the subsequent advances in hard- and software have led to a recent surge of cheap and efficient 3D photogrammetric recording, fostering an increasing number of excavation/ archaeological projects striding steadily toward the fulfillment of Reilly’s prediction. Forte has continued to be a pioneer in this field, and his 3D digging Çatalhöyük project,² running since 2010, has come closest to this goal (Forte 2014). The intensive use of 3D scanning has allowed them to reconstruct the excavated microstratigraphy of consecutive layers of wall painting in high detail. Physically lost forever, these artefacts continue to digitally exist and offer endless opportunities for re-analyses in cyberspace. With tools such as these we are a step closer to mitigating one of the seemingly inevitable evils of our trade: the destruction of our data through studying it. To complete the cycle and return back to the physical world (and to Reilly), we now can see the first thoughts appearing on the potential of *actual* re-excavation of a 3D print of our stratigraphy (Beale & Reilly 2015). Additive manufacturing has already showed its value in the field of reproducing or reassembling artefacts which are rare, fragile or simply stuck inside or bonded to other artefacts (e.g. Miles *et al.* 2014; Chapman *et al.* 2013).

The point of this far from exhaustive historical overview of how archaeologists have harnessed the power of 3D (e.g. the application/usage of 3D GIS and close range 3D recording), is to show that from the beginning archaeologists have seriously concerned themselves with finding ‘scientific value’ in the use of 3D applications. They experimented with it and described how it was advantageous to their goal of better understanding the archaeological record and to improve their interpretations of the past. In this light, the complaints of 21st century archaeologists ‘pioneering’ an underdeveloped field seem incongruent with reality. Or is there another issue at stake?

The fear of deception

There was something that stung from the beginning. In their provocative paper, “The good, the bad and the downright misleading: archaeological adoption of computer visualization”, Paul Miller & Julian Richards scornfully write: “to date the catalyst for visualization in archaeology has not been the search for improved techniques for discovering new knowledge but rather for improved ways for presenting existing knowledge to the public.” (Miller & Richards 1995, 19). According to them nothing new was learned from the models currently produced. But more importantly, they felt that sophisticated high-tech computer models were seen by the general public as inherently more authoritative and therefore have a greater capacity to mislead. The precision of the models suggested more certainty than archaeologists actually could have, and structural uncertainty is hard to visualize given the exact nature of 3D models. They argued furthermore that in practice, models generally give one politically correct version of the past instead of several interpretations. Derogatively they

² http://www.catalhoyuk.com/uc_merced.html

likened the 3D models produced up to the mid '90s to Alan Sorell's water colour paintings, artist impressions of the past that add nothing to our understanding. Their criticism was not completely new however, because we see Reilly already in 1991 anticipating this 'pretty picture' trap as well as giving suggestions on how to visualize uncertainty. One can discuss whether their criticism was fair, but in any case the pretty picture fear remained, as can be gathered from several article titles (e.g. Sims 1997; Barceló 2000; Sanders 2014). Barceló's paper in 2000 suggests that the virtual world hasn't become a better one, and his words echo Miller & Richards's points, again comparing 3D visualization to a 'mere' artist's reconstruction. Barceló emphasizes that the virtual model should never be conceived of as the end product, and neither should they be considered 'authentic' versions of the past. Again one is left with the impression that 5 years after Miller & Richards little progress has been made.

Part of the answer to the seemingly contradictory experiences outlined above may lie in the absence of a balance between applying VR and 3D modelling to answer scientific questions and its use for attractive presentations of archaeological reconstructions to the general public. In Pujol-Tost's (2008) analysis of the use of VR in archaeology, this unbalance comes across quite clearly. She proposes a typology of 4 different approaches for the use of VR in archaeology:

1. the 'traditional' approach: VR as a *conclusive illustration* for a process of description;
2. an approach borne out of the combination of a romantic perception of archaeology and economic interests which leads to sophisticated interfaces for experiencing usually spectacular monuments or sites;
3. an empiricist approach which considers VR as an experimental tool for the visualization and analysis of data and hypothesis verification;
4. a postmodern approach which views VR as semantic/symbolic resource aimed at developing a multi-voiced narrative (Pujol-Tost 2008, 106).

According to Pujol-Tost, current applications lean toward use 2, while 3 and 4 are not altogether absent but are somewhat underrepresented. Because of that, any attempt to make scientific use of applications using 3D computer modelling, is always accompanied by a defence of the method, in fear of being associated with those 'charlatanic pretty picture makers'. However, it is hard to find published examples of such projects. Most projects, even those with sophisticated custom made user interfaces claim that their aim is to make accessible data to a large audience of specialist and non-specialist users (e.g. von Schwerin *et al.* 2011), or state that research was an important goal (Acevedo *et al.* 2001). We shouldn't doubt these intentions, although some claims may be questioned (see below). But one could wonder whether authors such as Miller and Richards (1995) may have been exaggerating problems with VA.

Explanations

Although it may be argued that an overly grim picture of reality was sketched by those critical of VR applications in archaeology, it is clear that the implementation of 3DA and VA into broader archaeological practice and theoretical discourse developed slower than hoped for by its early innovators. Why so? Another VA pioneer, Donald Sanders (2014), has attributed this to the general conservatism in archaeological practice shown towards the introduction of new technology, and he draws a parallel with the delayed rise of photography for archaeological documentation in the late 19th century. Just as with sophisticated computer visualizations, sceptics felt that photography was biased in such a way that it should not be used for objective scientific documentation (Sanders 2014, 41). Jean-Claude Golvin (2012) generalises this phenomenon even more, and relates the lack of trust in visual modes of scientific communication to an iconophobia that affects a great deal of the scientific community which favours textual description.

The fear to deceive may have caused the subsequent focus on developing a common ground for 'good practices'. According to Frischer (2008) this 'phase' lasted from 1997 to 2008, but it may be argued

that thinking about best practices developed parallel to concerns about deception, and clearly hasn't ended. The focus on ways to visualize uncertainty and the development of a charter characterises this trend. Although these have been important, I feel that an unnecessarily large issue has been made over the visualization of uncertainty, as solutions of colour coding or transparency levels are rather obvious (as noted already by Reilly in 1992) and not that difficult to implement. Moreover, the anxiety about possible deception is overly patronizing, and underestimates the critical capacity of the 'general public'. That digital models have stronger deceptive qualities than text and analog 2D drawings is an assumption, a statement for which the evidence is never cited.³ Besides, I see it as normal proper scientific practice to document and make clear one's assumptions, interpretative reasoning and uncertainties, and to visualize these when possible in any interpretative model. In the end, it strikes me as curious that such concerns were only triggered by the introduction of *digital* visual models in the '80s, as 2D analog 'models' have been used in archaeology since the beginning of the discipline. In any case, the result was that these easily surmountable issues received more attention than necessary and obstructed larger questions regarding the technology's scientific value.

But it was not only this resistance that isolated VA approaches from the rest of archaeology. Bateman (2000), in his anthropological analysis of the sub-discipline, describes a community that is inward looking, mostly concerned with technological advances rather than aiming to change archaeological theory and practice. So Bateman concluded that VA constitutes a "coterie of technophiles" whose specialisation has no impact on archaeology as a whole. Such observations made Forte (2014, 115) ultimately conclude that VA was an immense failure and a project that should be left in favour of something new (see below).

Questionable claims

But can all the blame be put on a conservative sceptical community and a tendency of self-isolation? What about the claims made by the proponents of VA and 3DA themselves? Are they credible enough to overcome healthy academic scepticism? While the innovators and developers of VA and 3D have stepped forward to defend their claims, I think that in some cases, the 'advantages' of 3D may have been exaggerated in the past.

Reilly himself listed one of the advantages of VA in its ability to understand political or social relationships "reflected in the use of space within the monument" (Reilly 1992, 93). He recalls the personal anecdote of showing several visualizations to Barry Cunliffe, who subsequently inferred some statements in this line of reasoning. There are a couple of caveats to this example. First, because of the technological limits Cunliffe was shown a couple of rendered *views* of the reconstruction, which were essentially 2D images that could easily have been drawn by hand to the same effect. In this case we are not dealing with any proposed advantage of 3D display in VR but rather of making a reconstruction, whether made in 2 or 3D space. On top of that, his 'conclusions' are of such a general nature, that they can hardly be called 'new insights'. That social and political relations are embedded in the use of space can be considered an established fact in the social sciences. And neither does the observation that the Romans used architecture to communicate power come across as a new insight. The reconstruction may simply illustrate this fact nicely. One can object that we shouldn't judge such early examples too harshly from our present perspective, but such unconvincing examples clearly lead to the kind of scepticism voiced by Miller & Richards (1995). The problem here is that such observations don't come from the ability to see the monument in a 3D VR world, but are a priori assumptions, simply illustrated nicely by the model.

Another claim often made is that 3D is superior to older 2D ways of representation. Constructing a 3D model, it is said, prevents one from cheating because it is spatially explicit (Daniels 1997). One cannot 'cheat' so to say, while in a 2D drawing one can smudge and leave out of sight unclear parts.

³ A striking anecdote of a simple 'possible reconstruction' drawing that step by step became 'the reconstruction' is told by Simon James (1997).

First, why is the possibility to omit certain elements considered a bad thing? It is in sync with the idea that uncertainty should be visualized. Secondly, in reality it is very well possible to ‘cheat’ in 3D space. One can decide not to model certain structural elements, (e.g. buildings can be empty shells etc). The bottom line is that any visualization is as good as the research that went into it, whether rendered in 2D or 3D. And often, 2D can be just as effective to study, understand and visualize certain technical aspects of a building, or the construction of an artefact. What happened was that many 3D projects of the past ‘violated’ principle 2.1 of the London Charter: “It should not be assumed that computer-based visualisation is the most appropriate means of addressing all cultural heritage research or communication aims” (London Charter version 2.1, 2009). With the enthusiasm of a kid wanting to play with a new toy, they greedily accepted the new technology and were quick to label it ‘superior’, and exaggerating its scientific advantages. A lot of old wine was sold in new skins.

There is however a tipping point. 3D modelling has become so easy and cheap nowadays that 2D paper drawings simply are time-consuming and inefficient. The more complex the structure is, the greater the advantages of 3D modelling, both as a structured way of storing and visualizing your data, and of modifying complex designs. 3D is in this sense part of a larger system that profits from the advantages of digital data storage in general.

Limited use

So although many of the VA and 3DA projects often highlighted their scientific value, their claims may often be questioned. What many projects did was to simply graft old modes of thinking onto new technology to create something that was superficially different, yet remained fundamentally the same. This was seen early on by Mark Gillings (1999; 2005) who claimed that VA was not being used to its full potential. In his approach to VA he shows his contempt for approaches working in “a sterile functionalist, determinist framework” (1999, 248). He scorns the present use of VA, ridicules the completely silly ways of ‘experiencing the past’ that are offered by the VR interfaces; and, like Barceló and several others, he qualifies the striving for greater technological sophistication in order to satisfy the aim of greater ‘authenticity’ as defective. According to Gillings, the structural questions that archaeologists ask simply don’t justify the considerable investment of time and money required to create these models. Most of the work discussed above would fall into this category. So Gillings calls for a completely different type of use for VA, one diverging from the aims offered by Paul Reilly. He proposes an approach inspired by post-modern thought focussing on “embodiment, process and the social nature of space and time” (Gillings 1999, 248).

Although full of bright new ideas on how to use VA, his actual case-study doesn’t really convince. In his Peel Gap study, the question is posed: “if a tower, connected to a continuous stretch of walling was located here, what could be seen from it?” (Gillings 1999, 253). He emphasizes that the exercise was not driven by desire to re-create a stretch of Hadrian’s Wall. This may be so, but I don’t see the point in simulating a mobile observer in a 3D virtual world if visibility of the Watch tower has already been established using GIS viewshed analysis. What exactly is the ‘scientific’ benefit for experiencing (‘seeing’) the wall and tower from the point of view of the observer in a landscape instead of on an impersonal map? His visualization is quite simple even according to the standards of the day, and the experience is far removed from that of anyone who may have trodden the hilly landscape in Roman times. As Gillings maintains that ‘authenticity’ is a red herring, an exact recreation of the wall, tower and landscape was not strived after. But in that case, what do we actually learn from this virtual experience? Other previous attempts have not yielded very convincing conclusions either, beyond stating the obvious: ‘building your house is impossible in the dark’, or ‘smoke stains not only the walls but also the reconstructed roofs of the houses’, Colleen Morgan (2009, 475) learns during the process of rebuilding Çatalhöyük in VR world Second Life. None of these offer novel facts or insights. This is not the place for a critique of post-modern approaches to archaeology, as this has been done elsewhere extensively (e.g. Fleming 2006 for a critique of phenomenological approaches to landscape). However, any such cross-paradigmatic criticism will ultimately fizzle out since it

makes judgements based on dissimilar standards. This renders the questions of what amounts to worthwhile research and how scientific value is judged as irreconcilably subjective.

Going “beyond” illustration

From diverse archaeological theoretical schools of thought, as we have seen, archaeologists have expressed their dissatisfaction with VA/3DA from the beginning. Although explicit attempts have been made to apply VA/3DA to answer scientific archaeological questions, the perceived need to ‘go beyond illustration’ (e.g. Frischer & Dakouri-Hild 2008; Stanco & Tanasi 2013) – or pretty pictures – has persisted until recent years.

On how to move beyond illustration, archaeologists have taken several pathways of which Gillings’ solution is just one. In several papers published around the turn of the century, Juan Barceló (2000; 2001) has stated that authentic reconstructions of the past should not be the final aim, and builds a theoretical approach around the concept of ‘manipulation’. He describes virtual archaeology as a platform of experimentation in which a geometric, visual language is used instead of words to describe and explain archaeological data. As he equates any reasoning operation to a manipulation of data in order to explain it, he views the act of data manipulation in 3D virtual worlds as a way to reason with images. Barceló’s contribution remains largely theoretical however and offers neither a methodology nor any examples.

One solution to deal with the disappointment of VA comes from Maurizio Forte who decided to discontinue the term and leave it to denote a failed project of the past (Forte 2008; 2014). So he proposed a new name: cyberarchaeology. Cyberarchaeology is actually not so different from what Reilly originally imagined to be virtual archaeology, but Forte’s cyberarchaeology has a more elaborated theoretical grounding. He draws his inspiration from Bateson’s cybernetics (1972): a cross- and multi-disciplinary field that aims to study the world through a holistic perspective. The human mind is conceived of as an ‘ecosystem’, which contains a network of concepts: our cybernetic map of the world (Bateson 1972). Bateson’s theory on learning identifies several types, of which ‘deutero learning’ or learning how to learn, is the highest and most desirable type of learning. Because in VR information can be combined and manipulated, Forte sees VR as a place where deutero learning can be stimulated. By actively involving all the senses, this method further improves the favourable conditions for learning. Forte describes it as information achieved by a perception-action based interaction with the environment (2014, 113). He encourages further development of haptic interfaces that, for example, can improve our engagement or embodiment within the virtual world. With cyberarchaeology it seems we have closed another circle of history, for it was Leo Biek, our pioneer from the ‘70s, whose aims were exactly these with the development of LEARNIE: “We had not begun to think of putting the computer onto the most vital part of the loop: our own ability to think and, especially, to learn.” (Biek 1974, 59). Finally, after 40 years, we may be starting to pick up on these goals.

Conclusion

So why are we still talking about the scientific value of 3D? There are many examples of 3D recording that have revolutionized our field, on excavations, landscapes, artefacts: new discoveries are made every day by high resolution 3D recording. Testing of architecture reconstruction models using methods from modern civil engineering for example is already showing the first results (e.g. Miles *et al.* 2013). ‘Scientific value proved’, one could easily state. However 3D has from the beginning also been associated with Virtual Archaeology, which credibility has been eroded due to causes mentioned in this paper. Several influential papers have been critical about Virtual Archaeology, which led to negative aspects being emphasized therefore creating an impression of a completely stagnating field. On the other hand many archaeologists did take the opportunity to experiment with virtuality. The more critical papers usually reflected at the VA projects that *called* themselves VA projects, which as a

rule are those projects producing custom made sophisticated user-interfaces and spectacular models. While at the same time the development of 3D GIS and increasingly user friendly 3D modeling programs moved toward supporting a Virtual Archaeology as Reilly envisioned. However, these attempts are usually overlooked as they went by a different name (e.g. Kotsakis *et al.* 1995; Uotila & Tulkki 2002; Katsianis *et al.* 2008). They are fundamentally not different from what VA purported to be: a visual and digital platform for experimentation, visualizing data and testing hypotheses. Now that these systems are advanced enough to hold *all* of our data and manipulations thereof so that approaches and workflows can be integrated, an archaeology that is truly virtual (or cyber) is starting to appear. However, a danger still lies in viewing the advantages of 3D and VR as self-evident. Apart from a very few isolated examples (e.g. Acevedo *et al.* 2000) there is relatively little in existence of user-evaluation, specifically for the *academic* user. How does the use of digital 3D technology really assist our understanding and interpretations? As has been shown in this paper, in the history of 3D applications in archaeology, many have been misguided in assuming 3D's superiority over 'old fashioned' 2D analog modes of visualization. Of course, by now we have many examples of research that simply wouldn't have been possible without 3D digital technology. But questions remain. Forte's cyberarchaeology for example is justified with Bateson's cybernetics, which in its ideas about human learning, is in the end still mostly built on theoretical statements. How we really learn and understand the world remains a continuing project for those who study the brain and its interaction with the environment. If we want to improve, these insights must be implemented in our methodologies.

Over the years examples have piled up that proved the scientific value of 3D. On the other hand, we must remain critical of the claims made. But the discussion about the value of 3D modeling/ visualization/VA has turned stale, and the question of pretty pictures or research tool a cliché. What we need is a realistic approach to what technology can do for us, explicitly defining how we think it improves our work and enables us to answer questions otherwise unanswerable.

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3Di – enhancing the record, extending the returns, 3D imaging from free range photography and its application during excavation

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Abstract

Changes in digital photography, games computing hardware and software developments over the last decade, have transformed the potential application of digital photography during excavation. Most particularly when applied to photogrammetry using Structure from Motion software for documenting structures and even landscapes as well as excavations in progress. Experiments undertaken by the Landscape Research Centre in Yorkshire over the last six years have revealed the potential benefits of using 3D Imaging (3Di) for recording excavations, in plan and in section. However they unfortunately also provide an opportunity for field archaeologists to disengage with the recording process and diminish the returns from excavation. Like so many aspects of computing when applied in the field we can either enhance our potential to interpret the archaeology that we encounter, or use it to simply speed up our throughput and hide poor practice and limited observation. In many ways 3Di provides an opportunity for us to achieve the nirvana of archaeological recording, a record that is so detailed that we can truly re-examine excavations through their archived data. To do this, however, we need to apply the same levels of rigor and observation that we should to any part of the excavation and recording process and remember that new technology does not replace the eyes, touch and on site drawings but provides an opportunity to expand the record in a format that serves both the excavator and the public at large in a way that has never been possible before.

Keywords: *Archaeological documentation, 3D Archaeology, 3D Imaging, Field Archaeology*

Résumé

Les progrès technologiques de la photographie digitale ainsi que l'évolution du software et du hardware dans le domaine des jeux d'ordinateur pendant ces 10 dernières années ont ouvert la voie à une réévaluation des possibilités d'application de la photographie digitale pendant la fouille archéologique.

Plus particulièrement c'est le cas de la photogrammétrie, utilisant le software « Structure from Motion » pour la documentation de structures et même de paysages aussi bien que de la fouille archéologique en cours. Des expériences entreprises par « le Centre de Recherche des Paysages » dans le Yorkshire pendant ces 6 dernières années ont délivré des résultats bénéfiques pour l'emploi de la 3Di pour la documentation des fouilles au niveau de la vue de plan et de la vue de coupe.

Malheureusement l'utilisation de la 3Di fournit aux archéologues un prétexte pour se désengager pendant le processus de documentation, ce qui peut même mettre en cause les résultats d'une fouille. Comme tant d'outils rendus disponibles par l'informatique lors de leurs déploiement sur le terrain nous pouvons soit en bénéficier pour compléter notre potentiel pour l'interprétation de l'archéologie que nous rencontrons soit en profiter pour accélérer notre productivité entraînant éventuellement la mauvaise pratique telle qu'un manque d'observation

Sur beaucoup de plans, la 3Di nous aide à atteindre un nirvana de documentation archéologique où les données sont si détaillées qu'on peut vraiment revisiter une fouille en réexaminant les données archivées. Pour y arriver cependant nous devons nous astreindre au même niveau de rigueur et d'observation qui se doit à tout moment d'une fouille et du processus de documentation et ne pas oublier que la nouvelle technologie d'une part ne remplace ni les yeux ni le toucher ni les dessins sur le terrain et d'autre part nous offre la possibilité d'agrandir l'offre des données dans un format qui sert à l'excavateur et au grand public d'une manière qui n'est possible que maintenant.

Mots clés: *Documentation archéologique, 3D archéologie, 3D Imaging, l'archéologie de terrain*

Excavation – the unrepeatabe experiment

The process of excavation, as described by one of the most eminent British excavators Philip Barker, “is an unrepeatabe experiment”, an experiment in which the bulk of the material under study is

destroyed leaving only a subset of the material observed for subsequent examination (Barker 1982: 12). Excavation may well expose aspects of stratigraphic sequence and produce finds and samples which can be recorded and archived for future study but the 'site' itself, the complex mix of soils and their components with their integral three dimensional and stratigraphic relationships are entirely lost in the process of excavation. No two sites or rather pieces of excavated ground are the same and thus each archaeological deposit examined can be considered unique. This situation gives the excavator a particular responsibility for accurately observing and documenting what is destroyed; a responsibility to try to secure Preservation by Record. Whilst 'Preservation by Record' is a justifiable ambition, in reality, it is effectively an unachievable target, if it were then we could virtually re-excavate the 'site' reconstructed from the records potentially in alternative ways to the original excavation. What happens in reality is that we create a record not so much of what is there but what we can see and feel and this is by necessity biased by personal experience and by conditions at the time of excavation.

The record might be seen as the product of a conversation between the excavator and the site being examined, the result of a combination of factual observations and interactive and often very subtle interpretations and re-interpretations of the evidence encountered. Whatever the case physical re-excavation cannot be undertaken and we are very often left with a record that is not susceptible to detailed re-examination or re-interpretation as a consequence of that re-examination. The results of any excavation combine artefact and environmental evidence with written and stratigraphic evidence which is amplified through the drawn and photographic record, no matter how careful or detailed our records are re-interpretation of detail rather than re-assessment of the broader interpretation is rarely possible. If for instance multiple deposits are observed and excavated as one, it may be possible for instance to observe a problem in the record through contradictory information from finds contained in the deposits, but the opportunity to identify the boundaries within the deposits cannot be identified after the event. In every sense 'preservation by record' might be more correctly considered to refer to the 'preservation of the record' in which the interpretation of the excavator and recorder is embedded and to a large extent closed to re-construction or reinterpretation at the deposit level; that is not to say that aspects of interpretation of the recorded evidence cannot be changed to reflect information arising from post-excavation analysis of material evidence or functionality as for instance a change in the assigned date of a feature or the reinterpretation of a pit as a post-hole. The increased emphasis on commercially driven fieldwork, funded as part of the development process, has had an impact on attitudes to recording particularly as it pertains to the speed and thus cost of the excavation process. Although archaeologists have been quick to adopt some digital technologies such as the use of laser assisted survey equipment in the form of Total Stations or the use of CAD packages for producing site drawings the use of digital technologies such as handheld devices for data collection have hardly been adopted despite being available for thirty years.

The three dimensional nature of the raw materials of archaeology and the degree to which deposits that may have formed in a relatively simple situation have subsequently been transformed by complex processes of deposit de-formation have led to compromises in the conventional record. A variety of largely schematic solutions have been developed to describe 3D space in a 2D environment the most obvious of which is the use of hachures to show the shape of a surface or the combined use of sectional and plan views to encapsulate 3D space. Hachured drawings can be very attractive but without any clearly defined format the interpretation of these drawings is very subjective and two individuals might read a drawing in very different ways. Contours applied as a more consistently readable method of showing surface form are most effective where the change in slope over a surface is at its greatest. Spot heights scattered across drawn plans give a poor view of the true nature of the drawn deposits or features are effectively useless with regard to reconstructing complex surfaces after excavation.

In archaeological fieldwork our objectives might be best described in terms of trying to change the past or at least change our understanding of the past with a view to informing people in the present. Although some may be pre-occupied, for instance, with the study of individual aspects of material

culture, environmental change, stratigraphic sequencing or chronological development our target is to be able to tell more informed and scientifically sound stories about the past based on good evidence rather than supposition.

The process of excavation is highly complex and relies upon developed skills of observation coupled with tactile understanding and interaction with soils, textures and structures in the ground as well as the ability to describe and characterise the materials that combine to form each 'site'. The excavator must engage in a sort of dialog with the site and pro-actively seek to identify the stratigraphic sequence, the formation and deformation processes that result in the evidence being excavated, without proscriptive bias whilst remaining open to an ever-changing pattern of interpretations.

The recording tradition of scaled plans and scaled section drawings whether composite plans and full sections or single context plans and running sections have evolved over time and under the increasing pressures of commercially funded excavation have tended to be increasingly schematic, concentrated upon interpretation rather than simple detailed observation. The remaining components of the record include the finds, environmental and other samples and records of stratigraphic sequence, photographs and context descriptions; contexts here may incorporate cut features, the deposits that fill them, upstanding structural remains as well as general layers. While cross sections can give an impression of the three-dimensional nature of the deposits etc. within an archaeological trench the nature of the section as a 'slice' makes it difficult to appreciate over an area. Similarly a plan of one or more contexts drawn in 2D with conventions to reflect the form of the drawn surface, even when enhanced with spot-heights gives a very poor impression of an undulating surface. Single photographs can show the exposed surface and form projected onto a 2D screen or printed page but again give a poor reflection of the observed surface.

During the excavations conducted by the Biddle's in Winchester during the early 1970s site plans and section drawings were drawn in full colour; the resulting drawings which resembled very large slides scaled at 1:24 or 1:20 provided excellent scaled images of the excavations representing various phases in the site development sequence; they did however take a considerable time to draw. This approach was also used during the early years of excavation by the York Archaeological Trust and on Philip Barker's excavations at Wroxeter. The use of full colour multi-context phase plans was an approach that was considered by many to be too time consuming. Ultimately, the use of single context planning as developed by the Museum of London, in response to the problems raised by the need to rapidly excavate deep urban stratigraphy, was promoted as a more suitable approach to planning; accompanied by running sections drawn in segments as open plan areas were taken down in plan. It has been argued that the use of single context planning as opposed to the use of composite phase plans is inherently more objective; however, in both cases what is drawn is determined by the excavator who determines at which time to stop and record and thus is potentially influenced by a great deal of subjectivity. This is not the place to discuss the relative methods or framework within which plans and sections are drawn but merely to highlight the need to appreciate the degree to which a plan or section is a visual statement of fact or an interpretation of the observed. In reality the whole excavation process is highly subjective and relies upon the excavators' interpretation of their observations right down to the individual trowel strokes which define in physical terms the surfaces, layers, structures and cut features which become the subject for documentation.

Planning by TST

With the introduction of laser assisted theodolites during the early 1980s and subsequent rapid development of fully automated Total Stations (TST) with on-board and automated data storage archaeologist were provided with a tool which was ideally suited to gathering 3D survey data. Laser based survey equipment provided levels of speed and accuracy in terms of the collection of point data difficult to achieve using older technologies but also provided an opportunity to bypass the conventional drawing process and generate drawings in the field using TST surveys alone. At worst

the use of the TST underpinned recording procedures which used the absolute minimum number of points to define a computer generated smooth curve to map individual features and deposits. Whilst this approach might be appropriate for generating pre-excavation plans, for instance, of large ditched features during site clearance, it can compromise the evidence at source and hugely diminish the value of the site plans and thus their contribution towards the analytical process. The clearest demonstration of compromise in the record is where post-holes and post-settings are simply mapped by logging a single point and using this to centre a circle. From the recording point of view planning by TST beyond the generation of crude pre-excavation plans of large features, is a very poor compromise, drawn plans result from the interaction of the observer and the feature being drawn and can incorporate subtlety, degrees of confidence and alternatives in a way that is impossible with the hard lines derived from a point by point plan created with a TST. The TST can be exceptionally precise, more so than the trowel, but if plans are generated from points spaced a 20 cm intervals then the precision is lost. The process of planning by TST restricts the observers dialog with the ground as focus is lost whilst positioning the staff and keeping it vertical, and in most cases leaves a trail of points made by the staff which can give a false integrity to the drawn lines as seen on the ground.

Figure 1 shows part of the digitised plan of an Early Anglo-Saxon timber structure as revealed by the excavated post-settings at West Heselton, North Yorkshire. The field drawing was drawn at a scale of 1:10 and subsequently digitised by tracing the drawing on a digitiser at a resolution 0.01 mm. The drawing, in which relief within the features is expressed using contours at 5 cm vertical intervals, expresses the excavated feature in a 2D projection. The digital drawing can be viewed in section and isometrically, but the digitised contours and outline are not expressed in genuinely 3D lines but horizontal lines placed at the correct elevation in 3D space and should be considered as a pseudo 3D

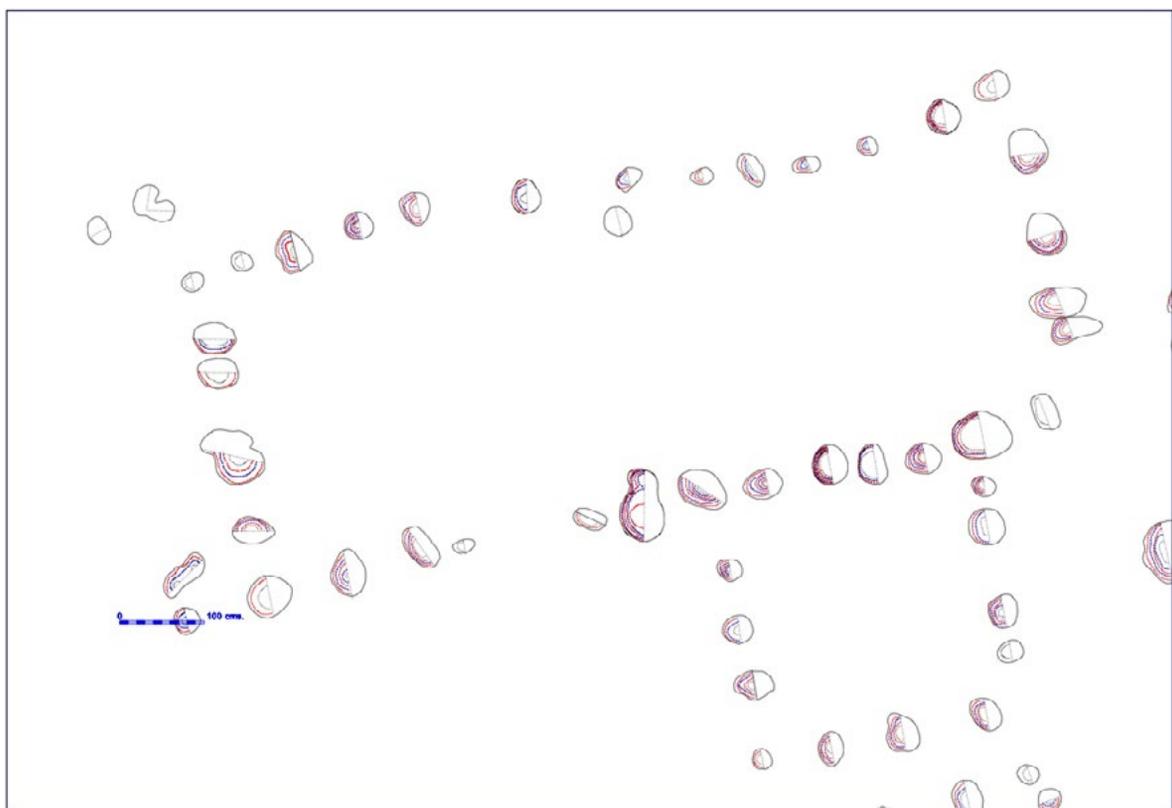


FIGURE 1. DIGITISED FIELD DRAWING FROM WEST HESLERTON, NORTH YORKSHIRE SHOWING THE POST-SETTINGS OF ANGLO-SAXON BUILDINGS.

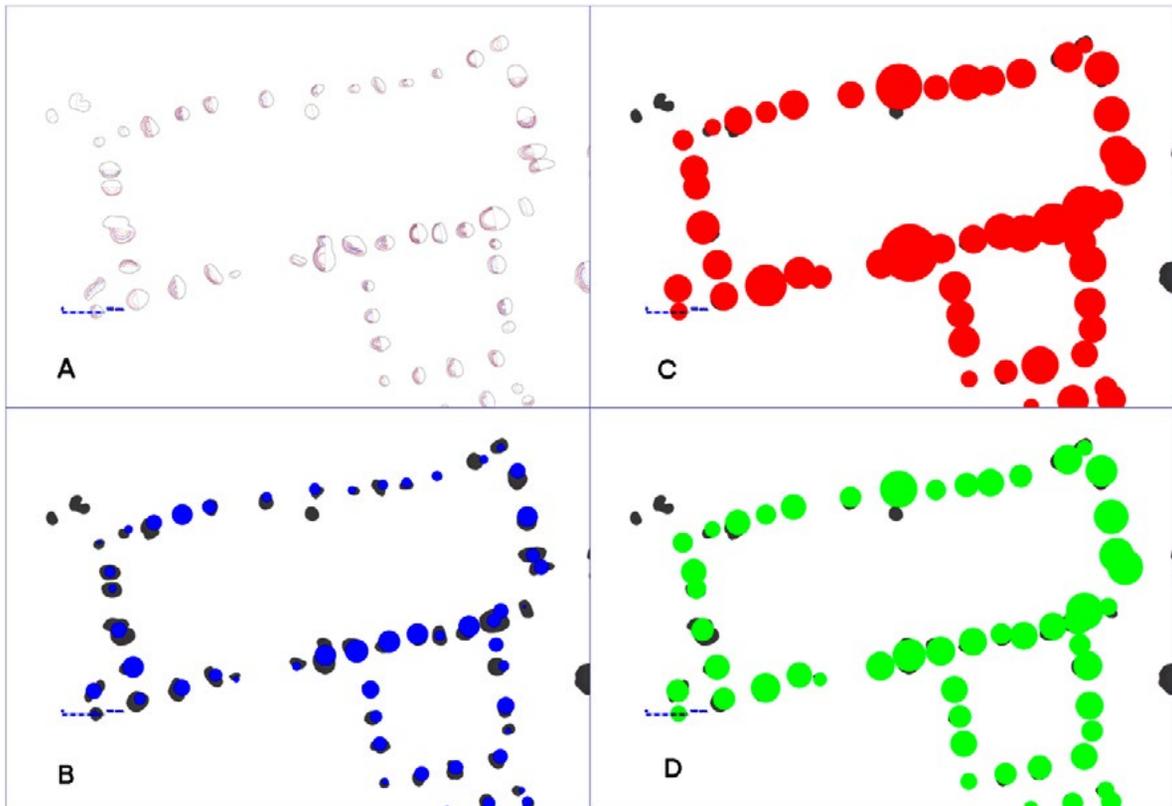


FIGURE 2. FOUR RENDERINGS OF THE PLAN OF THE POST SETTINGS OF A TIMBER BUILDING. A: DIGITISED PLAN FROM HAND DRAWN FIELD DRAWINGS, B: DIGITISED PLAN OVERLAIN BY CIRCULAR SYMBOLS SIZED ACCORDING TO THE DEPTH OF THE FEATURE, C: WITH SYMBOLS SIZED ACCORDING TO THE LONG AXIS MEASUREMENT OF THE TOP OF THE FEATURE, D: WITH SYMBOLS SIZED ACCORDING TO THE LENGTH OF THE SHORT AXIS.

representation. The form of the post settings has the potential to inform the interpretation of the long lost superstructure of the building where for instance the shape of the post-setting indicates that some of the settings are likely to have been used to position two uprights rather than one. Figure 2 shows a series of alternate views of the same structure which give quite different impressions of the nature of the evidence. Figure 2B may visually enhance the view shown in 2A by emphasising the depth of the individual features whilst 2C and 2D merely give an indication of the ground plan of the structure.

Clearly we need to identify the degree to which any plan or section is a subjective interpretation as opposed to an attempt to make an objective record of what is observed.

Photography ‘the objective record’

Analogue photography, long a cornerstone in the archaeological record, has effectively disappeared from mainstream photography at an unanticipated rate reflecting the advent and rapid development of digital photography which, more than any other technology, has been embraced by field archaeologists. The wholesale replacement of analogue photography with the use of digital cameras has until recently had the potential to diminish the quality of the record through the use of low resolution digital cameras. This, by virtue of their ease of use and high degree of automation, has often compromised the quality of the photographic record. Affordable higher resolution (12 Megapixel and above) cameras are now both available and affordable and with the exception of medium and large

format film cameras, digital cameras can now, with appropriate lenses, match the resolution and quality of film cameras for images printed at A4 size and below. The economic freedom provided by digital cameras which without the need for film appear to be 'free' to use denies the needs and long term costs of archiving the digital images and has vastly increased the number of images recorded, these digital image resources may in themselves form the greatest challenge in the battle to archive so called 'Big Data' which, if left unmanaged, will deny future scholars the opportunity to see what has been done in the name of recording and research. The ease with which vast archives of undocumented or unlabelled jpg images can accumulate during an excavation, if they are not gathered in a disciplined fashion, is alarming and reflects the need for well-defined strategies for photographic recording and most of all an archiving strategy- even if this means printing small high resolution thumbnail prints on archival paper.

Of all the components of the documented archaeological record the site photograph has always been the part of the record most suited to post excavation re-examination, to test, confirm or disprove interpretations made in the field, during the writing up phase or much later when new types of evidence are sought in the surviving pictures from old excavations. Compared to the drawn record which varies from rough sketches to precise stone by stone drawings, in some cases drawn in full colour, the photographic record is the most objective; however even this can be manipulated in the field to 'emphasise' particular 'features' for instance with careful spraying of areas of dry soil prior to photography. Whilst photography can generate a very detailed record of archaeology as encountered, single photographs or panoramas comprising multiple images stitched together compare poorly with direct viewing the same scene with the naked eye. Conventional photography is constrained by the 2-dimensional nature of a single image, whereas, provided we have good vision in both eyes, what we see when we look at something is a 3-dimensional image. The ability to see in 3 dimensions means that we are able to respond to aspects of texture that would otherwise be invisible. Some years ago when visiting Philip Barker's excavation of the Roman site at Wroxeter it was observed that both he and I would constantly move when viewing the excavation in progress, even if that movement was very slight resulting from the transfer of weight from one leg to the other. By moving our viewpoint only a small distance we were able to radically increase our perception compared with the view, when stationary because we were more aware of subtle texture differences in the soils. We were effectively using what is known in photogrammetric circles as Structure from Motion (SfM) to enhance our view of the site.

Mapping in 3D

3D imaging in archaeological research is inextricably linked to the increasing power of computers over the last three decades and more. Software and computing developments during the early 1980s allowed us to use computers to calculate and create dynamic surface or terrain models from survey data; these models were most often used to generate accurate contour maps or shaded models for display on computer screens and ultimately for inclusion within the emerging Geographic Data Management and Geographic Information Systems (GDMS, GIS). Coupled with new high precision survey instruments relying upon use of laser pulses to take measurements archaeologists were able to increase the accuracy and the density of survey data which could be manipulated and presented on computer screens and output onto the printed page.

Laser scanning

The invention and development of the Time of Flight Laser Scanner at the end of the 1970s and continued developments throughout the 1980s and 1990s offered the potential to calculate and map complex three dimensional surfaces in a way that had formerly been completely impractical if not impossible. Laser Scanning technologies are changing all the time but in essence they rely upon the precision timing of a transmitted and reflected laser pulse reflected from any surface coupled with high precision geometric recording of the angles of transmission of the laser pulse. Given a

known position for the instrument three dimensional point locations can be measured in some cases with sub-millimetre precision and recorded at rates as great as 500,000 per second or more. The cluster of recorded points is referred to as a point cloud. Point clouds generated by the use of a laser scanner require sophisticated software and powerful computers to filter out false points reflected from uneven surfaces and other interference and to combine multiple point clouds gathered from different positions to generate comprehensive 3D records.

Modern laser scanners not only record the three dimensional position of each reflection but also the intensity of the returned signal and sometimes also the colour. The highest resolution scanners, which tend not to log the colour, can be coupled with digital cameras in order to secure the colour at each reflected point. 3D scanners are, not unsurprisingly, constrained by what ‘they can see’ and thus to cover a large and complex area scanning may need to be undertaken at many positions. The results from these multiple scans have then to be combined and precisely georeferenced with reference to each other and ideally a world or local coordinate system before the data can be used. The software requirements of 3D scanning data are very considerable but can be used to transform the point cloud into a 3D mesh with added colour derived from the scan or from the synchronously recorded photographs mapped to the surface as a texture and can be particularly useful for visualising 3D surfaces and for underpinning 3D re-constructions. Laser Scanners have been effectively used to document buildings and excavations in progress; however, they are extraordinarily expensive both as instruments and also in user and computer time. No matter how much the software has improved and reduced the need for extensive post-processing this is still an expensive way of documenting archaeological sites and historic structures. Some have argued that the scanning process can ‘preserve the past’ unfortunately this is not the case but what it can do is produce highly accurate point-in-time 3D models of measured surfaces which can be visualised and manipulated on a computer both for analytical and presentation purposes.

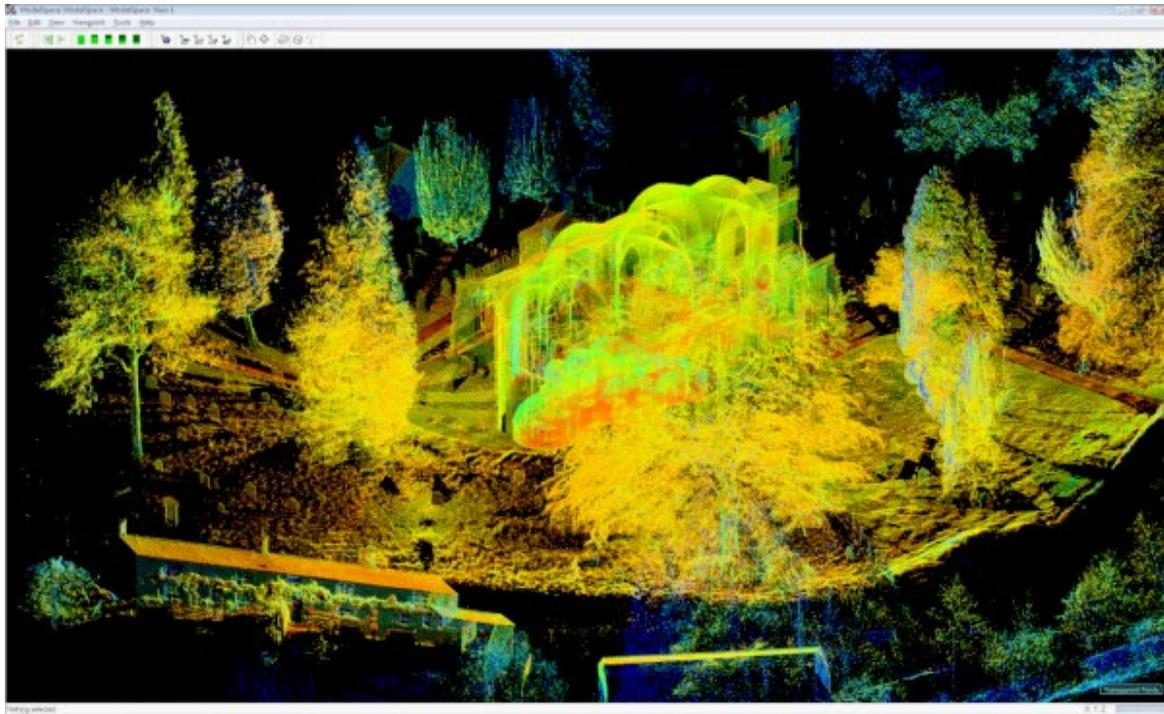


FIGURE 3. 3D LASER SCAN MADE USING A LEICA HD LASER SCANNER SHOWING INTERNAL FEATURES INCLUDING THE CRYPT, THE INTERIOR OF THE NAVE WITH ITS ELABORATE VAULTED CEILING ALL SHOWN IN RELATION TO THE CHURCHYARD.

One area of importance with reference to the laser scanner is the recorded intensity data, this has the potential to return information that is not visible to the naked eye and can be used to document information such as moisture in walls or surfaces which are otherwise invisible to the eye. A fundamental requirement for any record is that it has the potential to be multi-purpose holding information that is susceptible to re-analysis and future enquiry, a key factor in this is the accuracy and measurability of the record. Laser Scanners are highly accurate, do not require direct contact with the object being surveyed and have recording ranges which even at very high resolutions can be greater than 20 metres. The potential for recording without contact at long range offers significant advantages for building recording, but can be constrained by the weight of the instruments particularly if they need to be positioned in an elevated position to be able to scan areas not visible from the ground. Although the point cloud is the raw product of laser scanning secondary processing such as meshing is used to create surfaces that join the individual points defining a surface comprising very large numbers of triangular planes. These meshed surfaces can be viewed using virtual lighting, enabling fine surface detail to be emphasised through the production of shaded models. Further secondary work can include the application of textures derived from photographs to effect a degree of realism in the 3D model. Terrestrial laser scanners like airborne Lidar can also penetrate through vegetation and can thus be used to undertake ground survey even in woodland, as long as there are sufficient gaps in the vegetation to allow the laser to get through and be reflected back to the survey instrument.

Even with the best available software and hardware, converting raw point clouds into accurate and fully georeferenced, meshed and textured models can be very time consuming, generating results that pose serious challenges in terms of making the data readily accessible for a range of users and in terms of long term archiving. The singular problem of 3D scanning is the expense of the hardware and software and to some extent implementing a recording strategy that enhances the record without burying the user in vast body of data which may be of limited use. The scanning process undertaken as a specialist application or worse as a contracted ‘service’ during the excavation can also distance and to some degree isolate the excavator or primary observer from the record as they are unlikely

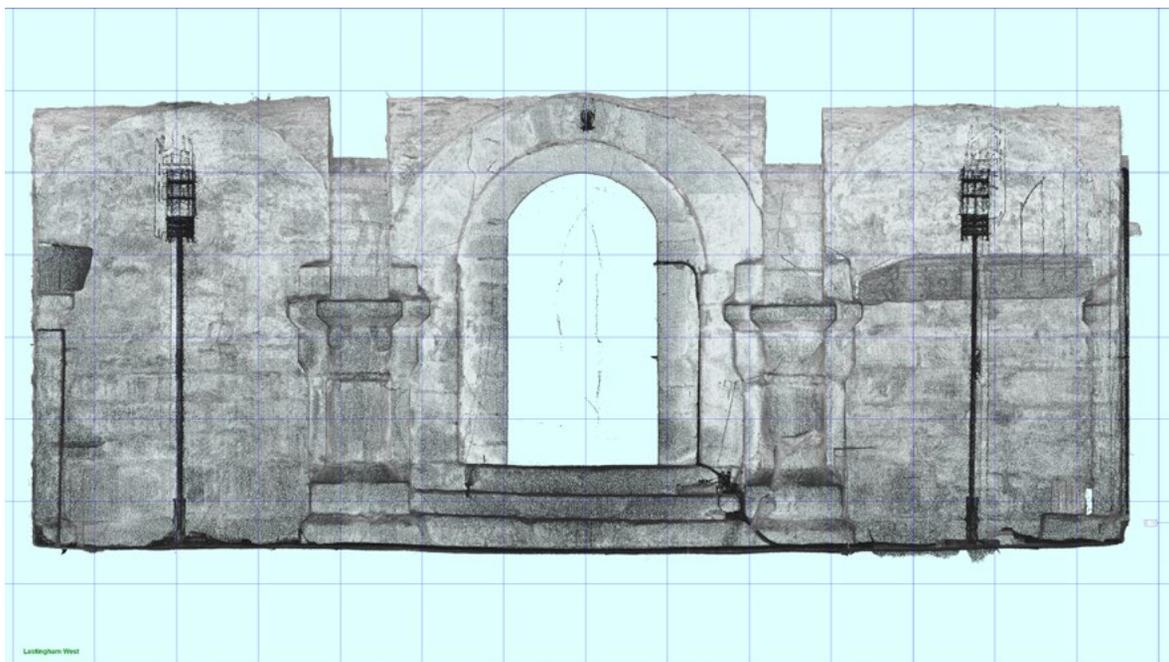


FIGURE 4. POINT CLOUD FROM 3D LASER SCAN SHOWING THE EAST FACING WALL AND DOORWAY INTO THE CRYPT AT LASTINGHAM, YORKSHIRE.

to be engaged in the offsite processing and are simply provided with a product, a product that most frequently is only viewable once the excavation has been concluded.

Figures 3 and 4 are derived from point clouds recorded at the Church in Lasingham, North Yorkshire, using a Leica HD Scanner, these allow the user to ‘look through’ the structure and study the relationship between the crypt and rebuilt church above. These images were generated as part of a collaborative project with the University of Siena and we are indebted to Leica UK for their assistance in this work. The use of the point-cloud generated gives insights into the form of the structure which could not be gained in any other way.

Structure from motion

Advances in both computer and digital camera technologies have led to the development of radically new methods of digital photogrammetry drawing upon sophisticated computer algorithms and information rich digital photographs to generate 3D models which can be as accurate as laser scans at a fraction of the cost and time investment. The increasing quality, resolution and simplicity of collecting digital images coupled with the developments in graphics hardware, primarily developed for computer games have fundamentally changed both the process of generating photogrammetric records but also the speed with which they can be created. Structure from Motion (or SfM) software uses multiple 2D digital images to calculate the precise location of the camera positions from which the images have been captured which can then be used to triangulate the precise 3D position of individual pixels recorded in multiple overlapping frames. In contrast with conventional photogrammetry which requires the use of carefully calibrated lenses and stereo viewing systems SfM can use information recorded within the digital images to calculate the characteristics of the lens employed; the EXIF (Exchangeable Image Format) comprises meta-data saved with the images created with a digital camera and includes a great deal of detail regarding the camera and sensor used, the lens and the many camera settings which can also include the GPS location of the camera at the time.

SfM software relies upon algorithms that in the first stage identify individual edges, boundaries or key pixels, identified within multiple photographs taken whilst moving around the object or view being recorded; this might be an individual small object, an archaeological excavation in progress or a landscape recorded from the air (Niccolucci *et al.* 2011; Pollefeys *et al.* 2001; 2003). These individual points or pixels identified in a minimum of 3 images are used to create a low resolution point cloud of the key points and use these to triangulate the precise camera positions. Once the camera positions have been calculated further processing, using a technique known as bundle adjustment can be applied to improve the accuracy of the camera positions before generating a high density point cloud using photogrammetric stereo processing algorithms. This high resolution point cloud which may incorporate tens of millions of points can then be used as the basis for creating a mesh image based upon the point cloud to which the original images can be finally be applied as a texture. Filtering of the mesh which may comprise many millions of triangles can greatly reduce the model size by combining adjacent mesh triangles that are in the same plane prior to applying the texture. This simplistic explanation gives a basic idea of what is involved but for this process to work well you must have high quality images.

The algorithms used to calculate the camera positions, refine those positions and calculate the 3D positions of each pixel as well as generate a triangulated mesh and apply image textures were first developed over 20 years ago. With continued refinement of the software and increasing sophistication of the data stored with digital photographs a wide variety of software is now available for generating SfM models. A variety of different software solutions are available for generating textured 3D models or 3Di images using SfM, this is not the place to compare and contrast the potentials of different software; the range of software includes free programs that use cloud computing to process images uploaded using the internet such as the Arc3D Web Service which remotely and automatically

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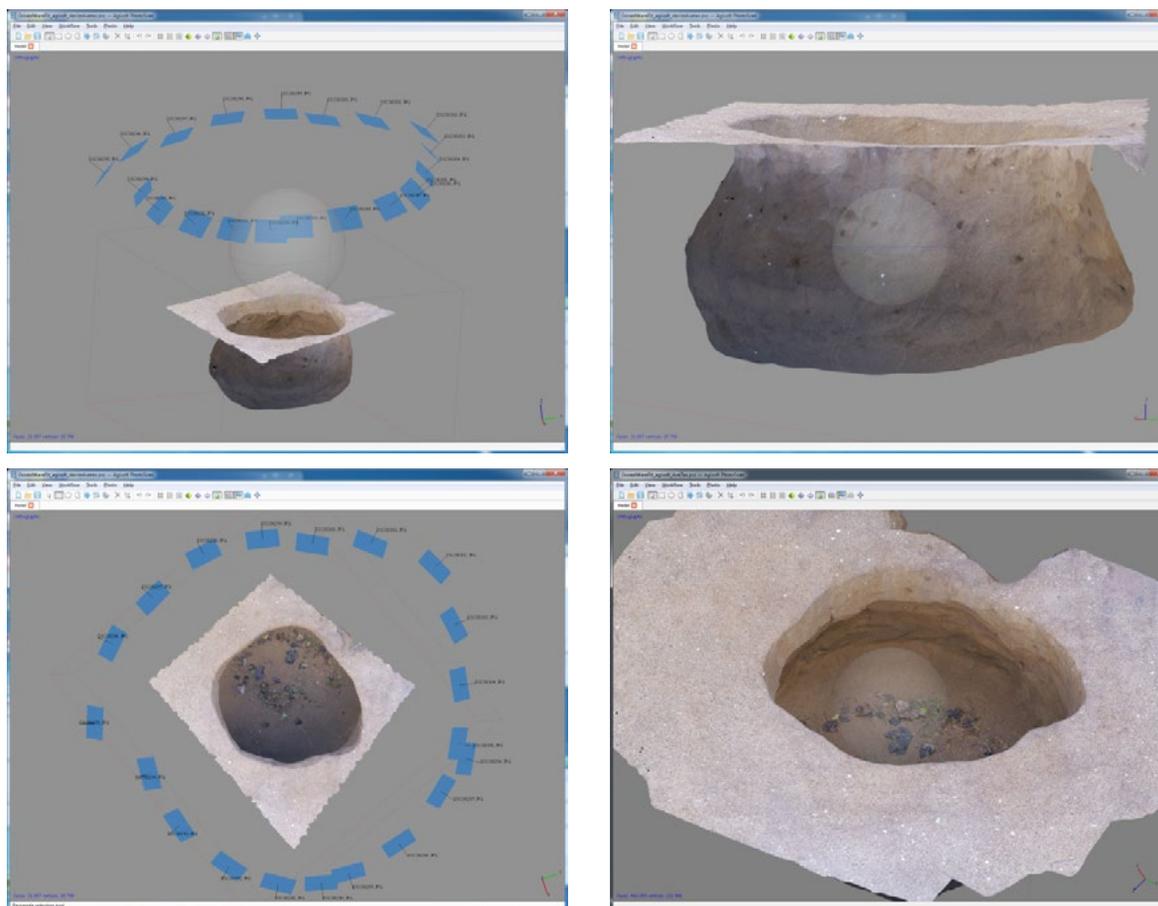


FIGURE 5. AN EARLY SfM EXPERIMENT RECORDING AN EXCAVATED NEOLITHIC PIT, WITH LEAVES AND 3D PINE NEEDLES BLOWN IN BY THE WIND! INITIALLY PROCESSED USING THE ARC3D WEBSERVICE, FROM 20 PHOTOGRAPHS RECORDED WHILST WALKING ROUND THE PIT. THE IMAGES ON THE LEFT SHOW THE CAMERA POSITIONS THOSE ON THE RIGHT SECTIONAL AND ISOMETRIC VIEWS OF THE FINISHED MODEL. ALTHOUGH THIS MODEL IS AN EFFECTIVE RECORD, SOME AREAS IN THIS UNDERCUT PIT WERE EXCLUDED, AN ADDITIONAL SERIES OF PHOTOS TAKEN FROM A LOWER ANGLE WOULD HAVE RESOLVED THIS ISSUE.

processes the supplied photographs and returns an email link to download the results of the modelling process in a number of different formats.

(<http://homes.esat.kuleuven.be/~visit3d/websevice/v2/index.php>)

Commercially available software includes reduced cost packages for academic and research purposes such as Photoscan Pro, which relies upon local processing of the image data but gives the user greater control than is possible using the faster offsite processing of the Arc3D Web Service. These two software solutions have been used to generate the results upon which this paper is based. See also (Brutto & Meli 2012).

SfM in the field

The application of SfM offers the opportunity to radically transform the usability and interactive potential of the archaeological record in a globally accessible environment. In contrast with traditional methods it offers a greatly enhanced potential for us to re-visit the 'site' after excavation has been concluded and to record with very high precision the three dimensional structure of the 'site' under

excavation. It does not however replace the need for the interactive dialogue with the ground that underpins all archaeological recording. The need for speed and the competitive economy, within which the majority of field archaeology is undertaken in Britain, at present, might be used as an argument in favour of dropping the traditional approach to recording and replacing the record with an ongoing and repeated process of 3Di this would be a tragic misuse of a very powerful technology.

Some notes on photography for 3Di

To produce successful and useful 3Di models requires the use of high quality images, if the images lack resolution or are not sharp the results will be very poor or it may be impossible to produce a model. Although it is possible to use a modern mobile phone to produce 3Di models, with mobile applications such as AutoCAD 123D Catch providing a software solution, the resolution of the models is insufficient for the quality of model and texturing required if we are to enhance our records. To use a substandard camera or poor lens because they are cheap is a pointless economy. A good understanding of the principles of photography and particularly depth of field is essential as pictures which are only partially in focus will also produce useless results. Where possible a tripod should be used, the camera should be set to a low ISO value such as 100 or 200 (the ISO value relates in traditional terms to the sensitivity of the film, which has been translated to that of the digital sensor, high ISO values allow faster shutter speeds and can reduce camera shake but tend to show more sensor noise). Images with a lot of sensor noise are useless for 3Di processing. The temptation to use Automatic or Programme exposure modes should be avoided as these will tend to generate results with a limited depth of field (determining the range in the image that is in focus). Aperture priority mode which allows the photographer to determine the depth of field should be used if possible, this may require slow shutter speeds but when the camera is on a tripod this should not be a problem. In many senses the parameters required to setup a camera for use for generating 3Di images is no different than required for excavation photographs in any case. Wide angle lenses tend to produce good results although fish-eye lenses should be avoided. All professional and high end amateur cameras record images in two formats, JPEG or .jpg files and RAW files. The JPEG format was developed as a standardised approach for producing images employing compression techniques to reduce the size of the image files, as such JPEG images incorporate pixels that have been averaged and combined to reduce the file size, and yet ‘appear’ to be unmodified. JPEG files should not be used for modelling if at all possible. Raw files, record what the sensor sees and although they may include what is termed lossless compression, they do not include the sort of compromise that is needed to make a JPEG compressed image. Because SfM relies on being able to identify the relationships between individual and groups of pixels it follows that RAW files will produce the most accurate results. Depending on lighting conditions it may be necessary to carry out post-processing of the RAW files to balance the lighting across all frames, rather than simply export the images to TIFF or .tif files for processing; RAW files will need to be converted before processing the model. Each lens and camera combination can have different biases and software that corrects distortion and applies tiny variations that modify the image in response to known sensor characteristics can greatly improve the results, DXO Optics PRO is an affordable package that allows one to bulk process corrections to hundreds of images at one time, producing sharper and more consistent results.

Taking the pictures

For 3Di to work the scene being recorded must be still and have no moving elements, such as people working (these would need to be masked in each frame individually so as not to compromise the model); in wetland environments working on peat in particular one has to be very careful to ensure that the surface being documented is not moving or changing shape as a consequence of people or plant moving nearby. Photographs should be gathered on the basis that each photograph should overlap with its neighbours by 60-65%, ideally covering the whole scene to be recorded by a net or dome of images if it is a trench or an object, or by a number of parallel picture runs if it is an archaeological section. Sections are most easily recorded by laying a tape parallel to the section to be recorded a



FIGURE 6. DETAIL VIEW OF PART OF A SECTION THROUGH A BRONZE AGE BARROW SHOWING TIP LINES OF TURVES WITH LEVELS OF DETAIL DIFFICULT TO RECORD USING CONVENTIONAL DRAWINGS EVEN IF EXECUTED IN COLOUR.

standard distance such as 1m away, aligning the tripod legs on the tape and moving the camera along the tape in 50 cm steps, making sure that at the pictures continue to be taken beyond the each end of the section if possible; this ensures that the modelling process will correctly process the section ends. For open excavation areas the process is more complicated, but still not difficult, it requires a little planning and a rigorous approach, for small areas and individual features photography can be conducted using a tripod on the ground or from a trestle ladder moved around the subject as required, oblique images taken near the ground are very good at identifying local relief but to get accurate overall coverage a long photo-pole is required. In an ideal world the process would be best served by having photographs which are perpendicular to every part of the scene, and experience has shown that for plan views of archaeological sites we do need near vertical images as well as lower oblique images viewed from around the trench. It is worth remembering that too many pictures can cause massive processing problems and that multiple pictures taken from the same position will cause the processing to fail.

For the results of 3Di to be of long term archaeological value they must support the production of precise scaled images. Scaling information can be incorporated in the photographs through the use of photographic scales but more usefully by the inclusion of measured photogrammetric targets, the target positions are best logged using a reflector-less total station sighted with the measuring beam on the centre of the target. Photogrammetric targets which can be identified by the processing software can be printed using the SfM processing software such as Agisoft Photoscan and Photomodeller. If one is to generate accurate models then it is absolutely critical to incorporate targets and survey their positions precisely, if the absolute precision is less important the inclusion of photographic scales of known dimensions can also be used to apply scaling to a finished model and if none is available rough scaling can be introduced provided some known distances or other points can be identified on the model. Doneus has demonstrated the very high precision that can be expected from carefully constructed and well referenced models in the excavation context with accuracies within 1mm (Doneus *et al.* 2011). The precision achievable using SfM software and digital photographs is



FIGURE 7. MULTIPLE SECTIONS OF TRENCHES EXCAVATED IN THREE DIFFERENT YEARS COMBINED TO PROVIDE A 'SEE THROUGH' VERSION WITH ALL THE SECTIONS GIVING A CLEAR PICTURE OF NUMEROUS ROBBING EVENTS. NUMBERED ANNOTATIONS IDENTIFY KEY FEATURES OBSERVED IN THE SECTIONS.

effectively as good as that possible with a 3D Laser scanner on an excavation, at a fraction of the cost. In most cases the accuracy of well-constructed 3Di models is rather better than we might expect from drawings done manually, especially in the winter when under great time pressure and weather conditions are bad. The 3Di model which can be viewed from any angle, including from behind (which has a particular bearing on the ability to view multiple sections simultaneously) is generated in an internationally accepted file format, the Object file (.obj) useable in almost any 3D viewing or rendering software and can also be archived in a scale correct format in 3D pdf files. 3D pdf files are not only in an internationally accepted archive format which can viewed by almost any computer with sufficient memory but support measurement functions and annotations which support detailed re-examination of a primary record.

Generating the model

The generation of the 3Di from digital photographs is computationally highly intensive and, as with any digital process, may require some compromises to be made to ensure that the resulting model can be used by the widest possible audience. The process of model generation is follows a relatively standardised sequence regardless of the software used.

Once suitable images have been gathered, checked, adjusted if necessary and exported from RAW to standard formats, employing lossless compression such as .tif or .png files, these are processed either locally or using a web service. The first stage of the process involves calculating and refining the camera positions and generation of a point-cloud, the point cloud of 3D points each with a colour value can be very large and processed at maximum resolution approaches the density generated by a 3D laser scanner. Very high density point clouds can perfectly encapsulate the surface form of the subject being imaged, which can in some cases include differences in texture, by mapping rough as opposed to smooth soils; very high density point clouds can require large amounts of memory but can

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FIGURE 8. SMALL EXCAVATION EXAMINING THE RAMPART OF A LARGE HILL-FORT AT ROULSTON SCAR, YORKSHIRE MOORS NATIONAL PARK SHOWING THE CAMERA POSITIONS USED TO GENERATE THE 3DI.

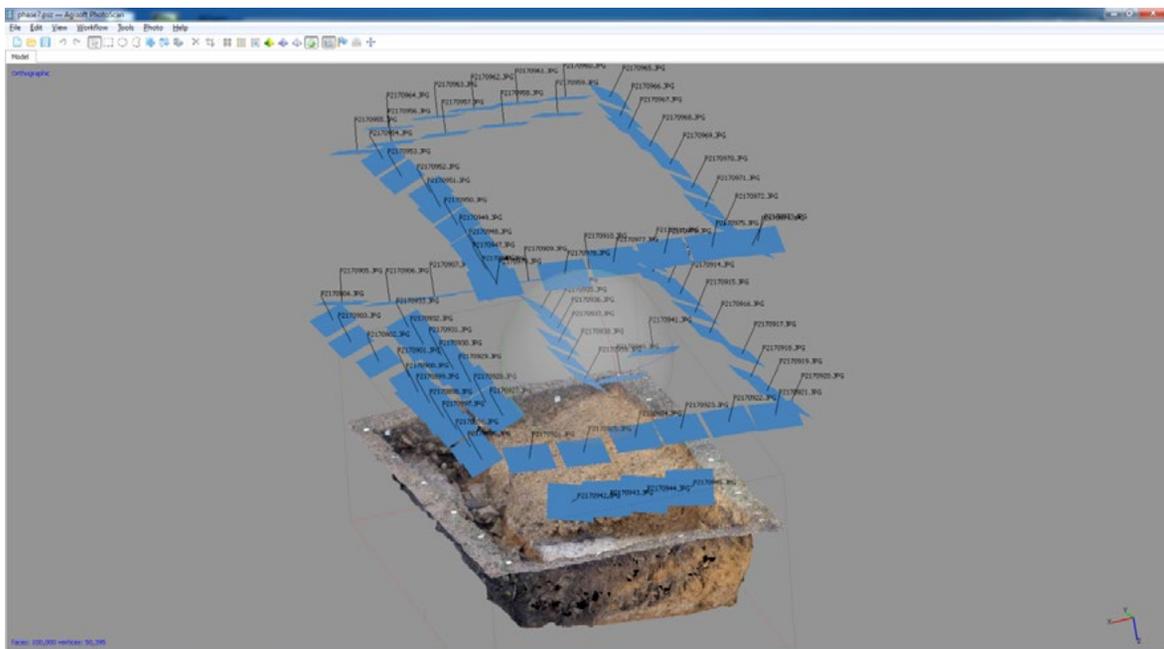


FIGURE 9. ISOMETRIC VIEW OF THE SAME MODEL WITH CAMERA POSITIONS SHOWN IN FIGURE 8. A PHOTO POLE, EXTENDABLE TO 6 M, WAS USED TO TAKE MOST OF THE PHOTOGRAPHS FROM TWO DIFFERENT HEIGHTS. FURTHER IMAGES WERE RECORDED BY HAND TO GUARANTEE THE COVERAGE OF THE SECTIONS AND SIDES OF THE EXCAVATED FEATURES.

still be manipulated on relatively low powered computers. The point cloud alone however does not give the quality of return needed to properly visualise what has been recorded.

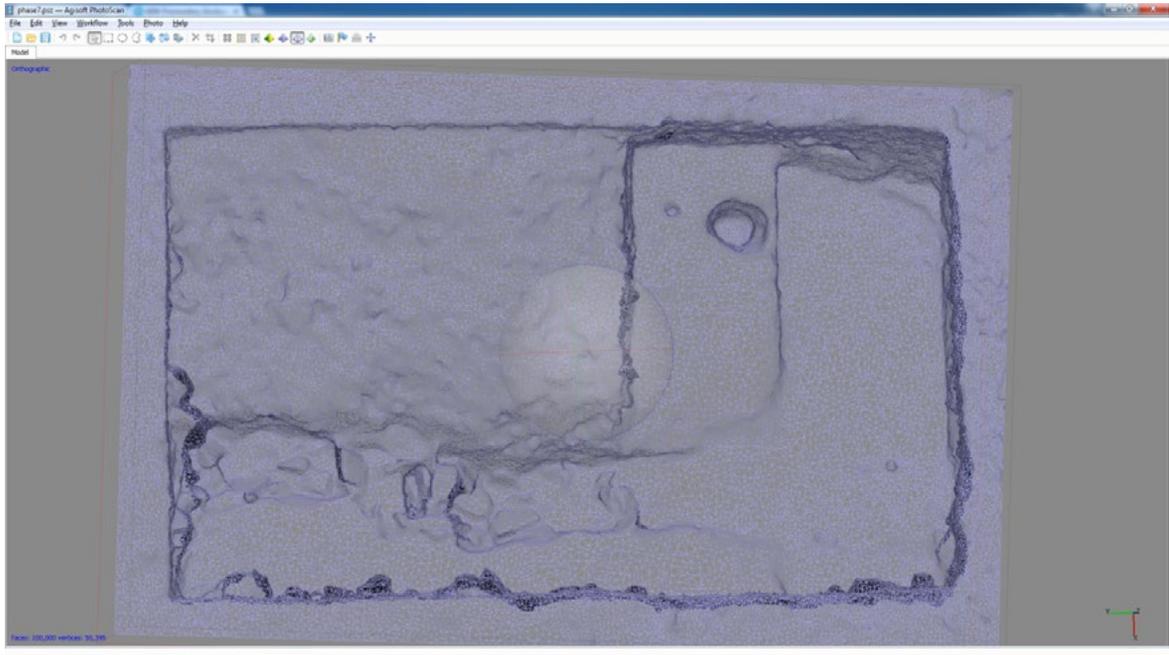


FIGURE 10. TRIANGULATED MESH COVERING THE TRENCH SHOWN IN FIGURES 8 AND 9. THE MESH COMPRISES 100,000 TRIANGLES CALCULATED FROM A POINT CLOUD OF MORE THAN 20 MILLION POINTS.



FIGURE 11. THE COMPLETED AND ANNOTATED 3DI MODEL SHOWING AN EARLIER STAGE IN THE EXCAVATION ALSO SHOWN IN FIGURES 8-10. ANNOTATIONS ADDED TO THE MODEL GIVE THE USER ADDITIONAL INFORMATION THAT HIGHLIGHTS THE INTERPRETATION OF THE 3DI MODEL.

The second stage of the modelling process uses the high density point cloud to generate a triangular mesh defined by the point cloud but avoiding the use of co-planer points so as to limit the number of triangles. In essence the triangulation process is focused upon curved areas rather than flat planes

so that the surface form is retained as much as possible with high densities of small triangles where the shape is very rough and larger triangles covering smooth areas. The processing of very high density meshes requires large amounts of memory and generates a result which at high density uses at least four times the memory required for the point cloud alone. If the models produced through SfM are to be of use, to those without very high specification hardware, it is necessary to reduce the resolution of the mesh through a process of decimation; remarkably once the mesh has been textured this reduction in the mesh density can be difficult to observe.

The final stage of the process is the overlay of the photographic images onto the mesh, in which image fragments derived from the photographs that are most perpendicular to the triangles in the mesh are identified and compiled into mesh images that contain the image fragments that are effectively overlain upon the mesh.

3Di role in 'the record'

If we are to use 3Di to enhance the primary record and increase the returns from the recording process then we need to embrace it within our standard recording procedures. Whilst I have argued that this approach, despite its ability to deliver views in plan and section and indeed both at the same time, does not justify its use as a replacement of established recording through the drawing of plans and sections it has the potential when fully integrated to support a change in the nature of the primary field drawings. Rather than attempt to offer an objective record, something difficult to achieve especially when faced with time constraints, efforts could concentrate on presenting the interpretation of the evidence in drawn plan or sectional formats with supporting detail provided in 3Di. This approach should not take longer than the production of carefully drawn field drawings we are used to. It would allow those doing the recording on the ground to concentrate their efforts on detailed interpretation of the evidence, drawing and annotating drawn plans and sections focussed upon interpretation, which could be viewed in tandem with 3Di models generated prior to the planning and section drawing process which by necessity often involves damage to the cleaned surfaces. If we are to do this then the photographic geo-referencing markers employed during the image collection process should also be precisely marked on the plans and sections. By incorporating shared geo-referencing points the drawings could potentially be added to the 3D models as an overlay.

After the digging is done – the returns from 3Di

The returns from 3Di as opposed to the use of conventional photography with drawn plans and sections comes from the simplicity with which very high resolution 3Di models can be examined after the excavation is completed. The use of virtual lighting to expose relief and large scale texture variation can greatly enhance the viewers understanding of the model being viewed and there is a real opportunity to reinterpret a 3Di model in a way simply impossible from drawings and single photographs alone. 3Di models can also be used to generate high precision contour plans and can increasingly be incorporated within CAD and GIS packages directly.

The Landscape Research Centre (LRC) has been experimenting with 3Di modelling for more than 5 years, during 2014 a small excavation designed to examine the defences of a hill-fort at Roulston Scar, North York Moors National Park, was intensively recorded using 3Di in addition to conventional methods. The objectives of the excavation were relatively simple, to try and recover dating and environmental evidence that would allow the monument to be viewed in its chronological and landscape context and related to the very much smaller Promontory Fort at Boltby Scar 2.5 km to the east, examined in 2011-12. The scale of the defences, where sectioned, turned out to be far larger than had been anticipated as, at this point, the rampart ran along the top of an already very steep slope. Down-slope from the rampart the ditch measured c6 m cross and was cut with largely vertical sides into bedrock to a depth of over 2 m. The massive scale of the ditch was such that the majority of the effort was concentrated on excavating this with focus on the rampart being the recovery of

environmental and dating evidence from the buried soil beneath the rampart and documentation of the north facing section of the narrow trench. The defences had been examined in 1969 and 1970 over 100 m further to the north where they were levelled when an aircraft hangar was constructed, the interior of the fort having been levelled during the development of the site as an airfield, home of the Yorkshire Gliding Club.

The earlier excavations had discovered the presence of a timber box-rampart as a primary component of the rampart and also what was described as a gully running along the back of the rampart. With posts spaced at approximately 2 m intervals in the box rampart it was accepted that the narrow trench dug in 2014, with less than 1 m width taken down to the base of the buried soils, might be unlikely to encounter any components from a box rampart had it continued into the area being examined which was, in contrast to the areas examined earlier where the defences ran across flat ground, was at the top of a steep scarp slope. A second feature identified in the previous excavations was a ‘gully’ at the back of the rampart. This was interpreted by Oswald (2001), who re-examined the evidence with the original excavator Tony Pacitto in 2001, as being from a second phase of rampart development. The ‘gully’ was identified at the back of the rampart in 2014, where it was observed to cut the tail of the rampart very clearly and to contain a series of large post-settings requiring its reinterpretation as a palisade slot. The fills of this feature were quite different to those related to the prehistoric rampart and ditch and the palisade was potentially linked to the Battle of Byland in 1322 where the Scots beat the forces of Edward II of England. Although dating material was recovered to show that the rampart dated to the Late Bronze Age/Early Iron Age and the ditch was re-cut in the middle of the Iron Age, no dating material was recovered from the palisade trench.

The 2014 excavations undertaken in November and December were constrained by resources and weather conditions as well as the winter lighting conditions; with high resolution 3Di models recording or capturing what was examined so much better than rapidly drawn interpretation drawings; these were then examined in some detail during the post-excavation reporting stage. A key aspect, observed but not fully interpreted in the field, was the presence of a series of tip-lines within the body of the rampart which, when examined carefully using the 3Di model, indicated the potential that a box rampart had been present which left a vertical boundary between the relatively smooth clay rich deposits in the centre of the rampart and more stony deposits on the side. Once this difference was observed on the western side of the rampart a similar but perhaps less obvious contrast was seen on the eastern side of the rampart. These observations were published in a live 3Di model (<https://skfb.ly/AZCI>) in September 2014 as part of the post excavation reporting process at the same time as a proposal to extend the excavation to test for the presence of a box-rampart structure and date the late palisade. That excavation is in process as this is being written but already the presence of the box-rampart has been confirmed through the identification of a very clear post-hole cutting the old ground surface but also by soils evidence visible both in section and in plan which confirm the suspicions arising from the detailed examination of the 3Di model. This simple example reveals the power of 3Di in the reflexive approach to excavation recording and interpretation (see Figures 8-11).

Archive implications of 3Di

If we accept that carefully and professionally undertaken 3Di within the context of field archaeology, which need not be limited simply to excavations but can also be used at almost any scale from documenting landscape to recording small finds, can both improve and enhance the record we have to be aware that certain archival requirements need to be considered. 3Di may come within the realm of so called ‘Big Data’ certainly this is the case with 3D laser scan data, and thus we need to be proactive regarding the long term archiving process. There is no point in using a technique that supports reflective re-examination of archaeological data when there is no mechanism to secure the future of the data. The processing of 3Di data is both computationally and memory intensive, the raw materials behind a 3Di model are simply the digital photographs and the computer software process that generates the model. In a similar way to 3D laser scanning SfM software processing can produce

vast 3D point clouds, as these words are being written a very high powered PC with 48 GB of RAM and a high performance graphics card has been running flat out for nearly 24 hours to produce a point cloud of nearly 77 million points; these generated from 125 camera positions to record a tiny 3 x 5 m trench. A 3Di model covering a mere 15 square metres of trench and incorporating a mesh covering all 77 million points would be unwieldy at best, even on a powerful computer, in reality filtering during the process of creating a triangulated mesh would reduce generate a result with 10-15 million triangles, still too large to manage on a standard computer. More significantly, once the textures have been added it would be difficult to see archaeologically significant differences in a model comprising 5 million triangles to one with 100,000. The intermediate files and point clouds created as part of the modelling process have limited value once the finished model is created and thus need not be saved for posterity; they can be re-created any time, and it is likely that new developments in software could increase the returns from re-processing the primary images in the future. New software initiatives such as those being developed through the Visual Computing Lab of the CNR-ISTI in Italy and available through the 3DHOP platform (<http://3dhop.net>) are addressing the challenges of delivering actively filtered very high resolutions on the web; the challenges of delivering full resolution information on the Internet will be solved and millimetre resolution views will be possible in a way similar to the delivery of high resolution airborne data viewable on almost any computer using Google Earth.

At a minimum, an archive record that comprises the primary digital photographs, a text file documenting the software functions and variables used and a resulting pdf would be an appropriate digital archive record. 3D pdf files are viewable on almost any platform and can be imported as 3D models into other software platforms. To maximise the usability of the archive models should also be archived in 3D object file format (.obj), which comprises multiple files holding the mesh model and the overlain textures stored in image files with a materials file; object model files can also be imported into the majority of 3D imaging or presentation packages. By archiving in both formats the

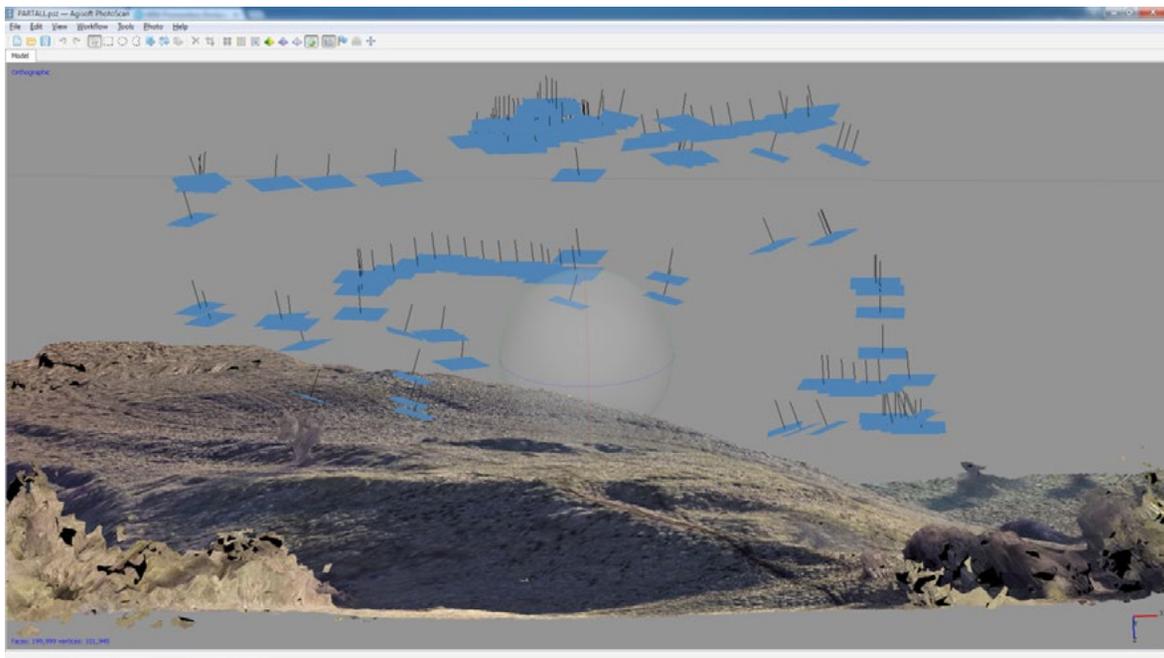


FIGURE 12. CAMERA POSITIONS RECORDED USING A SMALL QUADCOPTER TO MODEL AN EARTHWORK FEATURE ON THE LOWER SLOPES OF THE YORKSHIRE WOLDS, IN EAST HESLERTON.



FIGURE 13. 3DI MODEL GENERATED FROM MORE THAN 150 IMAGES GATHERED USING A DJI QUADCOPTER WITH A GOPRO 4 CAMERA. REMARKABLY ISOLATED TREES ON THIS MONUMENT PHOTOGRAPHED IN FEBRUARY CAN BE SEEN FROM THEIR SHADOWS BUT WERE EXCLUDED FROM THE MODEL WITHOUT ANY HAND EDITING OWING TO THE NUMBER AND VIEW ANGLES OF THE COLLECTED IMAGES.

maximum long term sustainability of the content can be secured. In the case of the LRC, working with the McDonald Institute for Archaeological Research at the University of Cambridge, our policy is to store the Raw images, the processing log file, 3D PDFs and 3D Object and supporting files at high and low resolutions in the University permanent online and publically accessible digital archive.

The potential long term survival of the pdf format is as secure as anyone could estimate, and as long as migration policies for digital archives are maintained TIFF files generated from the raw camera files have a similarly secure future.

An alternative would be to print high resolution archive prints of the photographs and archive these with the documented software steps needed to create the model; by so doing the images could be scanned and a new model built using any SfM software in the future. What is abundantly clear is that a degree of discipline is needed to clean up archive directories, deleting any out of focus or irrelevant images and temporary files and ensure that an intelligent naming policy is used that makes it easy for anyone to identify the resource and its source.

Distributing the results

In addition to archiving the results in standard data formats which support download and local re-examination, new web plug-ins and other software that facilitate live viewing of 3Di models are increasingly available. One example is Sketchfab which provides online access to models using web browsers on multiple platforms including, remarkably, smart phones. Enhancements to web based delivery systems such as Sketchfab allow one to attach notes to 3D points on a model which in turn can use a URL to link to supporting information which might anything from primary data to completed specialist reports. The LRC uses Sketchfab to provide a publicly accessible online archive of its 3Di models (<https://sketchfab.com/d.powlesland/models>).

Sketchfab which employs WebGL technologies to deliver dynamic 3Di material has proven to be a highly resilient, powerful and evolving platform for online distribution of 3Di material which, even in the case of high resolution models, can be viewed on computers, tablets and smart phones.

Other software includes virtual reality software which can provide simultaneous access to 3Di models in a virtual space where multiple people can view and discuss the same models live via a web browser. This sort of live viewing facility offers tremendous opportunities for researchers and the interested public at every level to engage with the three dimensional nature of the archaeological resource that has never been possible before. A colleague described the process of viewing the 3Di models of an ongoing excavation as ‘just like being there’ the description is imperfect, especially on a cold wet day, but it reveals a quality of information which exceeds that normally expected.

Conclusions

3Di recording and presentation of archaeological deposits during excavation, objects retrieved from excavations or features in the landscape photographed from the air is a transformational technology that has the potential to change forever the underlying level of detail, accuracy and usability of a core part of the archaeological record. It unfortunately also offers the opportunity for those less engaged in their fieldwork to believe that it can replace conventional approaches to recording and speed up the excavation process, and thus reduce the cost of fieldwork. This would be a catastrophe, we are given a great privilege when we destroy an archaeological site through excavation and if we are to benefit from the method we must use it to enhance our ability to observe and interpret on the ground. Modelling excavation in progress overnight so that we can return to field the next day with ortho-rectified prints, made on draughting film using waterproof inks, for on-site annotation and drawing interpretive overlays should become standard practice; thus freeing time spent on conventional field drawing to be devoted to close observation and interpretation in the field. In the very near future we should anticipate using truly 3D and 4D spatial data management systems that will bring archaeological research to an ever wider public through interactive 3D publication on the internet. As the hardware and software continue to evolve so will the returns of 3Di allowing us to achieve higher degrees of data integration than has been possible in the past.

The importance of the technique is best appreciated by the number of colleagues who, when they engage with the method for the first time, simply respond with “if only we had had this when we excavated at ...” (insert almost any excavation name you care to choose).

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Towards 3D GIS.

Notes from the 2012 CAA-NL/DE chapter session 'from 2.5 to 3 spatial dimensions'

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Abstract

After 20 years of '2.5D' GIS work in Archaeology we have seen in recent years the first signs that researchers are moving on to true 3D (volumetric) spatial representation and analysis – previously the preserve of oil geologists. At the same time, new technology is giving rise to a boom in '3D' (actually still 2.5) documentation and visualisation studies. This paper draws attention to the collection, management and analysis of true 3D spatial data from intra-site to landscape-scale contexts, drawing on data deriving from coring, geophysics, excavation, seismics, etc. The authors discuss current possibilities and desirable developments in 3D GIS.

Keywords: 3D GIS, volumetric representation, 3D topology, archaeological documentation, spatial analysis

Résumé

Après 20 ans de travail SIG en archéologie «2,5D» nous avons vu au cours des dernières années les premiers signes que les chercheurs passent au vrai représentation et analyse spatiale 3D (volumétrique) – auparavant l'apanage des géologues du pétrole. En même temps la nouvelle technologie donne lieu à un boom des études de documentation et de visualisation «3D» (en fait encore 2,5D). Ce document attire l'attention sur la collection, la gestion et l'analyse des vraies données 3D spatiales, d'échelle intra-site aux échelle du paysage, en tirant sur les données provenant de carottages, de la géophysique, de l'excavation, de la sismique, etc. Les auteurs discutent les possibilités du SIG 3D actuelles et les évolutions souhaitables.

Mots clés: SIG 3D, représentation volumétrique, topologie 3D, documentation archéologique, l'analyse spatiale

Introduction

Like GIS in the 1990s, '3D' is now a hot topic in Archaeology. New technology – laser scanning, software for digital photogrammetry, and 3D printing – is quickly being taken up by archaeologists for documenting and visualising surfaces of objects, monuments, excavation trenches and whole landscapes. It is, however, not our intention here to assess this development except to point out that the term '3D' has now effectively been claimed in scientific print and in the public's mind for this field, even though it does not refer to the three *spatial* dimensions. In GIS parlance, this is really '2.5D'; we here reserve the term '3D' for the recording, management and analysis of 3D spatial data.¹

After twenty years of '2.5D' GIS work in archaeology, we have seen in recent years the first signs that researchers are moving on to a true (three-dimensional or volumetric) spatial representation and analysis of their data. To foster this development, the chapters of CAA-NL and CAA-DE in their 2012 joint conference included a session focusing on the collection, management and analysis of 3D spatial data from intra-site to landscape-scale contexts, such as may be derived by coring, geophysics,

¹ A review of recent CAA proceedings confirms that none of the papers published under the '3D' heading is concerned with the inside of the objects discussed.

excavation, seismics, etc. Whilst ‘3D’ visualisation centers on the recording, reconstitution, and visualisation of the three-dimensional *outside* of objects, we are concerned here with the three-dimensional *inside*: the volume, and its analysis in a GIS-like environment.

Three papers on the use of 3D data representations in Archaeology were presented at the conference, but we will focus here on the ensuing discussion, chaired by Van Gessel. This revolved around the following questions:

- How and where could full 3D representation be helpful in Archaeology?
- What types of 3D models and software do we archaeologists want?
- What problems may we expect to have with the ingestion and analysis of 3D data?

3D GIS

What do we mean by ‘3D GIS’? The crucial element is the ability to ask and answer questions about the content and topological relationships of three-dimensional entities. 3D topological GIS functionality has also been sought after for geological and cadastral purposes (Peres and Benhamu, 2009), but current GIS do not come close to offering full 3D topology. World leader ESRI offers x,y,z vector recording and display but no volumetric topology: as in Autocad, you can calculate the volume enclosed by two or more surfaces, but that is not topology. True 3D entities should be able to have any number of attributes, including time-related ones. So a 3D GIS should be like the example shown in Figure 1 – a volumetric model specifying BOTH layers, features and objects in three dimensions AND their spatial relationships.

Why would we want this 3D analytical functionality? At the risk of stating the obvious, the archaeological record, and the landscape that contains it, is three dimensional. Archaeologists want to record and study this 3D structure, and heritage managers want to know about the risks run by cultural remains in relation to depth and soil processes. Some of the data sets that archaeologists generate are already ‘inherently 3D’ – think of coring data and GPR data, but nearly all traditional

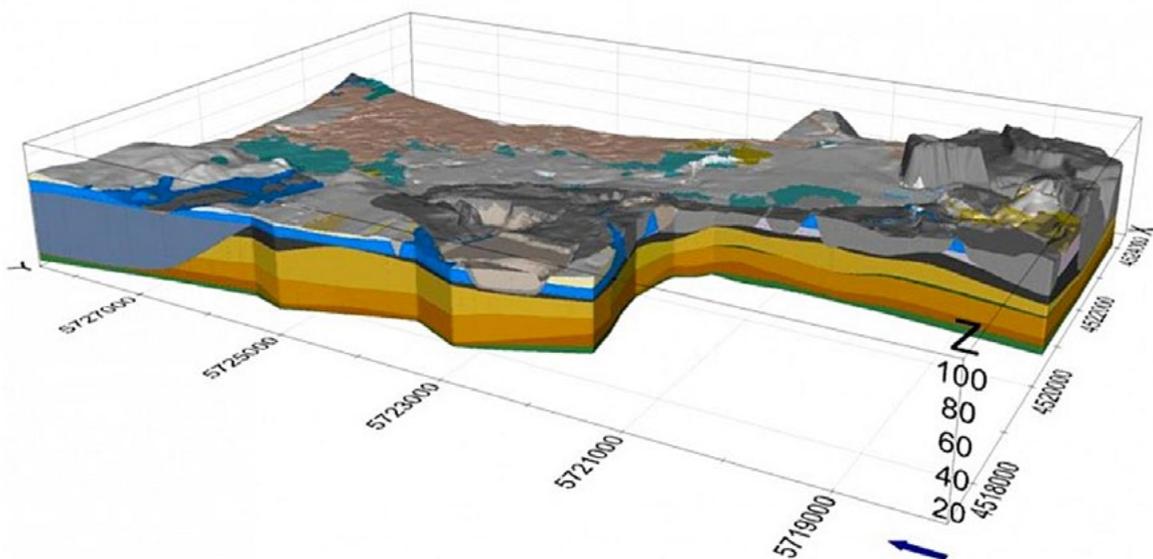


FIGURE 1. EXAMPLE OF WHAT A TRUE VOLUMETRIC MODEL MIGHT LOOK LIKE. HIGH RESOLUTION 3D GEOLOGICAL MODEL OF THE BITTERFELD AREA (SOURCE: 3D-GEOLOGY.DE. MARTIN-LUTHER UNIVERSITÄT HALLE-WITTENBERG; [HTTP://WWW.3D-GEOLOGY.DE/ANIMATED_GRAPHICS_AND_VIDEOS](http://www.3d-geology.de/animated_graphics_and_videos)).

recording methods rely on a reduction of the 3D environment to 2 or, at most, 2.5 dimensions – think of excavations plans and sections, and the Harris stratigraphic matrix. We can all *imagine* the true 3D relationships between cuts, fills etcetera, but as yet we have no way of representing them digitally.

Why is this? Firstly, no ready-made inexpensive software solution yet exists: all software mentioned here – Voxler3D, GSI3D, SGEMS, Grass GIS, RockWorks, ArcGIS – will go some way towards representing and visualising 3D data but does not offer much analytical capability yet. Secondly, we can only start building useful 3D models if we start recording data in 3D, but despite increased use of Total Station, LIDAR scanners, and photogrammetric reconstruction, much of what we record in the field is still firmly 2D. So we might not yet have the right data, or not enough of the right data, to build 3D models. Thirdly, we need to talk to geologists more often: they are further along than we are, helped by the fact that geological features and processes tend to behave in a more predictable manner than archaeological ones.

Discussion

Which situations would require, or benefit from, 3D models? The audience at the CAA chapter meeting were asked to consider situations where 3D modelling would be a useful addition to their current work process or would require alterations to that process. It was surprisingly difficult to come up with clear benefits; the examples discussed tended to be oriented towards heritage management:

- Finds have a 3D distribution but their absolute height above datum (Z-factor) is not always recorded. Yet this is essential for the understanding of the 3D finds distribution – for example, for understanding why some find locations are well preserved and others are almost destroyed by geo(morpho-)logical and anthropogenic processes.
- Having a landscape-scale three-dimensional model of the geology and soils would facilitate the assessment of prospective site locations: which subsurface features tend to be favourable/unfavourable to past uses and to postdepositional preservation? Could we make more specific and more correct predictions of site location?
- Creating/visualizing site reconstructions (e.g. buildings) would become a lot easier with 3D GIS, especially if im- and export to dedicated visualisation software were sorted out. Besides the obvious advantages in public outreach such models can also become tools furthering scientific discussion. Standards for the documentation and publication of 3D data and models will have to be developed.

Several examples of ‘somewhat 3D’ vector models of archaeological sites, using ArcGIS, were shown at the meeting, but it was noted that these require considerable discretization and simplification of the three-dimensional representation of complex layers and features, to the extent that no serious analysis can be conducted on them. Vector-based 3D topological GIS therefore still seems some way off for archaeologists – but how about voxel-based solutions, where no explicit topology is required? These are much easier to implement, since they are simply an extension of the 2D matrix of values underpinning raster-GIS: computationally very simple but needing high-end processors to process large files sufficiently quickly.

An example was discussed concerning the wish to record an excavation site in a 3D voxel model, where each excavated layer could be represented by a level in the voxel model: if each excavated layer were recorded in a 2D map it should be fairly easy to import these into the voxel model (discretizing and stacking of the 2D layers). Voxel-based solutions as used in geology and in games such as Minecraft (Figures 2 and 3) can already handle different scales (voxel dimensions) for the horizontal and the vertical. Obviously, the lack of formal topology means that spatial relationships must be *calculated* using a ‘voxel calculator’ – e.g., one can imagine using a 3D neighbourhood filter to select all archaeological feature voxels that are neighboured by ploughzone voxels. 3D voxels then have the advantage that they can hold many continuous or discontinuous attributes (e.g., calcium



FIGURE 2. LEGO MODEL USING VOXELS OF DIFFERENT DIMENSIONS TO REPRESENT OBJECTS, CUTS AND FILLS (SOURCE: CHRIS MALLOY, [FLICKR.COM/PORSCHECM2](https://www.flickr.com/photos/porschem2/)).

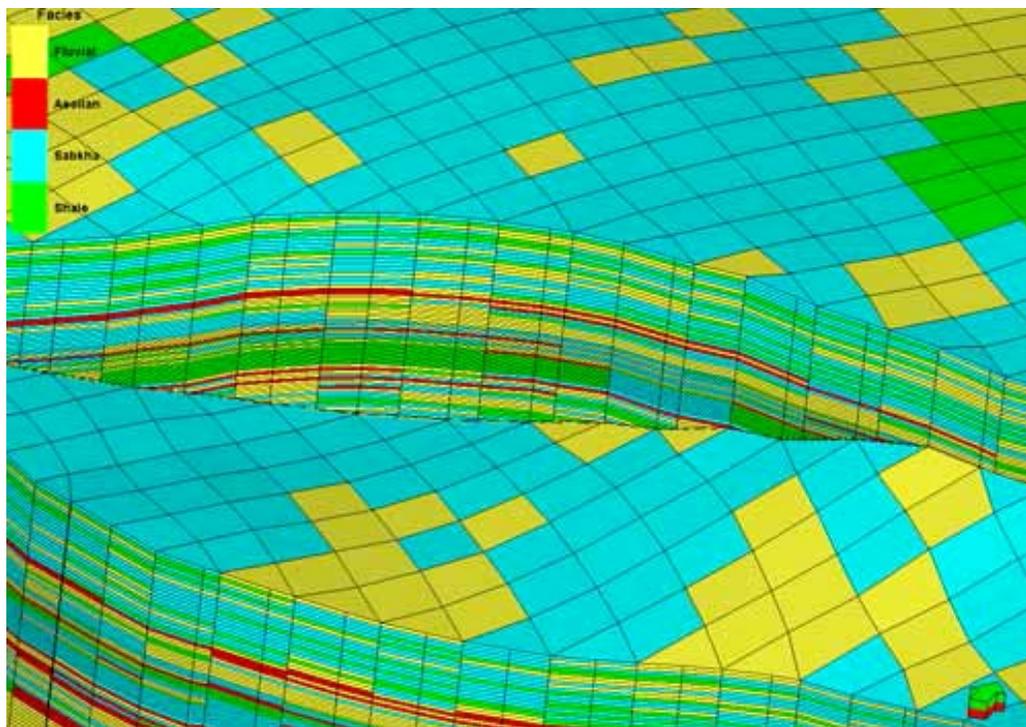


FIGURE 3. GOCAD MODEL OF SUPERFICIAL GEOLOGICAL DEPOSITS IN THE GLASGOW AREA (SOURCE: WWW.BGS.AC.UK/RESEARCH/ENVIRONMENTALMODELLING/GEOLOGICALMODELLINGSYSTEMS.HTML).

and magnetic susceptibility levels) at a single location, which can be analysed together in a spatial context.

Issues that would affect all types of 3D models, but perhaps voxels models more severely, are to do with the scale, resolution, and quality of typical archaeological datasets:

- The tendency of archaeologists to be interested in a wide range of spatial scales. This generates data with an even wider range of resolutions, from the geological scale to that of the individual find. A 3D GIS would need to deal efficiently with such scale differences.
- Absent data and uncertain data. Like 2D GIS, 3D GIS would have to allow the recording of the absence of information and the degree of uncertainty of attributes and spatial data; all the more so because our ability to *record* 3D information will lag behind the ability of a 3D GIS to *store* that information. The ability to create and compare *hypothetical* 3D models and simulations, and to *guide* any computer interpolation/modelling process (i.e. prevent nice and sophisticated looking geological nonsense) therefore takes on an added importance.

Conclusions

The aim of the 2012 CAA chapter meeting was to explore the desirability and feasibility of 3D GIS. It was concluded that 3D modelling can play a significant role in archaeology as a tool for presentation and publication, repository (of measurement data), prospection (predicting, understanding and analysing find and site patterns), and for studying processes that influence archaeological preservation in the subsurface. Whilst current '2.5D' GIS might suffice to handle *some* of our problems, being able to record, visualise and analyse in all three spatial dimensions will allow more realistic models and therefore a better understanding of complex three-dimensional archaeological situations. A voxel representation currently seems the most feasible road forward and would be ideal for representing complex heterogeneities in the x, y, and z directions. However, issues of scale and data quality will have to be addressed.

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Are we there yet? 3D GIS in archaeological research, the case of Tell Sabi Abyad, Syria

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Abstract

Geographic Information Systems (GIS) have been an important tool for archaeologists for decades. A promising recent development is the introduction of the third dimension in GIS. Many software developers have announced to have introduced a fully functional “3D GIS”. Because of particular limitations of these systems, some researchers have dubbed these 2,5D GIS. What 3D GIS should entail is however not discussed. In this paper I present a definition of 3D GIS and examples from my work at Tell Sabi Abyad to illustrate the presence and potential of 3D GIS in archaeological research.

Keywords: 3D GIS; spatial analysis; Middle Assyrian Empire; Tell Sabi Abyad

Résumé

Systèmes d'information géographique (SIG) ont été un outil important pour les archéologues depuis des décennies. Un récent développement prometteur est l'introduction de la troisième dimension en SIG. Beaucoup de développeurs de logiciels ont annoncé d'avoir introduit un “SIG 3D” entièrement fonctionnel. En raison de limitations particulières de ces systèmes, certains chercheurs ont surnommé 2.5D SIG. Mais qu'est-ce que SIG 3D devrait consister en n'est pas discutée. Dans cet article, je présente une définition de SIG 3D et des exemples de ma recherche au Tell Sabi Abyad pour illustrer la présence et le potentiel des SIG 3D dans la recherche archéologique.

Mots clés: SIG 3D; analyse spatiale; Moyen Empire Assyrien; Tell Sabi Abyad

Towards 3D GIS in archaeology

For decades archaeologists have used Geographic Information Systems (GIS) for the visualization and analysis of archaeological remains. As these remains are discovered and recorded in a three dimensional (3D) space, there is an inevitable need of properly dealing with this 3D location in GIS. Most early GIS applications have focused mainly on two dimensional representation on raster and vector maps. On these maps, if two finds were recorded on the same x and y coordinate, but at different elevations, they would be plotted on the same location on the map. As technology progressed through time the use of the third dimension has gradually been incorporated in GIS on a step by step basis. Initially in archaeology the creation and analysis of 3D surface and 3D intervisibility were used in conjunction with 2D GIS data (Fritsch 1996). The lack of full 3D functionality in common GIS software has led many researchers to dub these 2.5D GIS (Schmidt & Fritsch 1996; Zlatanova *et al.* 2002, p. 2). These 2.5D systems are characterized by being able to display three dimensional surfaces with no more than one elevation value per x and y coordinate, often sufficient for archaeological research. But because these systems do not allow for the creation, display and analysis of more complex 3D shapes, they are not considered “true” 3D.

In contrast to this skeptical perspective on the state of the technology, the term 3D GIS was already adopted to describe a wide variety of techniques in geological and geographical research in 1989 (Raper 1989). The case studies presented in Raper's volume exhibit no hesitation with the use of the term 3D GIS even with research dealing with ‘mere’ 3D surface creation. As the book is focussed on geological application of 3D GIS, a large number of the articles deal with voxel based GIS. Voxels can best be described as 3D pixels, defining a cube of space. The use of voxels has proven very worthwhile in describing three dimensional blocks of space, such as geological layers. In archaeology however, such a 3D raster technique presents most of the same limitations as two dimensional rasters

and there is a strong need for the use of continuous vector data. Therefore, in this paper, the focus of the archaeological application of 3D GIS is purposely limited to vector GIS.

It is however unclear what 3D GIS is supposed to entail, is it mostly the visualization aspect, the underlying data model or for instance the possibility for 3D analyses? According to Dieter Fritsch a fully 3D GIS would incorporate all three coordinates (x, y, z) of every object which it contains (Fritsch 1996, p. 215). In the same volume Fritz and Dieter Schmidt, claim that the transformation from a 2.5D GIS to a 3D GIS is best achieved by creating an underlying data model which described the 3D geometry. This model can subsequently be used for analysing the spatial relationships between 3D objects. Visualization is even considered of lesser interest for this system and is achieved in an external program (Schmidt & Fritsch 1996). And while no commercially available 3D GIS products were within the budget of Wheatley and Gillings (Wheatley & Gillings 2002, p. 235), they state that all systems were still largely based on two dimensional location of objects with elevation added as attribute data. In the same vein, Stoter and Zlatanova claim so-called 3D GIS is merely “a nice visualization tool” in need of maturing (Stoter & Zlatanova 2003, p. 8)

Despite the strong assertions about the non-existence of 3D GIS, no consensus seems to exist about what a 3D GIS is and what it should indeed entail. To answer these questions, we must first ask ourselves what a GIS in itself is, and then what makes it so distinctly three dimensional. Building on an earlier definition of GIS by Marble (Marble 1990), in their 2002 publication on GIS in archaeology, David Wheatly and Mark Gillings describe GIS to consist of four main subsystems and an indispensable interface (Wheatley & Gillings 2002, p. 10). The subsystems are data entry, a spatial database, manipulation and analysis and reporting and visualization (Figure 1). For a GIS to be fully working in 3D, all the subsystems should work in the third dimension. Of these, data collection and

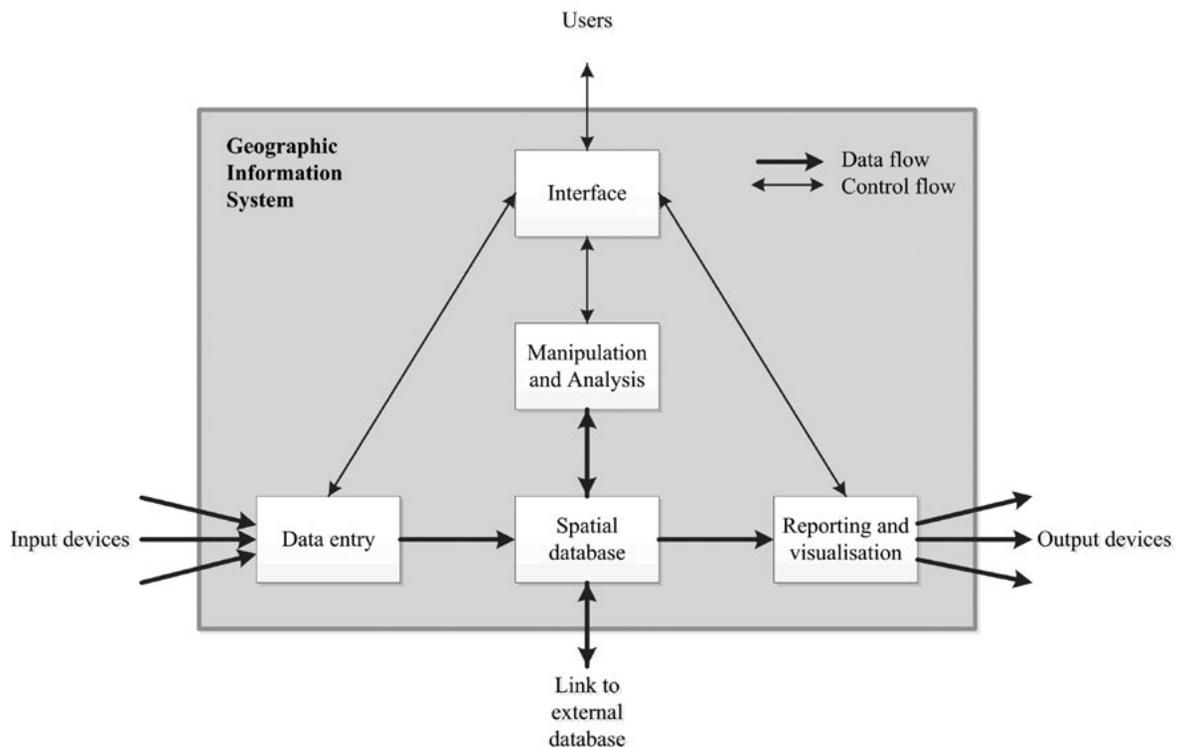


FIGURE 1. THE MAIN SUBSYSTEMS OF A GEOGRAPHIC INFORMATION SYSTEM (AFTER WHEATLEY AND GILLINGS, 2002).

input have often already been in three dimensions. Unfortunately, the location of finds which have been recorded in 3D by a total station or GPS are simplified onto a two dimensional plane in the case of a conventional 2D GIS. Herein lies the potential strength of a 3D GIS: to retain the 3D location of measurements as coordinates. Like the input, also the three dimensional visualization of GIS data is commonly present in most existing systems. Rather than as a two dimensional printable map, 3D GIS systems are able to export data as 3D models, which can be read by 3D modelling programs and viewers. If the 3D model allows it, it is even possible to 3D print the GIS data. As in this article, often the results of 3D analyses are exported as two dimensional images of a model. In contrast to the input and output, the two central subsystems of a GIS, the data storage and processing, are to a lesser degree known to be adapted to the third dimension. In this paper I present four case studies of my research into the site of Tell Sabi Abyad using a 3D GIS both for analysis as for data management.¹

3D GIS approaches at Tell Sabi Abyad

Near the Turkish border, along the Balikh river in Northern Syria the site of Tell Sabi Abyad rises some ten meters above the agricultural lands surrounding it. For nearly thirty years excavation work has been carried out here, yielding spectacular remains from both the Late Neolithic and the Late Bronze Age (Figure 2). The vast majority of the ruin hill consists of sequences of Neolithic settlements which were built on top of each other, creating a ten meter high mound. Millennia after the last Neolithic occupation, around 1200 BCE, the Assyrian army invaded the surrounding lands and instituted a large fortified settlement, a so-called *dunnu*, on top of the mound. Both the Late Bronze Age *dunnu* as well as the Late Neolithic settlement have been extensively investigated and are considered in this

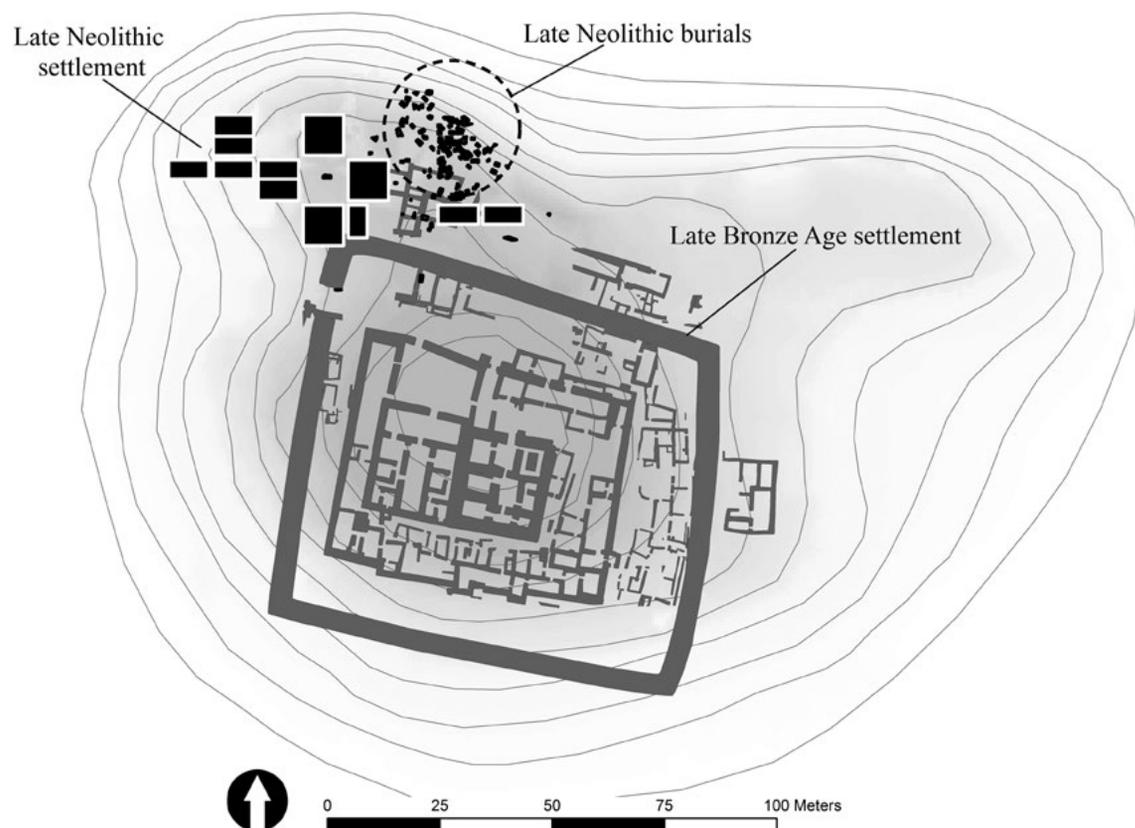


FIGURE 2. OVERVIEW MAP OF TELL SABI ABYAD WITH THE NEOLITHIC AS WELL AS THE ARCHITECTURE FROM THE LATE BRONZE AGE REMAINS DESCRIBED IN THIS PAPER.

¹ For all analyses and representations in this paper ESRI ArcGIS 10.0 has been used.

paper. Four cases are presented, two relating to the Neolithic occupation (pottery density and burial distribution) and two to the Late Bronze Age *dunnu* (3D spatial analysis and data management).

The Late Neolithic settlement and cemetery

The excavations at Tell Sabi Abyad were carried out by excavating down in spits varying in depth and slope, which covered the extent of the trenches. While excavating the Neolithic remains, a large number of pottery fragments were found. As these finds were unevenly distributed throughout the excavated horizons, an effort was made to map this pottery density per horizon. By creating a triangulated surface for every excavated layer, at the appropriate elevation and with the corresponding slope, it was possible to extrude three dimensional blocks for which the volume can be calculated. Subsequently the pottery density per horizon is easily calculated as number or weight of artefacts per cubic meter. The resulting densities have demonstrated a high concentration of pottery in the top layers and a gradual variation in the lower excavated horizons (Figure 3). Apparently, the amount of pottery in deposits increased through time, parallel to a gradual decrease of stone vessels in the same time-span (Nieuwenhuijse in prep.).

East of the Neolithic settlement a large graveyard from this period has also been excavated. The approximately 190 excavated burials covered an area of 40 by 50 meter as seen from the top. The area has been used for a number of centuries as a cemetery, with dates ranging from 6400 to 5800 cal BC. Consequently the graves were dug from increasingly high elevations which has resulted in a vertical distribution of six meters. Mapping the diverse characteristics of the burials on horizontal maps produced an inadequate picture because many burials were seemingly located on top of each other and no chronological distinction could be made. Additionally, the grave yard was located on a sloping side of the tell, so the absolute elevation of burials could not be used to filter out particular chronological elevation clusters. Obviously, the complexity of the three dimensional distribution could not be incorporated in the 2D plots. The solution to this problem was a 3D visualization of the spatial distribution of the burials in a GIS. To this end, the outline of every burial was digitized and raised to the average elevation of the excavated human remains. Subsequently, the resulting polygons were extruded by 50 centimetres to create a more realistic visualization of the burials as cuboids (Figure 4). Through a database connection the properties of each burial were linked to their 3D representation, providing the possibility of changing the appearance of the burials based on their characteristics.

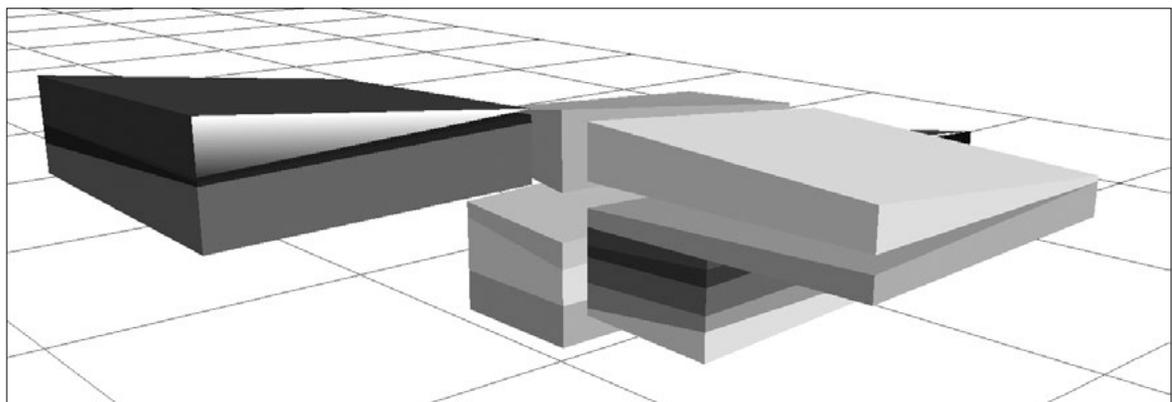


FIGURE 3. 3D VIEW OF EXTRUDED ARCHAEOLOGICAL HORIZONS.
DARK EQUALS HIGH DENSITY, LIGHTER IS LOWER DENSITY.

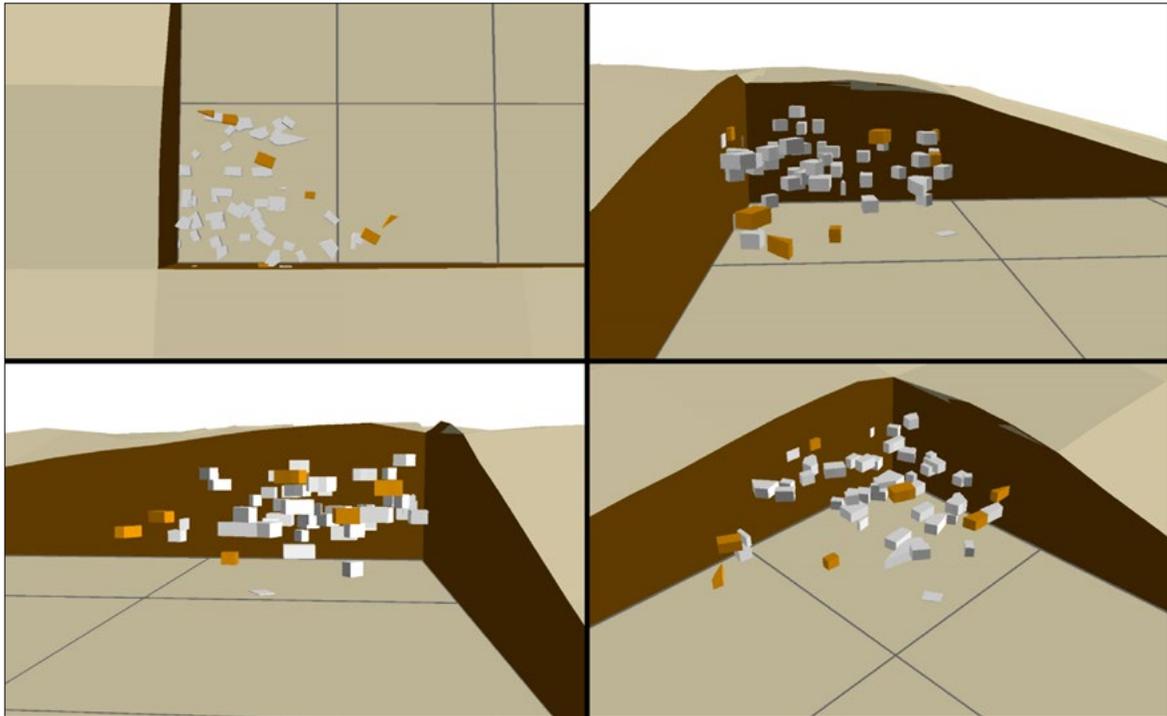


FIGURE 4. 3D DISTRIBUTION OF A SELECTION OF THE LATE NEOLITHIC BURIALS FROM TELL SABI ABYAD. THE DARKER COLOURED CUBOIDS ARE FRAGMENTED, THE LIGHTER COLOURED INDIVIDUALS ARE COMPLETE.

The resulting 3D thematic plots have been used to analyse several characteristics of the burials. For instance, the individuals of which the sex could be determined are located in a number of clusters of burials of the same sex. Despite the large number of individuals for which the sex could not be established, this might point towards a preference of burial location near burials of the same sex. A second issue with the burial distribution concerned the degree of fragmentation of skeletons. The fragmented nature of some graves was considered to reflect the practice of secondary burial of particular skeletal elements, as suggested by the reburial of a single skull in the south of the graveyard. The incomplete state of some burials however may also have been caused by erosion or other post depositional processes. In Figure 4 fragmented burials are dark coloured and largely complete ones are lighter coloured. The 3D plot shows that most fragmented burials are located along the slope of the hill, and therefore probably have been affected by erosion and ploughing. The few fragmented burials in the centre of the overall distribution should be considered in a different light, perhaps indeed as a result of reburial. Using regular 2D approaches this conclusion would not have been so easily reached.

The Late Bronze age dunnu

The remains of the Late Bronze Age fortified estate on the summit of tell Sabi Abyad has been the focus of a large ERC funded research project² since 2012. In this project, an attempt is made to reconstruct daily life under the rule of the Assyrian empire, based on the archaeological remains from the site. The remains consist of the walls and floors of many buildings as well as some 10,000 registered objects. All architectural features and objects have been digitized in a GIS. Using the

² This research project is part of the ERC funded project (282785) 'Consolidating Empire: Reconstructing Hegemonic Practices of the Middle Assyrian Empire at the Late Bronze Age Fortified Estate of Tell Sabi Abyad, Syria, ca. 1230-1180 BC' at Leiden University. See also www.dunnu.nl

known elevation of the objects, it is possible to plot them in 3D. Using a simplified 3D model of the architectural remains as background, it is possible to view the location of objects in relation to each other and to the architecture they were found in the vicinity of. These plots elucidate the fact that some objects were discovered on or near floor levels while others were found in the backfill of ruined houses. Obviously, the floor level finds often tell us more about the activities which were carried out there, so it is imperative to make a clear distinction between these types of deposits. The 3D representation of the finds in conjunction with the architecture has been helpful in elucidating the processes responsible for the final deposition of the objects.

Investigating these deposition processes has been particularly beneficial in a room in the north west of the settlement, where some 135 cuneiform tablets were found. It was assumed during excavation that these objects were all originally located on the floor of the room. The assemblage was interpreted to have been fallen on the floor out of a large wooden chest (Akkermans 2006). Consequently, the tablets were interpreted to have been stored or used in these rooms. In opposition to these hypotheses, the 3D visualization of the spatial distribution displays a striking vertical distribution of objects, implying that another process may have been at play. The complex composition of the assemblage is further elaborately shown by the distribution of refitted fragments of one particular tablet (T98_045) which has been reconstructed by joining at least thirteen fragments. As Figure 5 shows, these fragments are distributed throughout the deposit, both horizontally as well as vertically. The dispersed scatter of these tablet fragments as well as others in the deposit, together with their fragmented state indicate that their accumulation is not the result of an *in situ* accident but of a more complex secondary refuse deposition. Consequently, the objects may only have been discarded in these rooms, and not used or stored.

Likewise, the large amount and variety of finds in other rooms of the *dunnu* is analysed by creating 3D thematic plots. On these, the symbology of objects is displayed based on their properties such

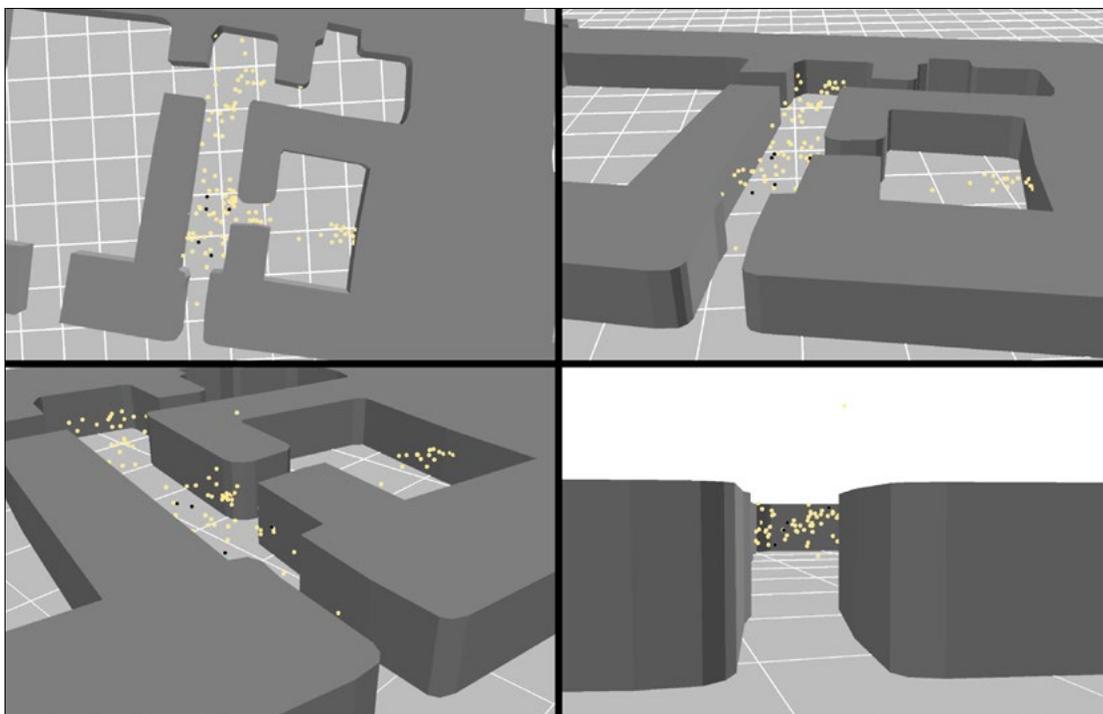


FIGURE 5. 3D DISTRIBUTION OF CUNEIFORM TABLETS IN A HALLWAY OF THE DUNNU.
THE BLACK DOTS ARE FRAGMENTS OF TABLET T98_045.

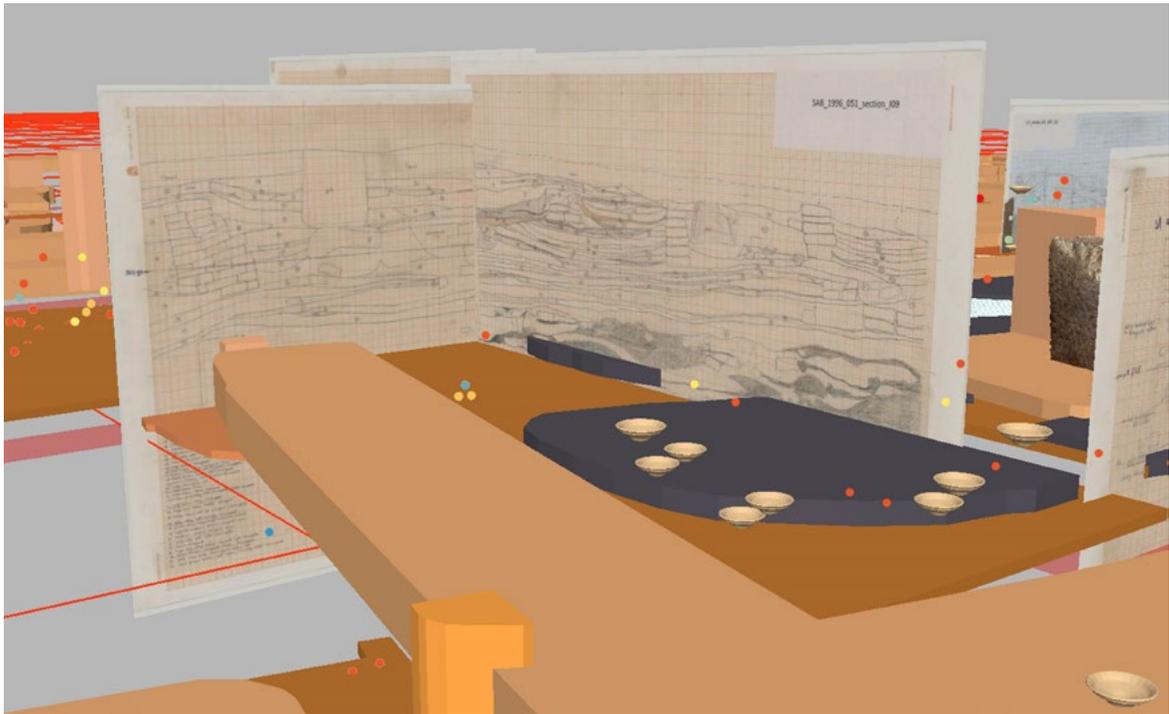


FIGURE 6. SECTION DRAWINGS AMONGST THE SCHEMATIC ARCHITECTURE AND OBJECTS OF THE TELL SABI ABYAD DUNNU.

as their size, their material and the presence of burn traces. A more elaborate view is achieved by applying 3D symbology for the finds. In Figure 6 for instance objects of a certain type of pottery are symbolized by a 3D model of the corresponding archetype. 3D symbology is part of the standard symbology settings in current GIS, providing an easy and fast way of producing comprehensible 3D thematic plots.

The 3D environment which has been created for the analysis of objects at Tell Sabi Abyad has proven to be more than simply a tool for some specific analyses. Through the incorporation of the 3D reconstructed architecture and georeferenced scans of all excavation plans and section drawings, the 3D GIS is used to relate all archaeological information with each other. The use of hyperlinks enables the retrieval of all field documentation related to objects, burials and features simply by clicking on the corresponding feature in the GIS. The added benefit of using the 3D GIS environment is that during the analyses all the original documentation can be queried to check the results. In the case of the Tell Sabi Abyad *dunnu*, particularly the addition of section drawings in combination with the 3D distribution of objects enabled to achieve a remarkably clear overview of the excavated areas (Figure 6). Because the 3D GIS environment is the most comprehensive platform for all types of documentation, it has become the central point from which all inquiries into the Late Bronze Age architecture and archaeology are started.

Are we there yet?

Using examples of my research into the site of Tell Sabi Abyad I believe I have demonstrated the existence and potential of 3D GIS for archaeology. The creation of complex 3D models from conventional elevation surfaces has been implemented to perform volumetric calculations, supporting the analysis of pottery density within the Late Neolithic settlement. The creation of a 3D model of both horizontally as well as vertically distributed burials has yielded an unparalleled perspective

on the Neolithic cemetery of Tell Sabi Abyad. The three dimensional representation of the interred graves enables the correct analysis of their complex 3D distribution. The model is not an exact reconstruction of the original cemetery but as a schematically rendered representation it helps answer questions about the spatial distribution of burial types. The examples shown here should be considered the 3D equivalent of two dimensional thematic maps. Because many burials have been discovered on top of each other, it was impractical to discover or illustrate spatial patterning on conventional two-dimensional distribution maps. In this case the 3D representation has a demonstrable added benefit.

The same technique has been applied to the analysis of a concentration of cuneiform tablets in a room of the Late Bronze Age settlement. Similarly, a 2D plot of the distribution of tablets would have demonstrated their wide horizontal distribution, which however could have still been interpreted as the result of some inconsequential post depositional process. The comprehensive 3D view of the tablet distribution has demonstrated the complex formation of the assemblage and has improved the understanding of the formation process of this deposit. Finally, the 3D GIS environment can be used as a platform for data management since it allows the merging of a large variety of datasets, enabling a visual combination of original field documentation with processed research outcomes.

The critique on 3D GIS which has led to the definition of 2.5D GIS seems to have changed through time in parallel with technological innovation: as one criterion is met, another is deemed vital. Much has been written about the subject but these exercises have not seemed to find consensus about what a 'true' 3D GIS in fact should entail. All researchers however seem quite eager to state that it *does not exist* or is *merely a visualization tool*. Such assertions discourage the use of and research into the application of 3D GIS and clouds the potential for the application of this technique in archaeological research.

Using the definition described above, based on the main subsystems of a conventional GIS, a 3D GIS should in principle work three dimensionally in all subsystems. It was already clear that the input and output features of modern GIS software are able to handle 3D data. The data handling and analyses are more complex subsystems, not always suited to the third dimension and have been the main target of scepticism. Within the 3D GIS environment which has been created for the research at Tell Sabi Abyad, both analysis and data management have been successfully applied. The analyses have been carried out using 3D models while retaining the GIS functionality. They have resulted in the revision of certain interpretations and have offered new perspectives on old datasets. As such, they have unambiguously shown the existence and potential of 3D GIS in archaeological research.

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Three-dimensional simulation of a fire in a simplified gallery of the Chauvet-Pont-d'Arc cave (Ardèche, France)

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Abstract

Numerous fire marks have been observed by archaeologists on the walls of the Chauvet-Pont-d'Arc cave (Ardèche, France). Questions arise regarding the dangerousness of the realisation of the fires or their function. Three-dimensional numerical simulations were achieved with a Computational Fluid Dynamics code with a combustion model. They were validated beforehand on fire experiments in an underground quarry, then used to realise a scenario of a fire in a volume like the Megaceros Gallery of the Chauvet cave. The first results describe the zones where it was possible to stay without being endangered.

Keywords: Numerical simulation, caves, fires, Palaeolithic

Résumé

De nombreuses marques de feu ont été observées par les archéologues sur les parois de la grotte Chauvet-Pont-d'Arc (Ardèche, France). Des questions émergent au sujet de la dangerosité de la réalisation de ces feux ou encore de leur fonction. Des simulations numériques tridimensionnelles ont été menées avec un code de mécanique des fluides doté d'un modèle de combustion. Elles ont été validées au préalable sur des expérimentations de feu dans une carrière souterraine, puis utilisées pour réaliser un scénario de feu dans un volume similaire à celui de la galerie des Mégacéros de la grotte Chauvet. Les premiers résultats décrivent les zones où il était possible de se tenir sans être mis en danger.

Mots clés: Simulation numérique, grottes, feux, Paléolithique

Introduction

Background

The Chauvet-Pont-d'Arc cave is located in the South-East of France. It especially shelters paintings exceptionally preserved among the most ancient in the world (Clottes 2001), they have been dated between 37,500 and 33,500 cal ¹⁴C BP, and attributed to the Aurignacian (Valladas *et al.* 2015; Quiles *et al.* 2014). The cave is 500 m long, and has wide volumes composed of successive halls and galleries (Figure 1). This cave has also been occupied by cave bears, before the presence of men, alternating with the Aurignacians, and after them as some scratches recover rock art. Dates on bones have drawn the limits of their presence (Fosse & Philippe 2005).

Numerous fire marks have been observed by archaeologists on the walls of the cave (Ferrier *et al.* 2014). Three thermal attributes can be recognized. First, the limestone changes its original colour to pink/red when it is heated up to 250°C (rubification) and to grey when heated at more than 350°C

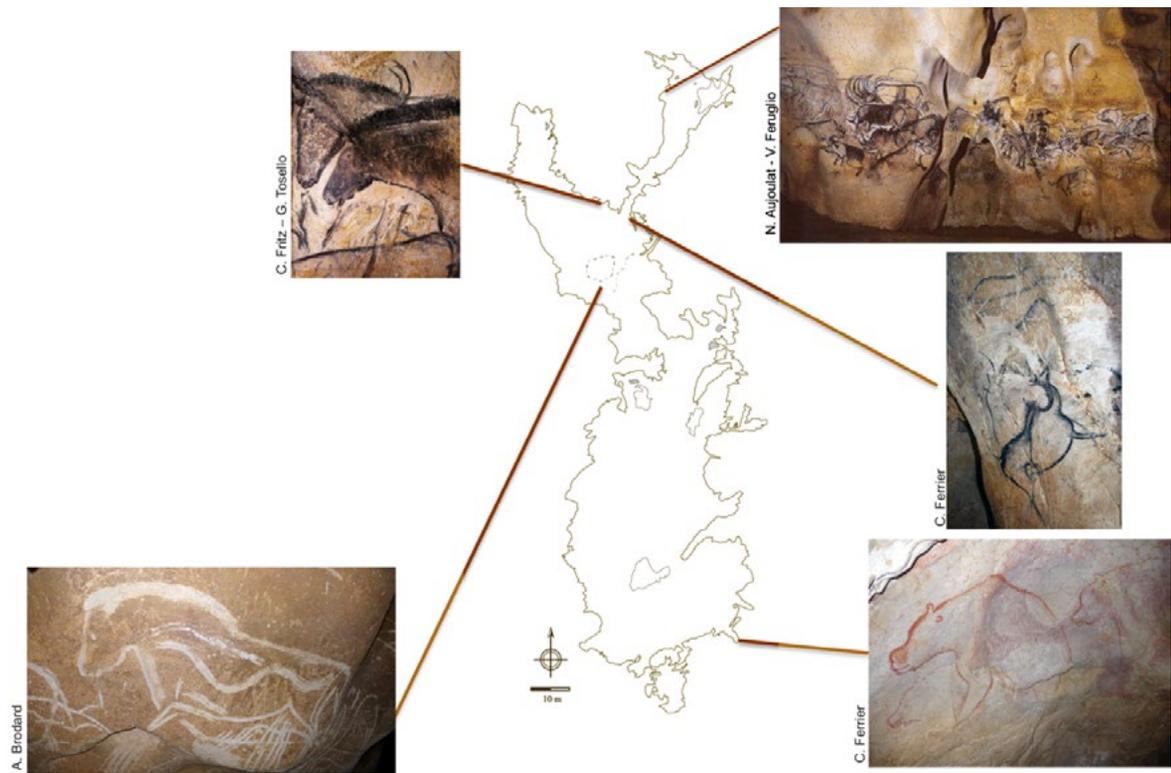


FIGURE 1. MAP OF THE CHAUVET-PONT-D'ARC CAVE WITH EXAMPLES OF FAMOUS PAINTINGS AND ENGRAVINGS (TOPOGRAPHY: Y. LE GUILLOU, F. MAKSUD, TRIBUTE TO F. ROUZAUD).

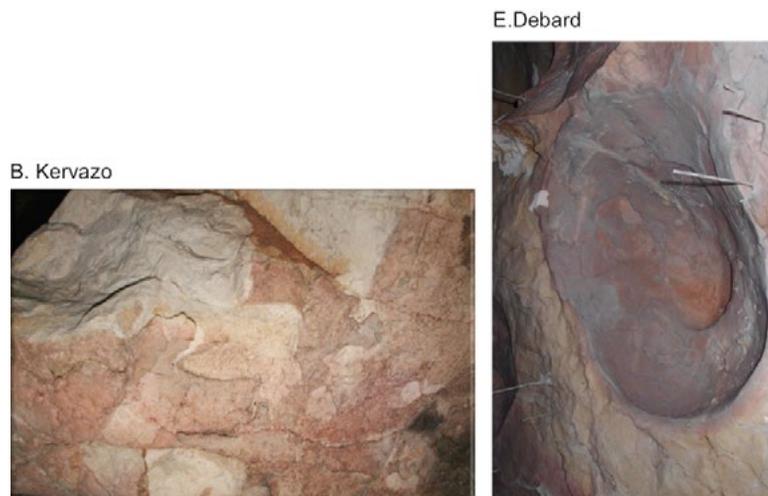


FIGURE 2. CHANGE OF COLOUR OF THE LIMESTONE, TO PINK/RED (LEFT), TO GREY (RIGHT) (CREDITS B. KERVAZO (LEFT) AND E. DEBARD (RIGHT)).

(Brodard *et al.* 2014) (Figure 2). The second thermal attribute is the presence of soot deposits due to the smoke (Figure 3 – left). Finally spalling can occur due to the restrained thermal dilatation of the rock (Figure 3 – right). It takes generally the shape of thin flakes, of centimetre thickness. Three-dimensional numerical simulations in computational fluid dynamics have already been successfully

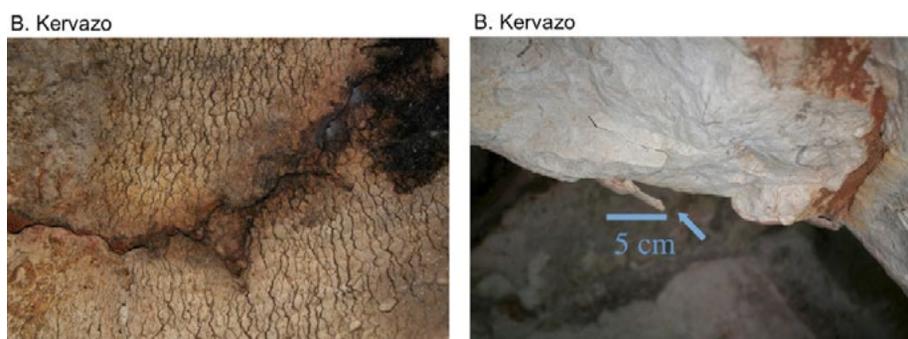


FIGURE 3. SOOT DEPOSIT (LEFT) AND SPALLING (RIGHT) (CREDITS B. KERVAZO).

used in rock art caves to study the microclimate of these underground areas (Lacanette *et al.* 2009; 2013). It is here applied to the knowledge of various parameters as temperature, breathability and air velocities during a fire.

Objectives

Locations of the fire marks in narrow areas (sections of 2 meters by 2 meters) of the cave question about the potentiality of making fires without being injured. Indeed, fires provide large amount of toxic gases, the evacuation of such gases from confined areas is very difficult. Moreover, in the Chauvet-Pont-d'Arc cave, few hearths have been found; bears or men have moved them, deliberately or not. Their absence leads to a lack of information, especially concerning the function of the fires. Unfortunately, for obvious preservation reasons, it is impossible to recreate the fires in the cave to generate the marks on the walls depending on the position of the fireplaces. At this point simulation will allow to virtually reproduce fires in a geometry similar to the one of a gallery of Chauvet, in order to check the potential behaviours of the people in charge of the fires at this time during the Palaeolithic.

Materials and methods

Location of the fire marks in the cave

In the Chauvet cave, thermal wall state is observed near the Palaeolithic entrance, and in the deeper parts of the cave. The concerned areas have various surfaces, 3 m² in the Chamber of the Bear Hollows, 11 m² in the entrance sector, 12 m² in the Megaceros gallery, until 25 m² in the Wallows room (Figure 4). Volumes are contrasted: ceilings at 4 meters high in the Wallows Room, whereas they are less than 3 meters in the entrance sectors and in the Megaceros gallery.

In this work, we focused on the Megaceros gallery. In this area, the cartography of the colour change and of the spallings highlights 6 zones distributed from the entrance towards the End Chamber. Starting from these observations of the walls, a possible location of the fireplaces (Figure 5) has been proposed. We propose to focus in this work on zone 3, the zone concerned with the largest area of fireplace.

Validation on experimental data

As it was impossible to recreate fires in the original environment, we proposed to characterize experimental fires in an equivalent medium in the framework of a research program supported by the National Research Agency (Labex LaScArBx, ANR-10-LABX-52).

THE THREE DIMENSIONS OF ARCHAEOLOGY

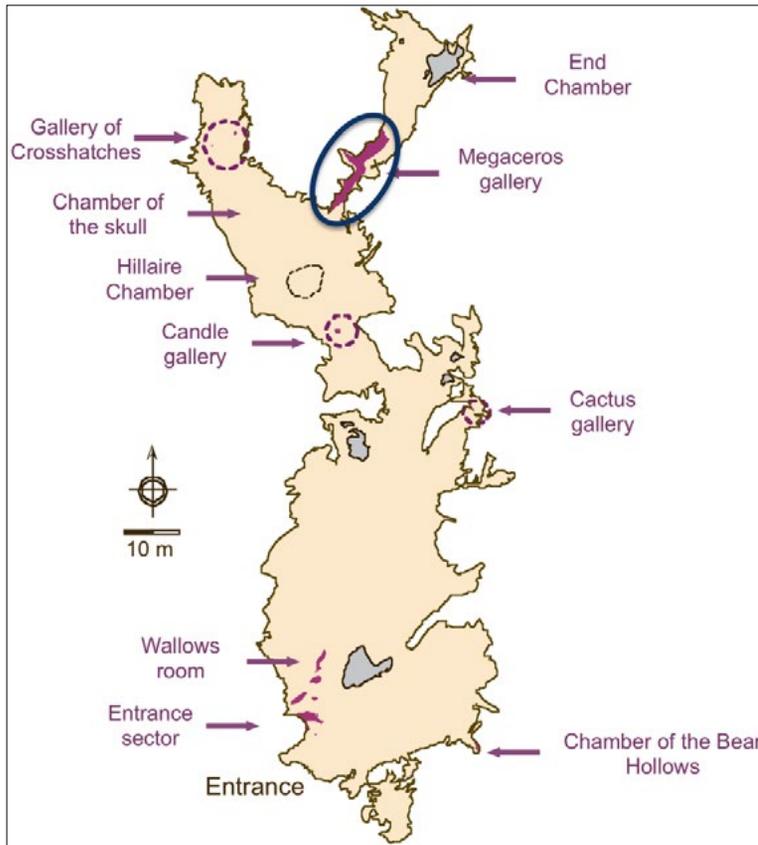


FIGURE 4. LOCATION OF THE THERMAL IMPACTS IN THE CHAUVET CAVE IN VIOLET (CREDITS C. FERRIER, E. DEBARD, B. KERVAZO).

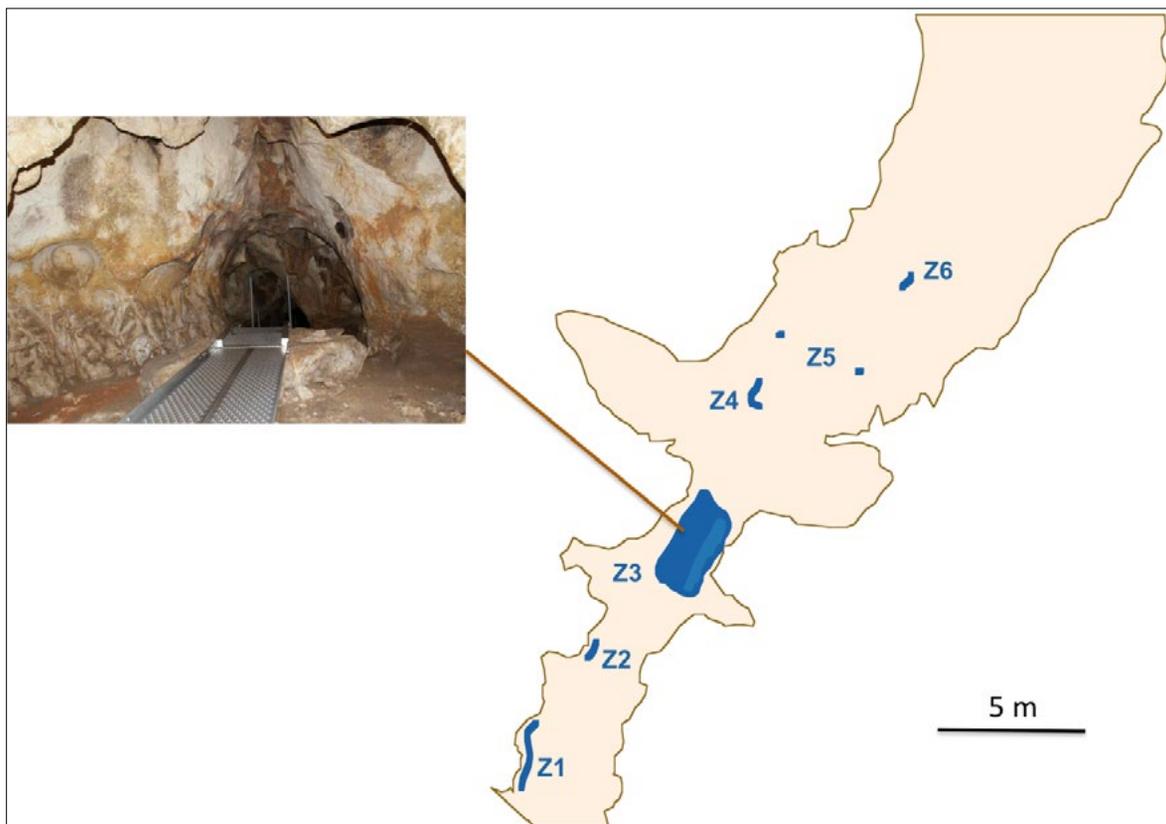


FIGURE 5. LOCATION OF THE FIREPLACES IN THE MEGACEROS GALLERY AS THEY WERE PLACED BY GEOARCHAEOLOGISTS STARTING FROM THE OBSERVATIONS OF THE THERMAL IMPACTS ON THE WALLS (CREDITS C. FERRIER, E. DEBARD).

As experimentation in a laboratory would not take into account the multiparameter and random aspect of the complex and constraining places of a cave like Chauvet, we monitored an underground quarry in Lugasson (Gironde, France) and experimented different types of hearths. We observed the three thermal marks previously shown and the simulation was useful to estimate the consequences of the fireplaces on the environment of the quarry, thermal balance, smoke spreading, and renewal of the air (Figure 6).

The 3D code Fire Dynamics Simulator (FDS) developed by the NIST (National Institute of Standards and Technology) in the US has been used to simulate the fire in the quarry (McGrattan *et al.* 2013). A model created by photogrammetry helped recreate the geometry using parallelepipeds constituting the rock. The fireplace was set in the second part of the quarry, as in the experiment (Figure 7).

During the experiments, temperatures, humidity, O₂ and CO rates were recorded in various places: the immediate environment of the fire, in numerous locations in the quarry and at the entrance. The calculated numerical data for the temperature on the wall near the fire, and for the carbon monoxide rates at the entrance of the quarry were compared to the observed experimental ones with a good agreement. The simulations were validated on the distribution of temperatures at the wall behind the fire (Figure 8).

Various parameters were observed, among them, the velocity vectors and the air temperature (Figure 9). They show a high thermal gradient both vertically and horizontally. Moreover, the higher the heat release rate of the fire is, the more the convections are established (here with the outside of the quarry), and the more the vision and breathing are easy in the lower parts. The experimentations show the creation of a smoke cloud each time the fire is fuelled (Figure 10 – left). It is dissipated less than 5 minutes later. Smokes have provoked a carbonaceous particles deposit, which give a black colour to the upper part of the wall (Figure 10 – right).



FIGURE 6. QUARRY OF LUGASSON. SOOT DEPOSIT AND SPALLING (LEFT) AND RUBIFICATION (RIGHT) (CREDITS C. FERRIER).

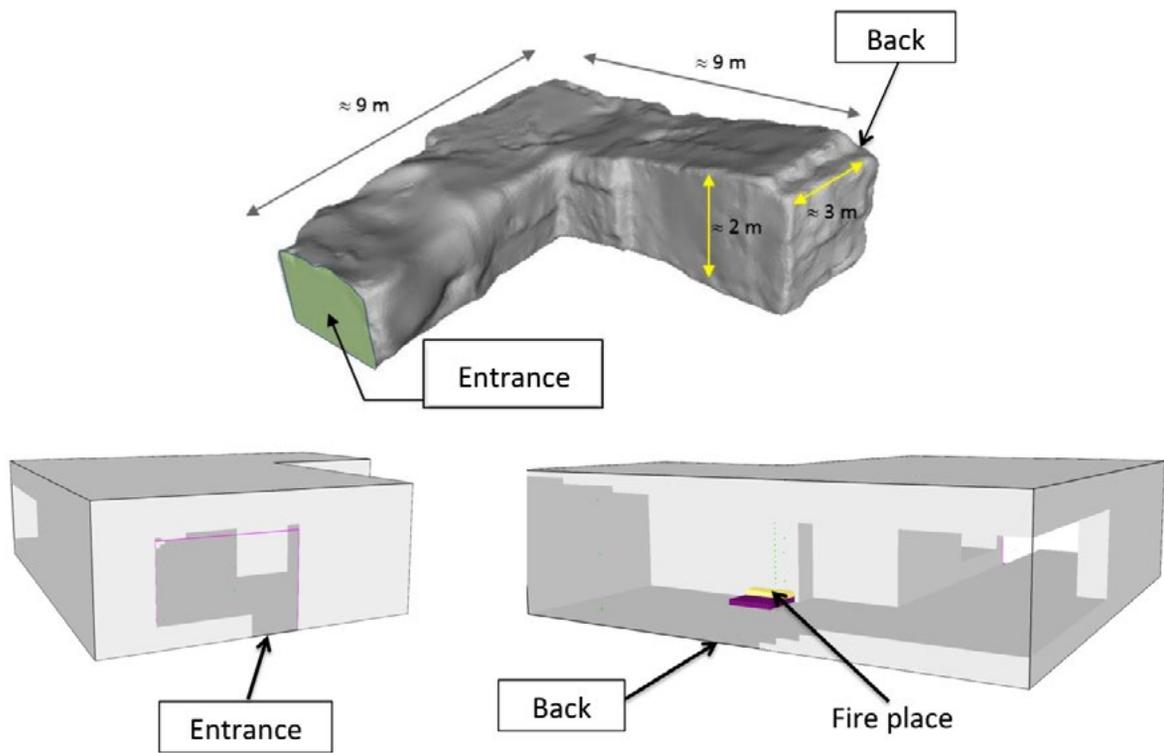


FIGURE 7. PHOTOGRAMMETRY OF THE QUARRY AND RECONSTRUCTION IN FDS WITH THE LOCATION OF THE FIREPLACE.

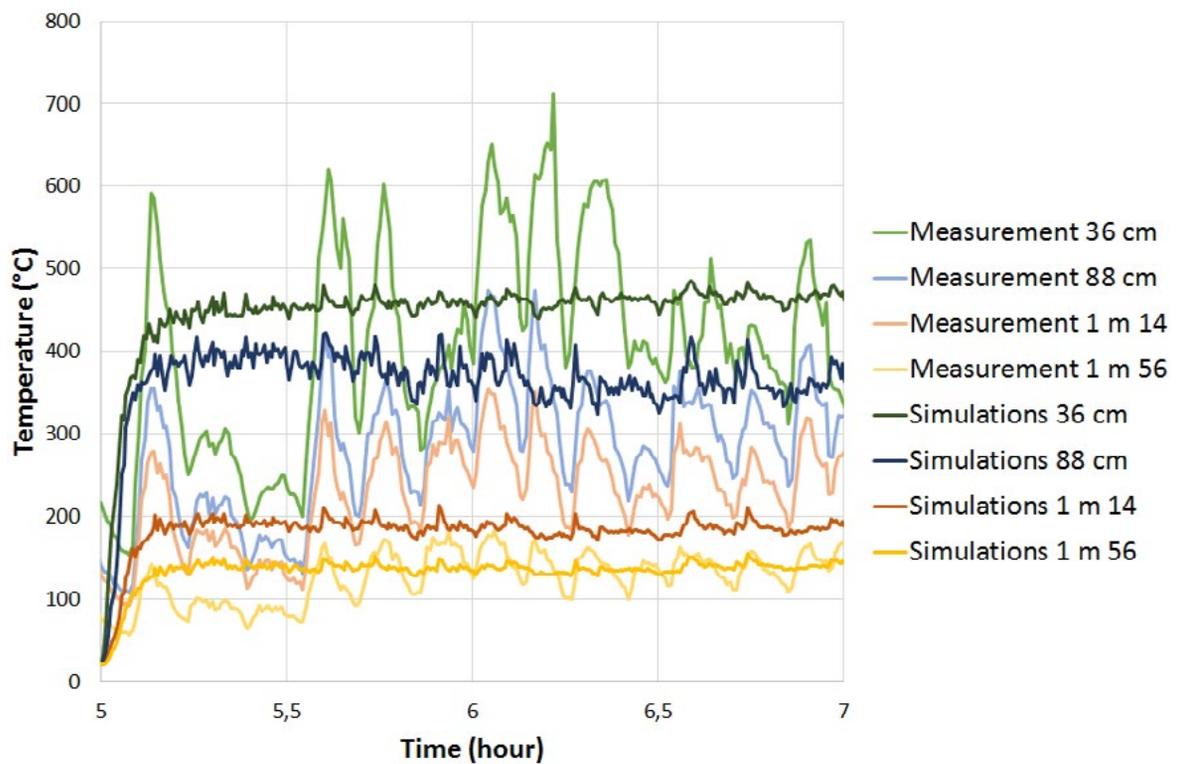


FIGURE 8. DISTRIBUTION OF MEASURED AND SIMULATED WALL TEMPERATURES.

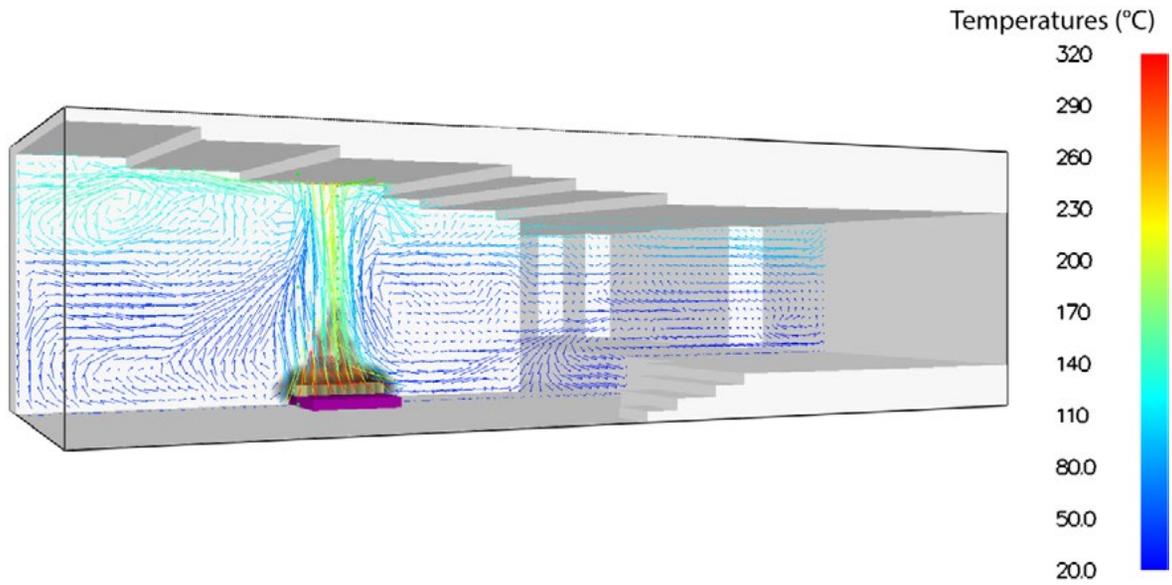


FIGURE 9. DISTRIBUTION OF TEMPERATURE AND VELOCITIES
(THE VELOCITY VECTORS ARE COLOURED FOLLOWING THE TEMPERATURE SCALE).



FIGURE 10. RELEASE AND DISSIPATION OF THE SMOKE (LEFT) AND SOOT DEPOSIT
ON THE UPPER PART OF THE WALL (RIGHT) (CREDITS C. FERRIER).

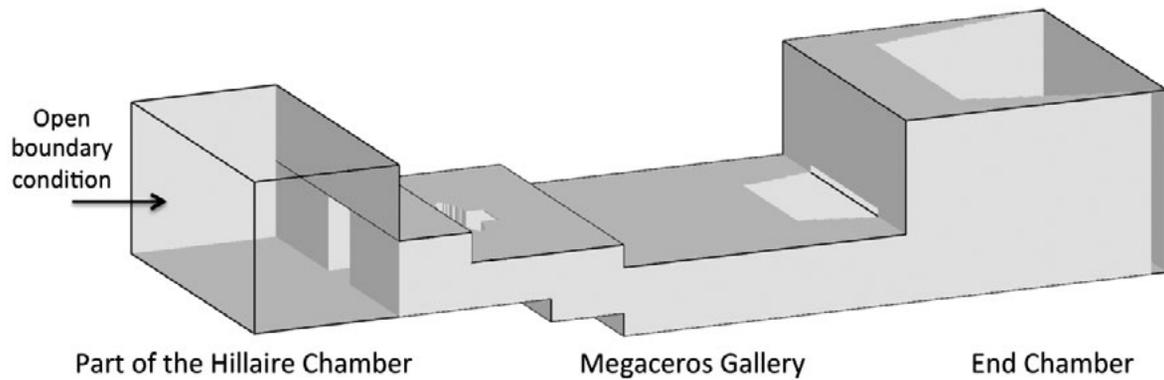


FIGURE 11. DOMAIN CONCERNED BY THE 3D SIMULATION OF THE FIRE.

Simulation case in the Chauvet cave

Once validated by this experimentation the simulation is used to determine temperature, smoke, and toxic gases distributions near the fires in the Chauvet cave. The choice of the area of the simulation of the fire was set in a zone of the Megaceros gallery close to fire marks in the upper parts of the walls and the ceiling.

Starting from the maps and slices of this gallery we designed a similar morphology in FDS, in order to simulate the burning of a fire in a volume like it. The objectives are to specify the Heat Release Rate (HRR) of the fires that have produced the thermal marks observed in the walls, and to check whether it was possible or not to stay near the fire during the combustion.

The Megaceros gallery is a narrow straight duct of 25 meters long linking two big volumes: the set Hillaire Chamber and Chamber of the Skull on the one hand, and the End Chamber on the other hand (Figure 4). In the first part, the width of the gallery is small (between 2 and 3 meters) and the ground is flat. Then, this one lowers by 2 successive stairs and the width reaches 6 meters, before the End Chamber.

For the numerical simulation, we considered a 3D domain including a part of the Hillaire Chamber, the Megaceros gallery, and the End Chamber (Figure 11).

In order to take into account the huge volume of the cavity prior to the Megaceros gallery, an open boundary condition is displayed, 10 meters into the Hillaire Chamber, whereas the end of the End Chamber is closed.

Simulations of the combustion in the zone 3 of the Megaceros gallery have been done on 1.5 million points and 8 processors.

Results

Temperatures

Temperature on a slice of the Megaceros gallery is presented in Figure 12. The value of the temperature at the vault reaches 350°C, which means that the colour of the limestone would change to grey, which is in agreement with the grey colour actually observed in the cave in these areas. The Heat Release Rate parameter of the fire has been correctly settled in the simulations to obtain such a temperature at

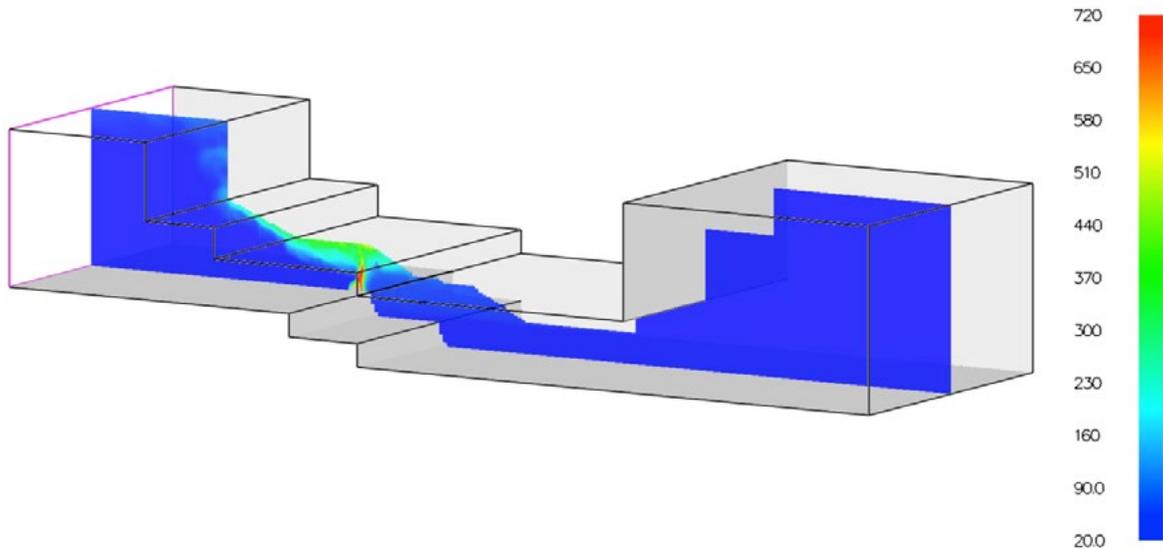


FIGURE 12. TEMPERATURE DISTRIBUTION ON A SLICE IN A VOLUME LIKE THE MEGACEROS GALLERY (THE BLACK LIMITS ARE THE BOUNDARIES OF THE DOMAIN, WHEREAS THE COLOURS PICTURE THE AREA OCCUPIED BY THE AIR).

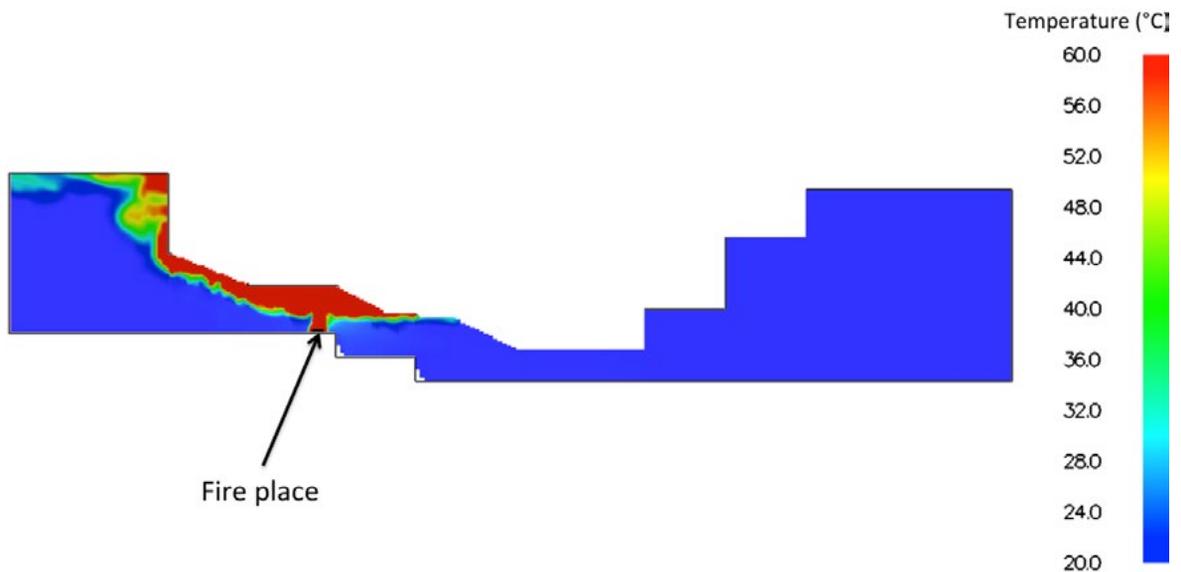


FIGURE 13. VISUALISATION ON A SLICE OF THE LOCATION OF THE HIGHEST TEMPERATURES DURING THE FIRE IN A VOLUME LIKE THE MEGACEROS GALLERY.

the vault. The thermal power needed to reach this temperature is quite high; this fire can be defined as a highly powerful fire.

During the fire, the highest temperatures are located towards the Hillaire Chamber, as the ceilings are higher. Hot air lighter than cold one goes to the upper zones of the gallery (Figure 13). The thermal gradients are high, both horizontally and vertically. Nevertheless, the air in the lower part remains at a low temperature, even near the fire.

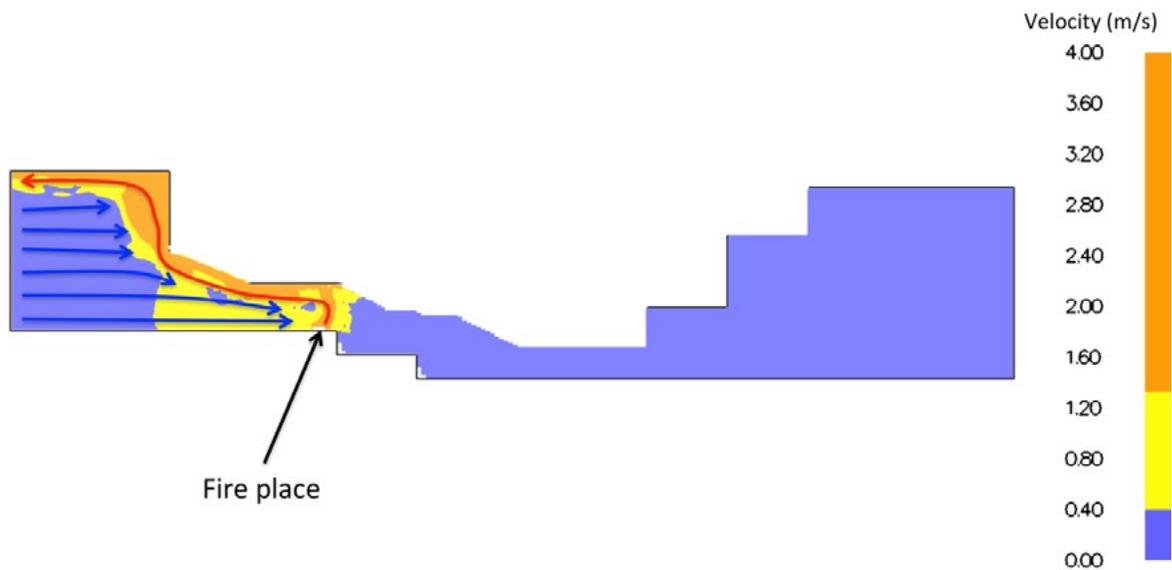


FIGURE 14. AIR VELOCITY DISTRIBUTION AND EVACUATION SCHEME OF THE AIR NEAR THE FIRE.

Velocities

The visualisation of the air velocity (Figure 14) is helpful to understand the dynamics of the scenario. The hot air goes to the highest areas, and is evacuated via the Hillaire Chamber towards the massive volume of the cave. Colder air replaces the hot one due to the convection currents, evacuating the smokes. It was possible to fuel the fire and to breathe near it thanks to the establishment of the convection currents.

Smokes

During the combustion, the smokes loaded with soot are concentrated in the upper parts of the domain. Observations by geoarchaeologists in the cave have located the soot deposits in the upper parts of the Megaceros gallery. The opacity is a parameter which can be set in the software, it does not reflect the reality, smokes were probably not so dark with a fuel as wood. It has here been set to a quite high value to be able track the evolution of the smoke in the gallery (Figure 15).

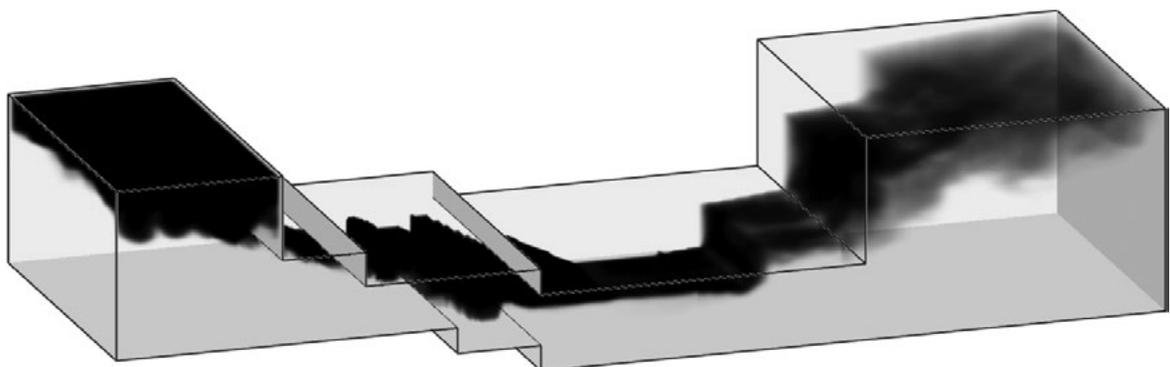


FIGURE 15. SMOKE DISTRIBUTION IN A VOLUME LIKE THE MEGACEROS GALLERY DURING THE FIRE.

The smokes are first coming to the Hillaire Chamber and are then pushed by the colder and smokeless air coming from the Hillaire Chamber towards the End Chamber.

Fractional Effective Dose

The Fractional Effective Dose is a parameter commonly used in toxicology. It evaluates the exposure time available to escape from a place in fire or to survive post exposure (Speitel 1996). It provides valuable data of the safe behaviour of people. The highest concentrations of the toxic gases are found numerically at the vaults of the gallery. The blue area indicates the zones where it is safe to stay, it is little risky in the yellow one and lethal in the orange one (Figure 16). It was possible to fuel the fire at the beginning, then Palaeolithic men and women would either stay in the Hillaire Chamber, the End Chamber becoming a trap, or would make intense but short fires in time.

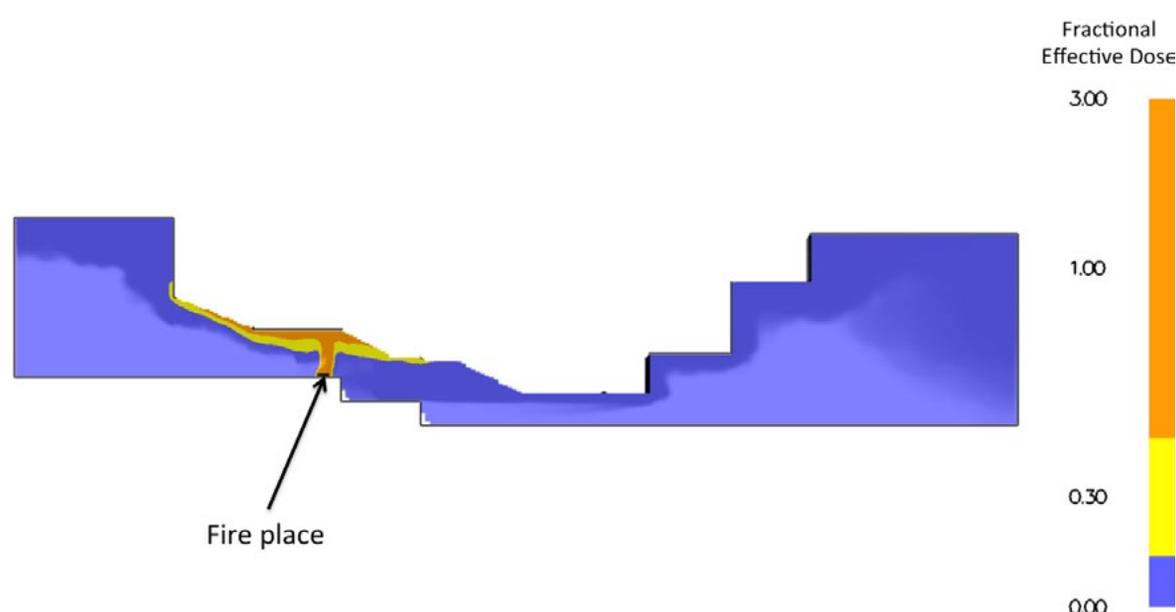


FIGURE 16. FRACTIONAL EFFECTIVE DOSE DISTRIBUTION ON A SLICE OF VOLUME LIKE THE MEGACEROS GALLERY DURING THE FIRE.

Conclusions and perspectives

Three-dimensional simulations have been validated on experiments in a monitored underground limestone quarry. Regarding a fire set in the Megaceros gallery of the Chauvet cave, they indicated a preferential evacuation of the smokes towards the Hillaire Chamber, at the ceiling. They have shown that the upper parts of the gallery concentrate the heat and the toxic gases. It matches with the observation of the distribution of soot deposits on the walls of the cave.

The 3D simulations contributed to bring additional information to archaeologist working on fire evidences in the Chauvet cave. First, the heat released by the fire has been adapted to obtain the wall temperatures corresponding to the rubification, opening the possibility to work on the power of the fires involved. Then, toxicological and thermal data gave valuable information on the location where it was possible to stay without being injured. Finally, the human behaviour near the fire is of great

archaeological interest, as they wish to learn more about the function of the fires. The work presented here is a first research on this topic. It has shown in the first place that if there were a possibility for Palaeolithic men and women to put additional wood to the fire during the burning, it was in the lower parts of the galleries. In larger rooms, it must have been easier to breathe in the lower parts as well; further simulations will concentrate on these areas and will give more accurate information.

Concerning the perspectives of this work, the morphology of the gallery has to be improved. A 3D modelling of the cave starting from the point cloud is in progress. Besides, the acquisition of software (pyrosim) will facilitate the transformation of the model into a more accurate mesh of the gallery. Moreover, there is a lack of accuracy in the soot model of FDS. We initiated a collaboration with a PhD student to enhance the soot deposit model. The objective is to propose the location of the fireplaces starting by the location of the soot found on the walls of the cave. Furthermore, we will try several simulations corresponding to different situations of the fireplaces, in order to identify which original position led to which mark on the walls, with the ultimate objective of giving elements to archaeologists about the function of the fires.

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Using digital photogrammetry to produce 3D models at prehistoric ditched enclosures: Perdigões as a case study

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Abstract

The Perdigões archaeological complex (Reguengos de Monsaraz, Portugal) is a prehistoric site near the Guadiana River, comprising at least 12 ditched enclosures, several hundred pits, an area with megalithic tombs and a set of standing stones (cromeleque). It is located in one of the richest archaeological landscapes of Iberia, with notable examples of Prehistoric monumental architecture such as menhirs and portal tombs (antas). A team from the University of Málaga (Spain) has been carrying out fieldwork in collaboration with the Portuguese entity ERA Arqueologia at the site since 2008. This includes geophysical (2008-2009) and micro-topographical (2011) surveys of the whole site, as well as both open-area excavations (2012-2013) and trenches (2009-2010, 2013) in the area surrounding Entrance 1.

Digital photogrammetry is an inexpensive computerised method that enables the creation of three-dimensional models from photographs using image pattern recognition. The technique can be employed during the process of excavation to better record the archaeological evidence, to generate 3D models of the stratigraphical units and to digitalise singular findings. It is also useful for activities aiming to spread knowledge and awareness about the site. In this paper we will describe the basics of the method and its workflows, and three specific applications at Perdigões.

Keywords: Prehistoric Enclosures, Close Range Photogrammetry, 3D, Archaeology, Prehistory, Iberia, Neolithic, Copper Age, Perdigões

Résumé

Le complexe archéologique Perdigões (Reguengos de Monsaraz, Portugal) est un site préhistorique près de la rivière Guadiana, comprenant au moins 12 laissés tomber enceintes, plusieurs centaines de puits, une zone avec des tombes mégalithiques et un ensemble de menhirs (de Cromeleque). Il est situé dans un des plus riches de paysages archéologiques Iberia, avec des exemples remarquables de l'architecture monumentale préhistoriques comme menhirs et des tombes de portiques (antas). Une équipe de l'Université de Málaga (Espagne) a mené sur le terrain en collaboration avec l'entité portugaise ERA Archéologie sur le site depuis 2008. Cela comprend géophysique (2008-2009) et micro-topographiques (2011) enquêtes de l'ensemble du site, ainsi que deux fouilles à aires ouvertes (2012-2013) et des tranchées (2009-2010, 2013) dans la zone Entrée 1 environnante.

Photogrammétrie numérique est une méthode informatisée peu coûteux qui permet la création de modèles en trois dimensions à partir de photographies utilisant la reconnaissance de motif d'image. La technique peut être utilisé pendant le processus d'excavation pour mieux enregistrer les preuves archéologiques, pour générer des modèles 3D des unités stratigraphiques et de numériser conclusions singulières. Il est également utile pour les activités visant à diffuser les connaissances et la sensibilisation sur le site. Dans cet article, nous allons décrire les bases de la méthode et de ses flux de travail, et de trois applications spécifiques à Perdigões.

Mots clés: Boîtiers préhistoriques, photogrammétrie rapprochée, 3D, Archéologie, Préhistoire, Iberia, néolithique, de l'âge du cuivre, Perdigões

Introduction

The digitalisation of archaeological evidence for its scientific and heritage interpretation is a hot topic nowadays. Public access to archaeological heritage through new technologies, especially 3D models, for example, adds value that benefits professionals, teachers, students and visitors in general (Caro 2012). First, because through 3D models spatial details that cannot be perceived in photographs can be observed; and second, because they can become the foundations of virtual recreations. Thus, if initially heritage was presented on the Web using photographs and textual information, it is now more and more frequently complemented with virtual elements based on 3D modelling (Koutsoudis *et al.* 2008).

But 3D techniques can benefit archaeology in other ways. The increasing power of information systems, as well as the growing capabilities and accuracy of the electronic elements used for the production of 3D models have made possible their employment, not only after, but during the process of archaeological excavation as well. Today, because images from the field can be recorded and transformed into virtual 3D entities relatively quickly, 3D techniques have become convenient and powerful tools for multiple kinds of archaeological recording activities. 3D design devices and applications, for example, can produce ideal models – virtually 3D drawings –, while faro LASER scanners or desktop scanners provide very accurate data (Guidi *et al.* 2014).

3D digitalisation can be an expensive process in terms both of equipment and execution, nonetheless. Fortunately, there are more inexpensive alternatives, such as photogrammetry, that provide 3D models from photographs of the artefact or building in need of digitalisation (De Reu *et al.* 2013). Using pattern recognition algorithms, spatially referenced point clouds are generated, from which 3D meshes are produced. From photographs rather realistic textures can be generated, as well. Photogrammetric procedures require more time and processing power and in that sense they may be expensive, but, given the advanced capabilities of most modern computers, they are comparatively cheaper.

Products obtained after the application of photogrammetric techniques can be directly presented as 3D models for the Web or PDF documents (following the U3D – X3D standards), or they can be used as the basis for future reconstructions and interpretations. They can also be employed in virtual reality systems, augmented reality frameworks or even *game engine* (Caro *et al.* 2014). Regardless of the specific form adopted, data directly recorded from heritage elements can serve as means for their public knowledge and recognition.

The main objective of this work is to show what methodological actions have been executed in order to obtain 3D models for scientific analysis at European Prehistoric ditched enclosures. At all times, these activities have been made in accordance with the Charter of London (Denard 2012), which proposes a set of principles for the digital representation of heritage, exactness and assessment or evaluation to stimulate methodological discussions are recommended. These sites require specific methodological procedures due to their sometimes large size, subterranean features and highly complex intra-site temporality. These actions include from the work done prior to the collection of data to the production of the models themselves. The paper is structured in several sections. In section 2 we shall introduce the site where these techniques have been put in practice – Perdigões (Portugal) – and the preliminary work carried out. In section 3, we will discuss the workflows and tools used at the site. Lastly, in section 4 we will make some concluding remarks.

Case study: the Perdigões archaeological complex

The site where the work that we shall describe below was carried out is Perdigões (Portugal) (Figure 1). The site comprises no fewer than 12 roughly concentric ditched rings, some of them wavy ditches, with at least one palisade (inner circle) and thousands of pits. Both ditches and pits are of diverse chronologies, from the Late Neolithic to the Late Copper Age (second half of the 4th millennium

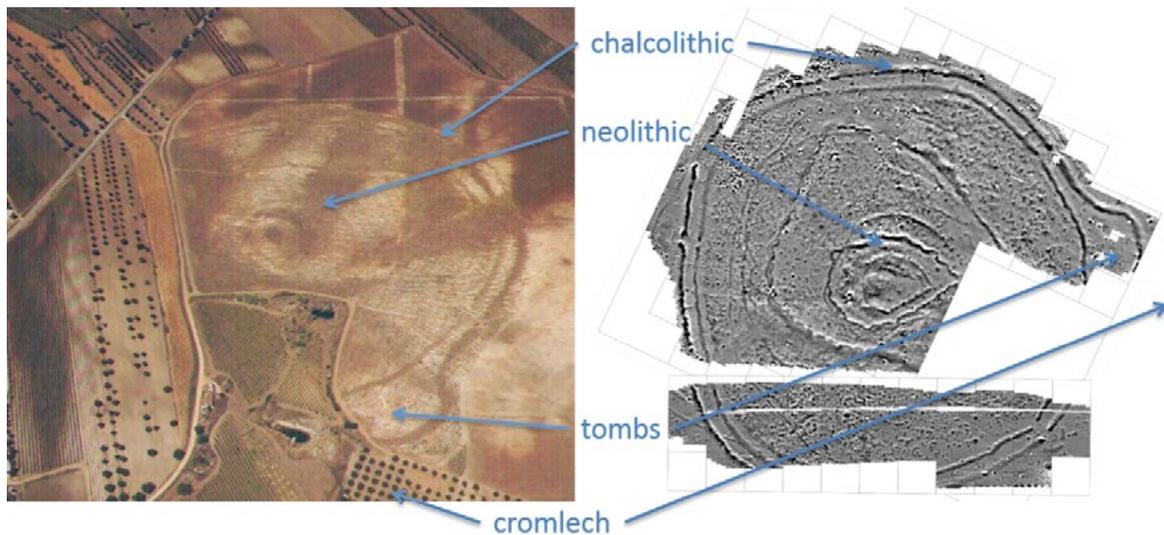


FIGURE 1. AERIAL VIEW (LAGO *ET AL.* 1998A; 1998B) AND MAGNETOGRAM OF PERDIGÕES (MÁRQUEZ *ET AL.* 2011A).

to the last third of the 3rd millennium cal BC). To the E of the enclosures there is also an area with several tombs and a cluster of standing stones (*cromeleque*). The site as a whole occupies an area of about 16 ha. It is located 2 km NW of the town of Reguengos de Monsaraz (Évora, Alentejo Central, Portugal), in the middle of the Ribeira do Álamo valley, a tributary of the Guadiana river. The valley, quite flat and with predominantly granitic bedrocks, is covered by Mediterranean soils, sometimes clay-based, fertile and with low erosion. That is in sharp contrast with its surroundings, especially North and South of the valley, which are hillier, more exposed to erosion, and with a geology mostly based on schist.

The site sits on the right margin of the Álamo valley. The local topography is characterised by a gentle slope going down from W to E, and from the N and the S of the place to the centre of the ditched enclosures, resulting in a basin-like shape, or even better, a Greek theatre: the centre of the site is lower than its surroundings, and from there visibility is almost non-existent to the N, the S and the W. Visibility is, however, good to the E, which is where the necropolis and the menhirs are located, and where the valley begins. It is therefore a location with easy access from most directions.

At the moment, Perdigões is probably the Iberian Prehistoric ditched enclosures which provides the most relevant information, in large part thanks to an international research project coordinated by A. Valera (*Programa Global de Investigação Arqueológica dos Perdigões* or INARP) that involves a team from the University of Málaga since 2008. An area around the so-called Entrance 1, formed by an interruption of the two outer ditches, at the NE side of the site, has been the research zone for the Málaga team in the last few years. There, geophysical surveys were carried out in 2008 and 2009, including extensive magnetometry almost covering the whole site (Márquez *et al.* 2011a) (Figure 1). Excavations of different kinds have also been done (Márquez *et al.* 2011b; Márquez *et al.* 2011c; Márquez *et al.* 2013). First, a medium-sized trench cutting Ditch 1, the outer of the two ditches in the area; and later, an open area excavation on that part of the site.

The process of research that eventually enabled the creation of photogrammetric products followed a sequence from broader, more general surveys, to narrower and more detailed views of the archaeological evidence. Regarding the former, remote sensing techniques constitute excellent means for the adequate understanding of these sites and their features. Their primary advantage is

that because of their relative speed and low price per surveyed square unit, archaeologists can ‘see’ the site they study in its entirety or in a large part, and therefore observe its limits, the distribution of features in space or how these relate to the micro-topography of the place and its surroundings. Perdigões and other Southern Iberian Neolithic and Chalcolithic ditched enclosures, often invisible at ground level, and sometimes very large and complex, can benefit a lot from the application of remote sensing techniques that produce wider and more complete pictures – i.e. floor plans – than that provided by traditional diggings.

A general picture of the site was obtained in the late 1990s via an aerial photograph taken by Manuel Ribeiro (Lago *et al.* 1998a). Even though it was not an orthophotograph and lacked the resolution necessary for advanced analysis, it was still a very good starting point, revealing the existence, among others, of two parallel, roughly circular ditches circumscribing most of the site, with the exception of the menhirs in the eastern side. Later, in 2009, magnetometry proved to be a very effective method at Perdigões, allowing the identification of many new features in the area, particularly pits. It also showed five astronomically aligned entrances to the enclosures (Valera & Becker in press), at least three of them monumentalised following the same pattern, a fence-like feature that we provisionally called an ‘imbrex. An ‘empty’ strip (i.e. space without pits) that extends parallel to the so-called Ditch 2, the inner of the two, which hints at the presence of an inside bank at some point in the past, could be seen as well. All the newly discovered elements were georeferenced and mapped based on magnetic contrasts.

In 2011 and 2012 an open area excavation was performed with the intention of getting even more detailed data about the features in the area (ditches, pits), their distribution in space and the stratigraphic relationships between them (Suárez-Padilla *et al.* 2013).

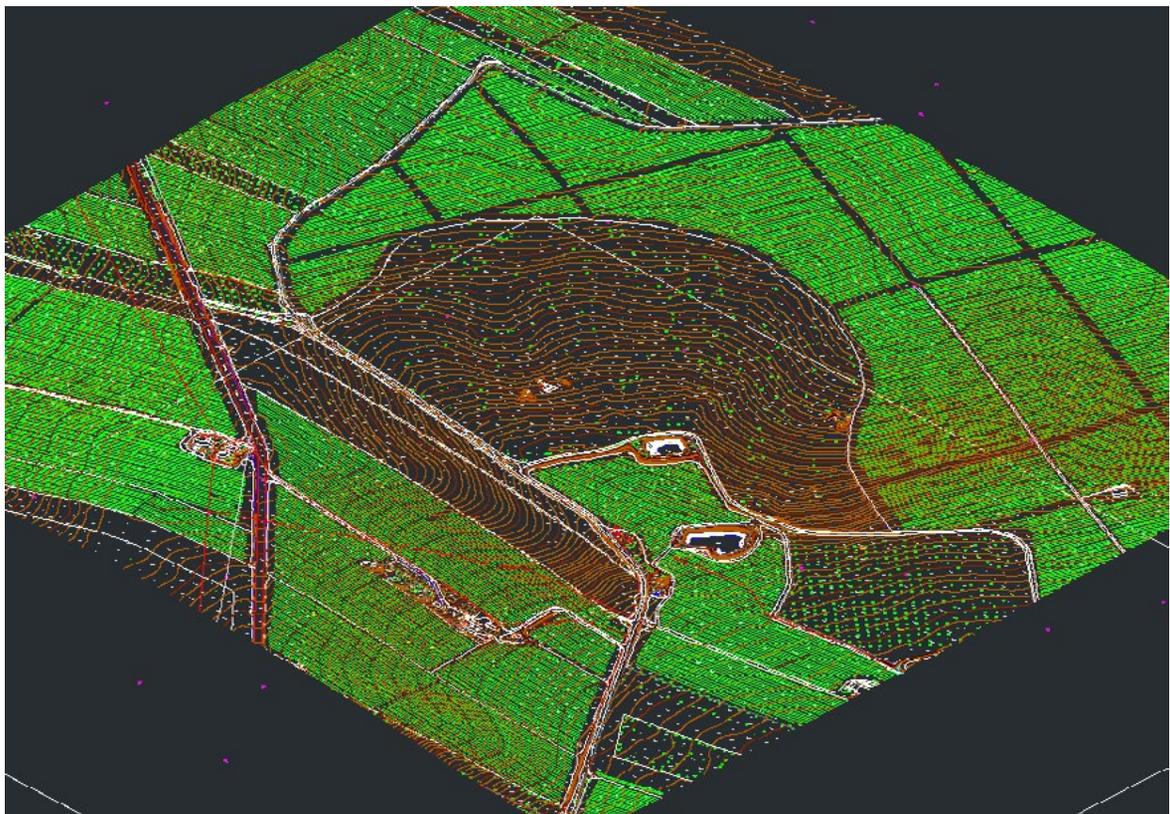


FIGURE 2. MICRO-TOPOGRAPHIC SURVEY AT PERDIGÕES.

At the same time, a micro-topographic survey was conducted (Figure 2) and a higher quality aerial photograph was taken. This was made in three phases:

- Phase 1. Digital photogrammetric aerial survey.
- Phase 2. Field walking survey aimed at linking key reference points in the photographs taken with the local topography and existing geographic grids and coordinates.
- Phase 3. Rectification of the photos and definition of contour lines every 0.50 metres, with a hypsometric precision of ± 0.10 metres.

After that, a Digital Terrain Model (DTM) was created. All this data was put together to serve as the cartographic basis for future activities, both involving the 3D recording of items and features at the micro-spatial level and virtual reconstructions.

Photogrammetry at Perdigões

Photogrammetry is being used as part of the archaeological excavation process at Perdigões by the University of Málaga team since the 2012 season. It serves 3 distinct purposes: a) the recording of archaeological items and features; b) as the foundation for 3D topographic models to be used in virtual recreations of the site; c) the smaller scale digitalisation of specific items that require detailed study (outstanding objects).

Workflow

When developing a digital product, workflows, as well as the tools to be used in its execution, must be carefully chosen, particularly as regards the match between them and the objectives of the activity (Koutsoudis *et al.* 2008). In this section we will describe the workflows and tools that can be employed to create 3D models representing archaeological heritage elements in an effective and attractive way, for the purposes of public access to it. The aim of this exercise, hence, is not so much to make a ‘reconstruction’, as it to generate a faithful representation of reality for its interpretation and knowledge by the public at large (Pavlidis *et al.* 2007).

From a methodological standpoint, photogrammetry, based on *Structure from Motion* (SFM) algorithms, is the key. Photogrammetry, as stated above, is the creation of 3D models from 2D photographs. Its mathematical foundations have been known for a long time: photographs taken from different perspectives can be combined to obtain a three-dimensional view. The position of the camera in relation to the object being photographed can be estimated in digital images; further calculations can give us the relative position of its points in a 3D system (Longuet-Higgins 1981). The model thus generated, although initially does not possess absolute coordinates, it includes a sense of proportion and relative coordinates that can later be converted into absolute ones.

However, the technique has traditionally been applied almost exclusively to aerial photos, in order to create maps and Digital Elevation Models (DEM), and only a few years ago, the use of photogrammetry to generate more detailed and smaller scale 3D models was rare. An enhancement in the processing power of modern computers, particularly their Graphic Processing Units (GPU), and optimisations in pattern recognition algorithms in digital images has changed this, making possible a much more generalised employment of close-range photogrammetric methods. They are now being used in archaeological research (Almagro Gorbea 1988), in the scientific recording of artistic, historical and archaeological heritage (Chong 2003; Caro 2012; eg at Çatal Höyük; Forte *et al.* 2012), in public access and interpretation of this heritage (Caro & Hansen 2014), in the recovery of old pictures (Aparicio Resco *et al.* 2014), or as a source of models for augmented reality (Portales *et al.* 2009).

As regards software, there are multiple options. For instance:

- VisualSFM (<http://homes.cs.washington.edu/~ccwu/vsfm/>),
- iWitness™ (<http://www.iwitnessphoto.com>),

- EsriCityEngine 2012™ (<http://www.esri.com/>),
- Autodesk's 123DCatch™ (<http://www.123dapp.com/catch>),
- Photomodeller™ (<http://www.photomodeler.com/>),
- Photoscan™ (<http://www.agisoft.ru/products/photoscan/>).

For our work at Perdigões we have used Photoscan, from Agisoft (AGISOFT 2014), which offers a complete solution for our workflow, including:

- Image manipulation, necessary, for example, to remove non-essential or distracting areas of the photographs before the algorithm comes into play, thus reducing some processing power requirements.
- Establishment of ground control points from pairs and common features between the pictures.
- Creation of point clouds from ground control points.
- Generation of a mesh, that is, a network of polygons to model the space/object.
- Mesh editing, to remove flaws or shortcomings of the model (although for that purpose graphic design applications such as 3D Studio or retouching software such as MeshLab can be used).
- Creation of textures from photographs, to give the models a more realistic look.
- Exportation to standard formats with which the workflow can continue in other applications.

Lastly, we would like to underline the importance of planning and of preparatory actions before taking the photographs. Good lighting, well-chosen points of view for the photos and a well-prepared environment can make a big difference later, during the creation of the models, both in the effort needed to generate and edit the models and in the processing time. Good lighting in particular can depend sometimes on factors out of our control, especially in large areas (as was the case in our work during the open area excavations at Perdigões).

Application of photogrammetric techniques

In what follows we will describe the actual application of photogrammetric methods at Perdigões by the University of Málaga team. The basic workflow followed is represented in Figure 3, and consists of a sequence starting with archaeological excavations, during which the photographs were taken, and ending with the production of 3D models for scientific interpretation and assessment, and heritage presentation.

Our first tests were intended as support actions in the recording and graphical representation of the features unearthed by archaeological excavations. The workflow depicted in figure 4 was put in practice: ground control points were set and photographs taken over large survey areas, particularly during the 2012 and 2014 seasons (Figure 4), so that composed floor plans could be obtained from them.

The results of this experience were encouraging and we decided to continue digitalising a more restricted area at sector L (Figure 5) that covered Entrance 1, the outer semi-circular ditched 'imbrex' we mentioned before and a few big stones, probably stelae or menhirs (Suarez *et al.* 2013).

The process of 3D modelling developed there (Figure 6) began with the capture of 33 photographs in full daylight with a Nikon D90 digital camera and a 10-24 mm Nikkor wide angle lens. For the processing of the images a PC with 64 GB of RAM running Photoscan was used. The images had a 100% success percentage in the pair matching check. Photoscan produced a point cloud with 99882 points and 198854 polygons, with a rather realistic texture. After that, Meshlab was employed to make corrections and 3D Studio Max to simulate a 3D view of the area. All this data, together with the magnetogram and micro-topographic data was processed by rendering machines in order to create a realistic recreation of Entrance 1 and its surroundings. At all times during this process, data from excavation was taken into account to help guide some decisions.

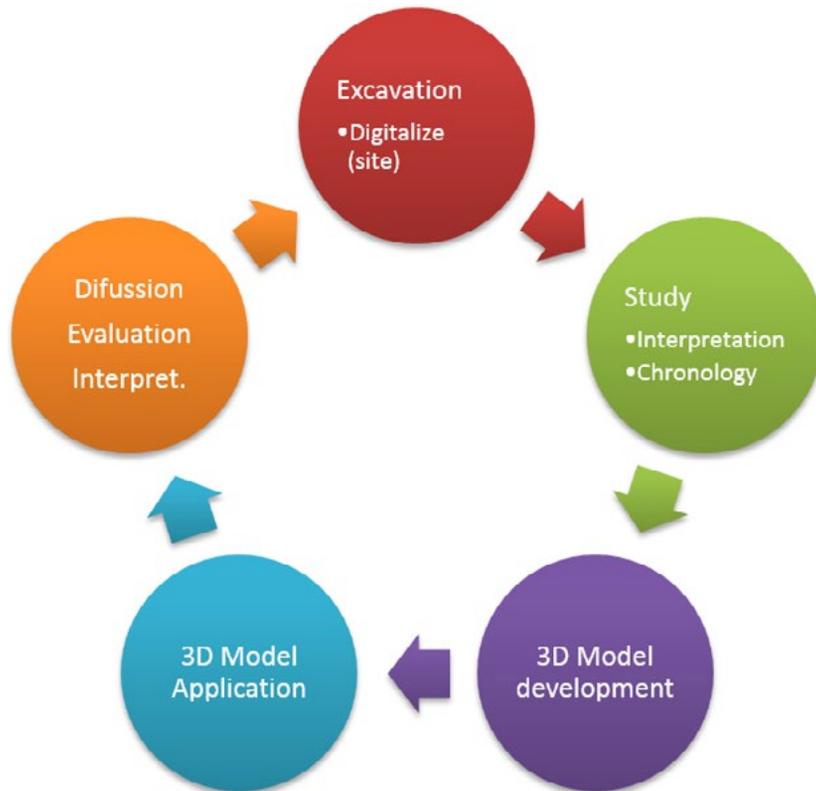


FIGURE 3. BASIC 3D WORKFLOW AT PERDIGÕES.



FIGURE 4. CREATION OF PHOTOGRAMMETRIC COMPOSED FLOOR PLANS AT PERDIGÕES.



FIGURE 5. SECTOR L AT PERDIGÕES, AREA AROUND THE 'IMBRES'.

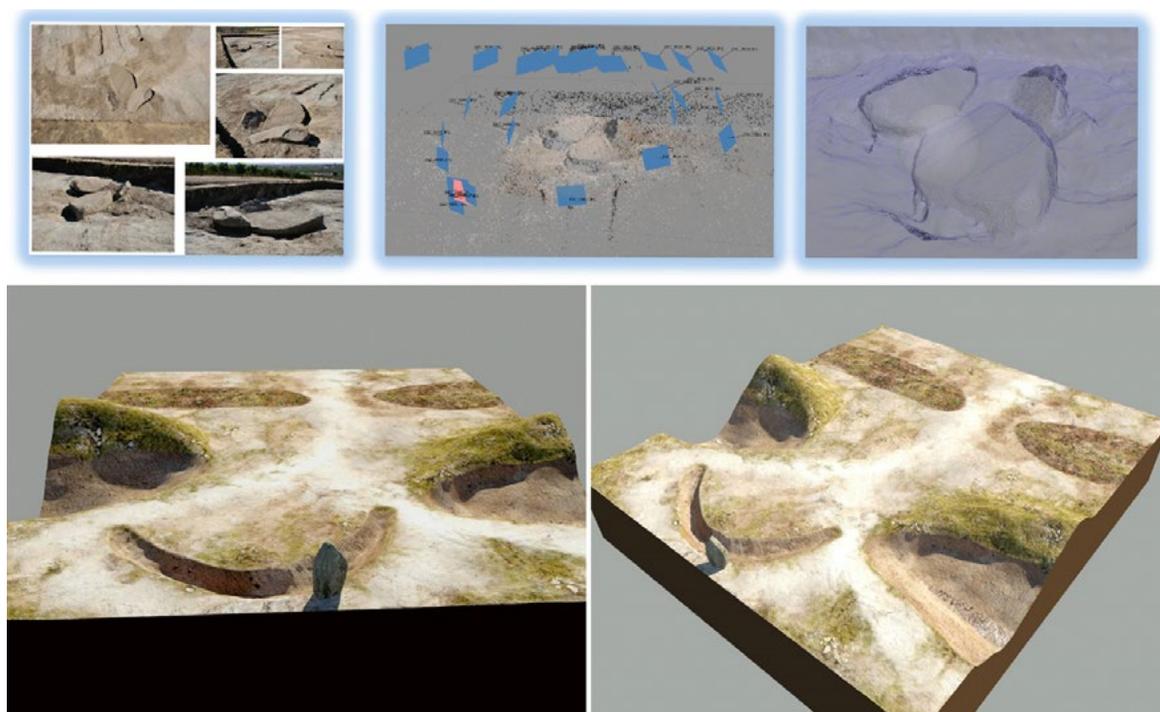


FIGURE 6. PHOTOGRAMMETRIC RECONSTRUCTION AND SUBSEQUENT 3D MODELLING AT SECTOR L IN PERDIGÕES ([HTTPS://VIMEO.COM/59471957](https://vimeo.com/59471957)).

Lastly, photogrammetric procedures were also put in practice at Perdigões to digitalise much smaller elements; ie specific artefacts. A ceramic 'idol' and a decorated loom weight (Milesi *et al.* 2013) were selected for this. The objective was to test these methods as a way to generate 3D models that served as record for further study of these micro-elements. Despite following the same basic workflow, the need to capture small details in relief made the process a bit more complicated, especially in terms of planning (Figure 7).

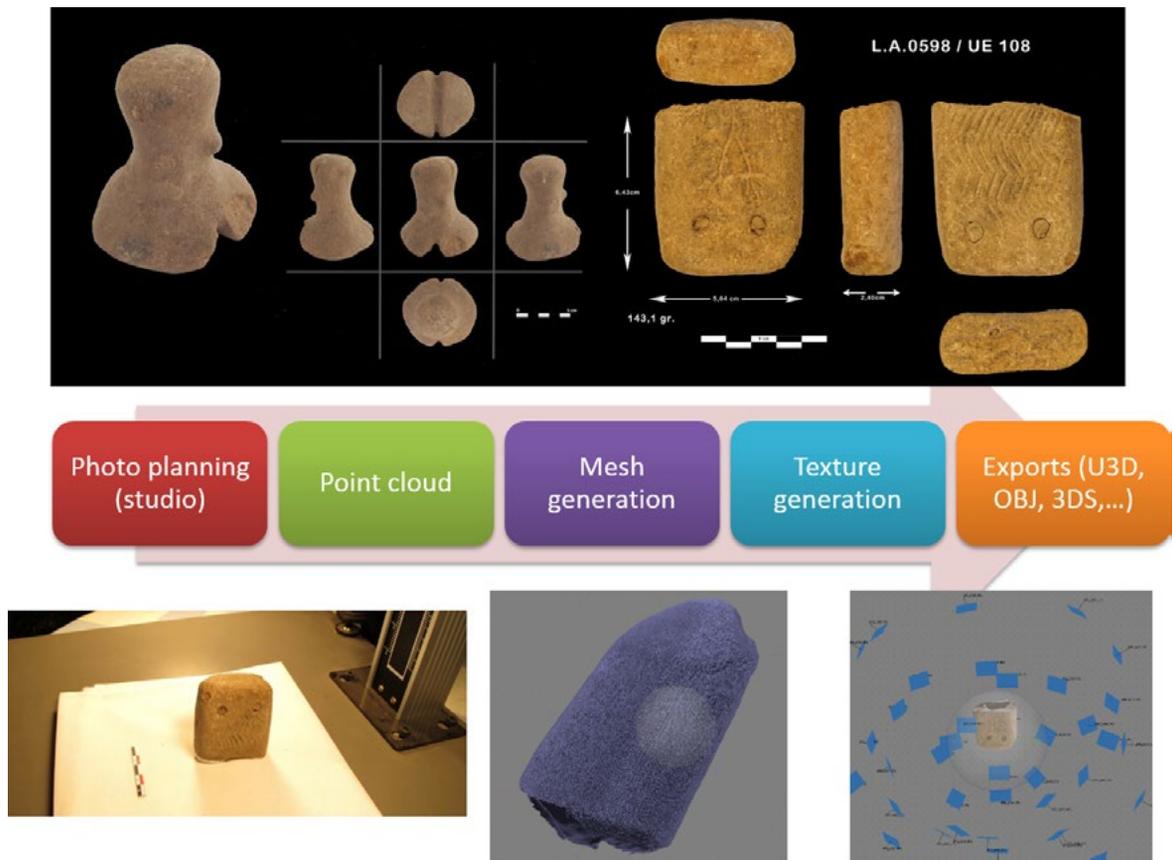


FIGURE 7. ARTEFACTS FROM SECTOR L AT PERDIGÕES SELECTED FOR THE 3D MODELLING TEST ('IDOL' ON THE LEFT, LOOM WEIGHT ON THE RIGHT).

FIGURE 8. SYNTHETIC IMAGES REPRESENTING THE IDOL AND THE LOOM WEIGHT FROM SECTOR L AT PERDIGÕES.



The results were good in general terms, but more photographs had to be taken to obtain the desired models (Figure 8). For the idol 38 pictures were captured, what allowed the software to produce 94813 vertices and 187767 polygons. The loom weight, with its fine but shallow incise decoration, needed even more cameras (52), vertices (97110) and polygons (194020).

Concluding remarks

Photogrammetry is nowadays a relatively low-cost technique and an intriguing tool both for scientific research and for the presentation of archaeological heritage to the public at large. These techniques

are relatively inexpensive (Habbib *et al.* 2004), especially when compared to others such as Light Detection And Ranging (LiDAR) or 3D scanners, although these ones are capable of generating high quality point clouds both in closed environments and open landscapes (eg the reconstruction of the Stonehenge landscape undertaken by Wessex Archaeology; Wessex 2007).

The examples from Perdigões show that photogrammetry can be used for archaeological recording, for it can produce realistic and accurate models of a wide range of subjects, from buildings and monumental features to small figures, as a complement to more traditional recording procedures in archaeology such as drawing and photography. In terms of heritage interpretation, it can serve as the foundation for 3D virtual recreations, traditional videos, augmented reality and virtual reality through game engines. If the models produced are detailed enough, photogrammetry could potentially be used as a source of data for 3D printing, not least when it comes to small artefacts.

It is important to remember, however, that models produced this way will not be very effective unless they are contextualised within the site and its general plan, with absolute coordinates and dimensions. In the case of Prehistoric ditched enclosures in general and Perdigões in particular, having previously obtained high quality data about its features and setting (eg micro-topographic and geophysical survey) ended up being extremely helpful to get the most out of the 3D models produced.

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3D modeling by digital photogrammetry applied to the Palaeolithic mammoth bone dwelling settlement of Gontsy (Ukraine)

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Abstract

The digital photogrammetric method was used to obtain a 3D modeling of a Palaeolithic settlement with mammoth bone huts in Gontsy (Ukraine). The processed settlement area contains three mammoth bone huts, pits, working areas and hearths. The difficulties that had to be overcome are the lack of contrast (color of the loess), the small discrimination of artefacts (repeatability of the mammoth bones), the weak light under the hangar and the existence of many blind areas due to the numerous overlays of the bones.

Keywords: *Upper Palaeolithic, 3D photogrammetry, mammoth bone dwellings*

Résumé

La technique de photogrammétrie numérique a été utilisée pour obtenir une modélisation 3D de l'habitat paléolithique à cabanes en os de mammouths de Gontsy (Ukraine). La zone de l'habitat étudiée contient trois cabanes en os de mammouths, des fosses, des zones d'activités et des foyers. Les difficultés qu'il a fallu surmonter sont l'insuffisance de contraste (couleur du lœss), la faible discrimination des objets (répétitivité des mêmes ossements de mammouths), la faible lumière sous hangar et l'existence de zones aveugles dues à la multiple superposition des ossements.

Mots clés: *photogrammétrie numérique, paléolithique supérieur, cabanes en os de mammouths*

Introduction

Photogrammetry is a long successful story since the XIX^o century for cultural heritage management. But the recent development of digital photogrammetry could be a technical revolution in archaeology, due to an easier digital photography acquisition and powerful algorithms at a cheap cost, which could replace the usual data acquisition with manual drawings and vertical silver photography for each square meter. The context of application is nevertheless different for prehistoric layers which are most of time limited to artefact distributions without volumes and archaeological sites of historical periods with elevation structures of partially preserved buildings. In this paper, only the first case is considered.

From the fifties, some photogrammetric acquisitions have been applied to prehistoric layers but the restitutions by stereo plotters have never been achieved. It is for example the case for A. Leroi-Gourhan with the rescue operation on the dwelling n°1 in Pincevent, France (Brézillon & Leroi-Gourhan 1966) or in Melka-Kontouré, Africa by A. Chavaillon (Y. Egels personal communication).

The first applications of digital photogrammetry started from 2010, as experiences to compare with the results of acquisitions with topographical stations or scanner laser 3D stations (for a synthesis of first researches, see Kjellman 2012).

In Gontsy, the project of 3D Digital photogrammetry has started since 2012 on the mammoth bone dwelling Palaeolithic settlement of Gontsy (Ukraine). The main difference with a Palaeolithic artefact distribution is here the huge accumulation on mammoth bones over 1 meter deep due to the collapse of the dwellings. The purpose of this article is to give the first results, to present some technical difficulties met during the progress of the project and to propose improvements in the acquisition of data.

The Upper Palaeolithic site of Gontsy, a general overview

The Upper Palaeolithic site of Gontsy is located at about 180 km South-East of Kiev, near Lubny. The settlement is located on a terrace of the slope of the valley Udaï, an eastern subsidiary of Soula and Dnepr. The terrace has been cut by two converging ravines designing a promontory, on which the settlement has been located surrounded by the convergence of two paleoravines, going down from the river (Figure 1).

The geomorphological studies have shown that the promontory, on which the settlement was installed, had an area of approximately 50 m x 30 m, cut on the East and West by fossil ravines, currently filled.

However, bone remains, and vestiges of human activities, have been found by surveys on a surface of more than one hectare around the promontory.

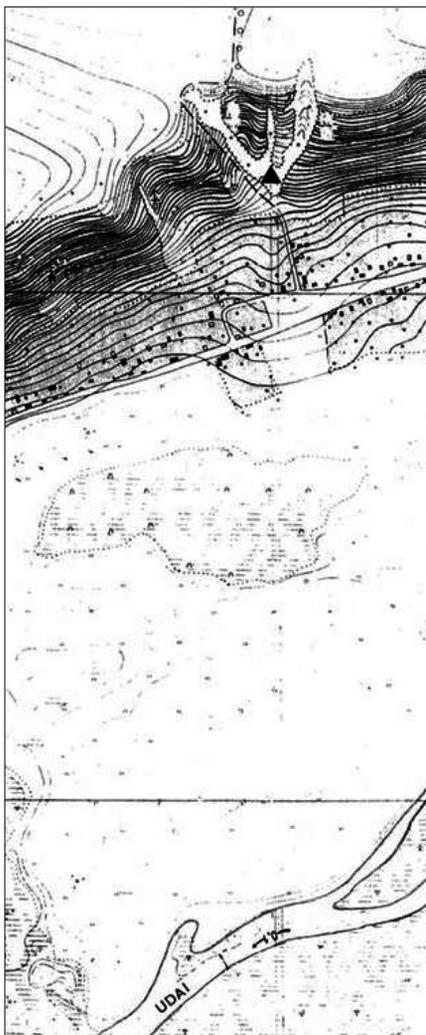


FIGURE 1. TOPOGRAPHY OF THE SLOPE OF THE UDAÏ RIVER AND LOCATION OF THE SETTLEMENT OF GONTSY.

The stratigraphy of the Gontsy settlement has been established with numerous sections over the promontory of the site and inside the paleoravines. The sections reveal a multi-occupation site with two archaeological layers (upper layer and lower layer), demonstrating that the site has been occupied at least twice within a very short time (less than 500 years considering the standard deviation of the ¹⁴C dates). The difference of depth between the two layers is greater inside the paleoravine, around 75 cm of laminations, where the sedimentation rate has been particularly fast during the short period of human occupation, than on the promontory, around 20 cm of loess, in the area of the mammoth bone dwellings. In the lower layer, the archaeological remains are particularly dense, and the mammoth bone huts, pits and related working, dumping and butchering areas, are directly associated with the mammoth bone bed along the slope of the promontory and the bottom of the paleoravine. In the upper layer, archaeological remains are less dense, revealing a short seasonal occupation. The site has been dated by ¹⁴C, in the Oxford radiocarbon laboratory, with a series of 13 dates, between 14,110 BP and 14,620 BP, including the bone bed. The ¹⁴C dates of the whole mammoth bone hut settlements of the middle and upper Dnepr basin have been recently revisited and the occupation has been reduced from a 22,000-12,000 BP interval to the 15,000-14,000 BP interval (Iakovleva 1999; Iakovleva & Djindjian 2005).

History of the excavations on the settlement of Gontsy

The discovery of the Palaeolithic site of Gontsy (Ginsy in Ukrainian language), has marked in 1871 the beginning of the Prehistoric research in Eastern Europe. Many other mammoth bone dwelling settlements of the late Upper Palaeolithic, have been excavated since 140 years by numerous archaeologists (Iakovleva, 2010), in the middle and upper Dnepr basin defining a territory of peopling of hunter-gatherers specialized in the economy of the mammoth during a short period 15,000-14,000 BP (Djindjian *et al.* 1999; Iakovleva 1999; 2009).

The discovery of the site by G. S. Kyriakov in 1871 has been followed by the first excavations directed by F. I. Kaminski from 1873 who published with the geologist K.M. Feofilactov its first results at the 3^o Russian archaeological congress in Kiev (Kaminski 1878). The site has then been excavated by an amateur Guelvig (1905), by V. M. Scherbakivski (1914-1915), director of the Poltava museum, who found the dwelling n^o1 (Scherbakivski 1919; 1926; Gorodtsov 1926), by I. F. Levitski and A. I. Brusov (1935) who excavated mainly the mammoth bone bed (Brusov 1940; Levitski 1947) and by V. I. Sergin (1977-1981) who found again and dismantled the dwelling n^o1 protected by Scherbakivski (Sergin 1981; 1983). In 1993, a new research project restarted by a program of long-term excavations, directed by L. A. Iakovleva (I.A. NASU) and F. Djindjian (University of Paris 1) in order to reconstitute the entire settlement in its environment (Iakovleva & Djindjian 2000; 2005; 2014; Iakovleva *et al.* 2010; 2012). After 21 years of excavations, the settlement of Gontsy has delivered several different mammoth bone dwellings, various working, dumping and butchering areas around the dwellings and nearby inside a paleoravine, a large mammoth bone bed allowing for the first time a quite complete reconstitution of a the settlement. Since 2000, the actual excavations are developed under large hangars which allow excavating without any constraints of time and weather, and to keep in situ the archaeological layers and the dwellings. The hangar n^o2 has been erected over the bottom of the eastern paleoravine which has delivered a dense mammoth bone bed. The hangar n^o1, extended twice, has been erected on the promontory and is protecting three mammoth bone dwellings and large working areas with hearths (Figure 2, 3).



FIGURE 2. THE SETTLEMENT BEFORE EXCAVATIONS (DURING THE WINTER) AND DURING EXCAVATIONS (WITH THE HANGARS OF PROTECTION).

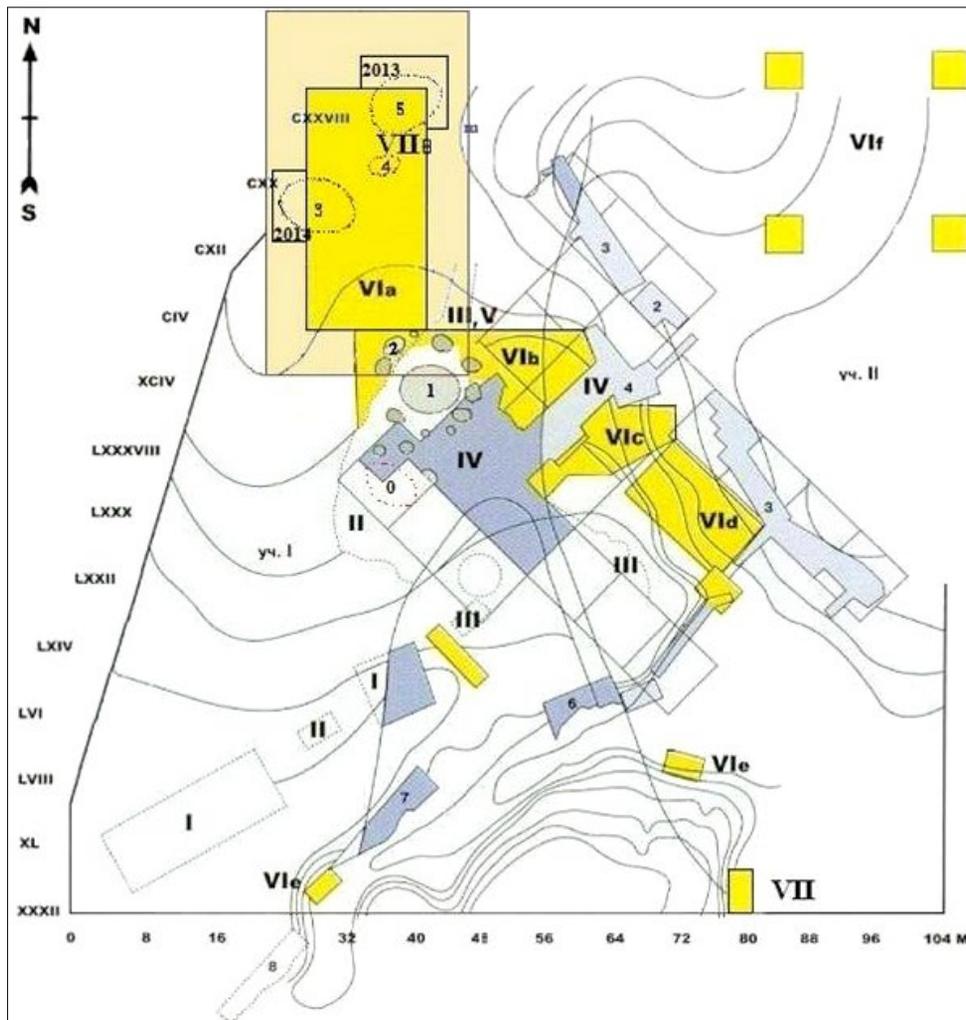


FIGURE 3. THE MAP OF THE EXCAVATIONS SINCE 1871.

The first and main occupation IN Gontsy

The spatial intra site analysis of the lower level has shown an organized occupation layer through several specialized areas (A to D). On the promontory, several areas, from the interior to the exterior, have been distinguished (Figure 4).

- (A) the area of mammoth bone huts and other related structures and surrounded pits (up to 9 pits per hut), separated by about 10 meters of working areas with hearths,
- (B) Dumping areas, with remains of hearths cleaning and flint chipping works,
- (C) Butchering areas, limited to middle and small mammals (reindeer, carnivores, rodents) or part of large mammals,
- (D) On the slope and the bottom of the paleoravine, a mammoth bone bed, associated with other mammals bones, but also with hearths, bone and flint artefacts, demonstrating a large exploitation of the bone bed by the inhabitants of the settlement.

The mammoth bone bed and mammoth bone dwellings

On the site of Gontsy, the accumulation of mammoth bones, excavated in the Eastern paleoravine, has a stratigraphic, taphonomic and functional direct relationship, with the mammoth bone dwelling settlement. The accumulation of mammoth bones corresponds to a unique event of a natural herd



FIGURE 4. A GENERAL VIEW OF THE SETTLEMENT UNDER THE LARGE HANGAR N°1.

composed of variable age female adult, sub adult, juvenile and baby individuals, dead in the bottom of a dry and shallow ravine. Their carcasses have been widely exploited by the human group that have abandoned only legs, ribs, vertebrae and hyoid bone, often still in a quasi-anatomic position mixed with flint, bone and ivory tools and with many hearths (Figure 5).



FIGURE 5. THE MAMMOTH BONE BED UNDER THE HANGAR 2 IN THE BOTTOM OF THE EASTERN PALEORAVINE.

The first occupation of the settlement is the installation of a human group on the site, which has operated the carcasses of mammoths of the ravine and built the huts with their bones. The settlement has a residential function, where all of the human group is installed, and is occupied a long time since the beginning of spring until the end of the winter. The site has revealed to date at least four large oval or circular mammoth bone huts and a small one.

The dwellings of the settlement on the promontory

In the actual state of the knowledge, the dwellings seem to have been aligned from the southern to the northern part of the settlement:

- The first dwelling (n°0) would have been supposedly found by Guelvig in 1905, of which we have only the supposed proof of three pits excavated by Levitski & Brusov in 1935.
- The second dwelling is the only mammoth bone hut (hut n°1) found during the 1914-15 excavations by Scherbakivski. Nine pits have been found around a 5.5 meters diameter hut, built above the foundations of mammoth skulls. The structure, protected in 1915 by Scherbakivski under a wood protection, has been unfortunately dismantled by Sergin in 1977. The archives of V. M. Scherbakivski, I. F. Levitski, V. I. Sergin and our excavations are documenting about 80% of the structure with a minimum number of 28 skulls, 30 tusks, 30 scapulae, 3 half pelvis, 1 complete pelvis, 4 long bones, 20 ribs and 10 vertebra.
- The third dwelling (hut n°2), located at the north-western part of the previous one, has been discovered during our excavations in 1998. Exceptional by its small size and structural evidence, it is a hut of about 2.7 x 1.7 m², mainly built with only a large fragment of skull in a central position, a femur, a humerus, two complete adult male tusks (1.70 meter long) and several fragments of skull alveoli. The dwelling has been built with two large male mammoth tusks, erected as an arch supported by two long bones, a skull and alveoli, above an oval depression fulfilled by black organic sediment, resulting either in the decomposition of a litter or having trapped the ashes of the hearth at the top of a pit located just near the structure. Inside the hut, three pieces have only been found: a hammer made on a base of a reindeer antler, a fragment of pelvis with red ocher traces and the point of a juvenile engraved tusk and two tools on a mammoth rib. It is the first dwelling of this type found in a settlement of the Dnepr basin (Figure 6a). A reconstitution of the hut n°2 has been designed from a model in modeling clay and was presented both in the exhibition of Gontsy and in the exhibition of the Crozatier museum in Puy-en-Velay in France (Figures 6b).



FIGURE 6A. THE SMALL MAMMOTH BONE HUT N°2.



FIGURE 6B.
RECONSTITUTION OF
THE SMALL MAMMOTH
BONE HUT N°2.

- The fourth structure is a limited unexcavated accumulation of bones, perhaps a large pit, actually protected under the hangar 1, showing at the top of a surface of less than 3 m², a minimum of 3 pelvis, 1 scapula, 2 tusks, 2 long bones and one fragment of skull.
- The fifth structure is a large hut (n°3), of more than 6 meter diameter, located at un meter to the West of the hut n°4. It has been partially excavated in 2009 and 2010 on a surface of 40 m² (Figure 7), and 10 m² in 2014 and the 2015 program is dedicated to excavated it totally. The temporary inventory of the mammoth bones at the end of the 2011 campaign is about 73 tusks, 34 scapulae, 8 skulls, 2 pelvis, 8 long bones, 3 mandibles, 2 vertebrae, 9 ribs, corresponding to about two third of the total hut.
- The sixth structure (hut n°4) has been totally excavated during the 2011-2012 campaign, is a mammoth bone oval hut of 3 x 2.5 m². The dwelling has been erected with 15 skulls, 6 half pelvis, 14 scapulae, 24 tusks and 3 long bones. The hut collapsed inward (Figure 8).
- The seventh structure (hut n°5) has been circum-excavated from 2011 to 2013. The hut n°5 is a large oval mammoth bone hut of about 8 meter of diameter. The wall has been particularly well protected. It has been erected with a large number of skulls of different ages, mandibles, scapulae, basins, and long bones (Figure 9).

The classical recording

The archaeological recording of the spatial structures is complex, due to the numerous superimpositions of mammoth bones, fallen altogether during the collapse of the hut. It implies a very particular excavation management in order to dig until finding the soil of the hut.

The classical recording is involving the following tasks:

- Identification of the precise anatomic part of the bones and also indication, when possible, of the sex, age, laterality, etc. of the individual,
- Identification of bones owning to the same individual,
- Recording upper and lower absolute altitudes of each bone,
- Identification of the modification of bones (piercing, sharpening, digging, fragmentation) for fastening bones in the building,



FIGURE 7. THE MAMMOTH BONE HUT N°3 (EXCAVATIONS 2014).



FIGURE 8. THE MAMMOTH BONE HUT N°4 (EXCAVATIONS 2010-2011).



FIGURE 9. THE MAMMOTH BONE HUT N°5 (EXCAVATIONS 2013).

- Recording and study of the entanglement of bones (until ten superimpositions) with Harris matrix analysis and associated software package,
- Manual plotting, square by square,
- Vertical photography recorded by 1/4 square,
- Corrections of parallax errors, square errors and plotting errors,
- Scanning, corrections and fitting of square by Illustrator,
- Plotting bones of the dwelling by altitudes, and by anatomic part of the skeleton,
- Reconstitution of the collapse process for a hut, explaining the location of each bone and their superimpositions,
- Reconstitution of the architecture of the hut.

The classical recording is a very huge work, spending a lot of time. It needs a good erudition about mammoth bones and a rather good experience for a precise manual plotting. Limit of squares are often difficult to locate precisely and definitively because of the accumulation of bone. The consequence is the difficulty to check the importance of the errors of recording. It is the reason why it has been decided to realize a 3D recording, using the digital photogrammetric method, to improve the quality of the recording.

The project of 3d digital photogrammetry

The collapsed mammoth bone dwellings n°3, 4 and 5, kept fully in situ under the hangar, allow in-depth studies, without any constraints of time and weather.

The surface to record is up to 25 x 40 m².

THE THREE DIMENSIONS OF ARCHAEOLOGY

The goals for a 3D recording are the following:

- A precise and corrected plotting,
- A right plotting, with a minimum of errors,
- A plotting allowing vertical and horizontal projections,
- A digital plotting for easier processing,
- A 3D plotting for handling the vertical accumulation of bones,
- A digital recording producing data for mathematical models developed for the 3D reconstitution of the dwelling,
- A 3D printing of the occupation layer and the dwellings, for museography projects.

The 3D recording

At the end of the preparatory step, it was decided to specify the photo recording so as to allow the relevant restitution of millimeter details. Because constraints strongly limiting or banning walking on the in situ archaeological layer (with many fragile artifacts and piles of bones), it was decided to achieve all photographs from shooting points external to the site, which has mandated the use of oblique photographs.

A first shooting was carried out on the ground. A second shooting was carried out on scaffolding at a height of four meters and the rolling scaffold was moved to shooting all around the archaeological level (Figure 10).

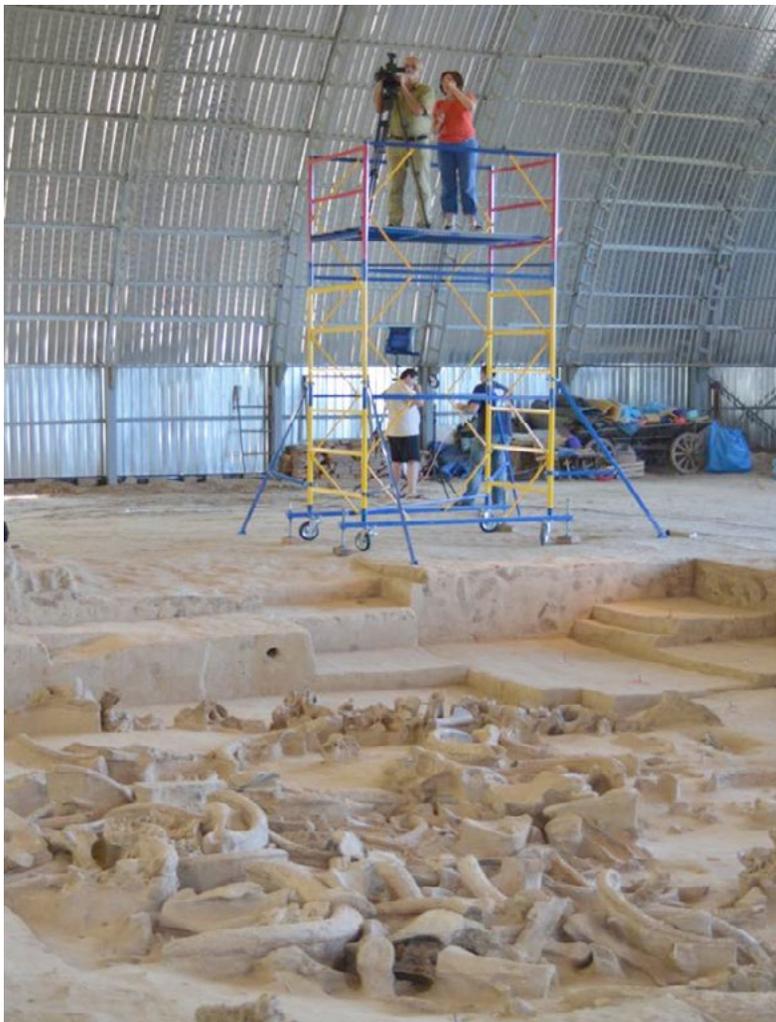


FIGURE 10. THE DATA ACQUISITION BY OBLIQUE PHOTOGRAPHY.

So as to limit variations in scale and thus resolution between different points on the surface of the archaeological layer, two series of photographs have been used, with different focal lengths. All images were recorded in natural light with a Sony Alpha 55 (16 Megapixel) apparatus, forming bands with a strong stereoscopic recovery (about 2/3). Due to the lighting very attenuated inside the hangar, and the need for a large depth of field, it was necessary to work on a tripod with a long enough exposure time.

In order to allow fitting the photogrammetric record with the already completed hand plots, a number of nails marking the boundaries of the squares of the grid were leveled, and marked to put the 3D survey in the same system of coordinates as former surveys. The overall operations of recording in the open full area (approximately 200 m²) necessitated 3 working days.

Another solution would have been to make the shooting directly through walking on the archaeological layer. But unfortunately, it is not possible to do that because of the impossibility to walk on the layer in most of cases. And the places where a local shooting would have been very useful to avoid blind areas, are just the areas of accumulations of mammoth bones where it is impossible to walk or even to approach (see under for an alternative solution).

The 3D processing

The use of photogrammetric upon prehistoric soils is not a novelty. Unsuccessful tests were conducted in the 1960s at Magdalenian camp-site of Pincevent (France), and in the 1970s at the Lower Palaeolithic site of Melka Konture (Ethiopia). However, processing time made this method inapplicable in practice on the ground. Technological advances now allow progressive exploitation of images during the archaeological campaign, and the production of documents (at least provisional) according to the needs of the excavations.

The orientation of 220 images was made using the software AgiSoft Photoscan, widely used by archaeologists, adding numerous manual aids. Indeed, the detection of bond points was often faulty in corners of the archaeological surface, due to many hidden parts and large angles between the images). The calculations were made after each working half-day, which enables to check the quality and completeness of the model.

The photogrammetric survey was able to highlight the inaccuracies of the grid, which have been corrected. Graphic documents (orthophotos, sections, contour lines) were produced by specific software (“Redresseur” and “Cumulus”) developed by the National School of Geographical Sciences under his teaching activities.

The results

The digital photogrammetry first provides a 3D textured model of the archaeological layer (here with about 30 million of points, one point all 2.5 mm on average). Of course, this model, even if it is visually attractive, cannot be used only for plotting the archaeological layer. But it has the advantage of forming one archive containing geometric information of the archaeological soil, and therefore can be archived as such. 2D documents were derived for the purpose of the search, with an orthophoto across 20 cm/m superimposed on contour of equidistance 5 mm for every square meter of soil. The archaeologist may have then for each square a reference document plot for both horizontal and vertical dimensions.

Advantages and difficulties of the 3D project

The general results are very satisfactory and answer well to the goals of the project (Figures 11, 12). Nevertheless, it is possible to find some difficulties during the acquisition step:



FIGURE 11. GENERAL VIEW OF THE THREE MAMMOTH BONE HUTS BY 3D DIGITAL PHOTOGRAMMETRY.

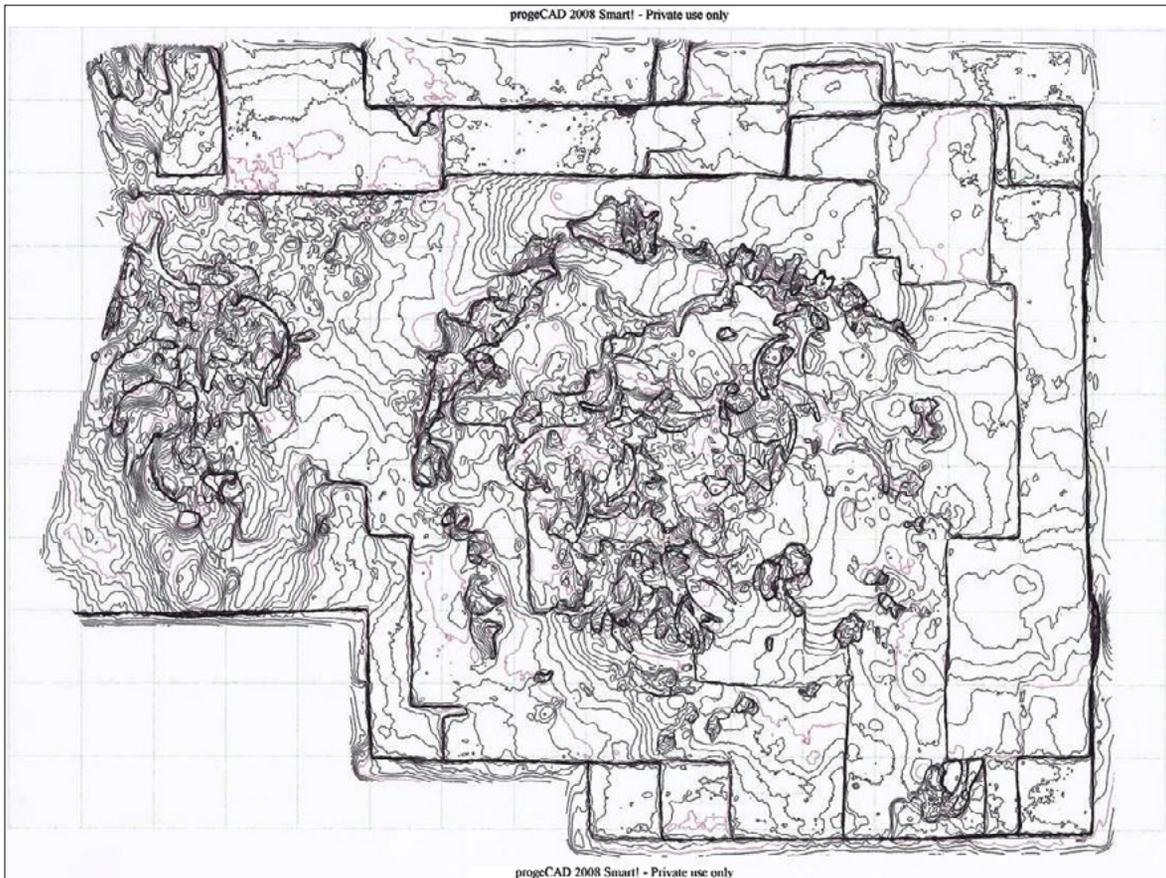


FIGURE 12. 3D DIGITAL PHOTOGRAMMETRY: THE CONTOUR LINE OF THE MAMMOTH BONE HUT N°5.

- The platform is not totally stable, making more complex to avoid blurred recording,
- The lighting of the hangar has to be improved, for a better record of the limit of the bones,
- The oblique photography cannot avoid several small blind areas at the scale of the square in the case of many superimpositions of bones (Figure 13).

To improve the results, it will be necessary to abandon the oblique photos for vertical images shot up to about 5 m above the archaeological soil. The technical implementation is not obvious. A solution would be the use of a drone or its equivalent, but the weakness of the lighting may be a handicap. Otherwise, it must be considered the use of a supporting and hauling cable attached to the structure of the hangar or a long articulated tripod carried from the periphery of the archaeological surface, which will be tested in 2015.

Conclusions

A 3D digital photogrammetric recording has been applied for the first time on a large Palaeolithic occupation layer with dwelling structures.

If the global and detailed (structure by structure) 3D maps are satisfying, the acquisition at the scale of the square meter needs to be improved.

A project of a new recording by vertical photos made with an adapted mean and improved lighting has been planned for the next excavation campaign.

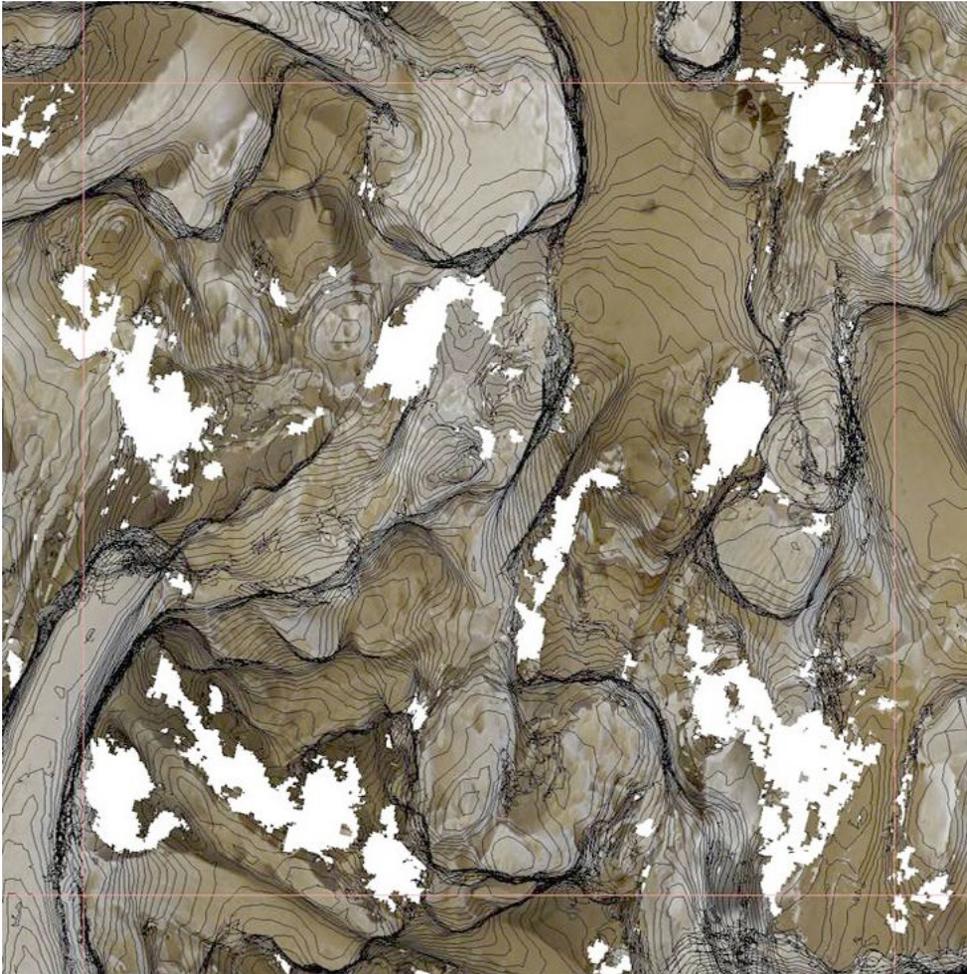


FIGURE 13. 3D DIGITAL PHOTOGRAMMETRY: SQUARE L5 OF THE MAMMOTH BONE HUT N°4.

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Archaeology and coastal erosion: monitoring change through 3D digital techniques

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Abstract

The vulnerability of coastal heritage is increasingly becoming a major issue, particularly in areas such as the European and American Atlantic shore lines, where the combined forces of sea-level rise, coastal environment dynamics and human activity are significantly altering the coastline. In this context, 3D recording and modelling techniques can provide valuable solutions to both digitally preserve and analyse threatened archaeological sites. In this paper we will discuss the potential of close-range photogrammetry as a cost-effective way to efficiently monitor and manage coastal archaeological site erosion. This methodology is currently being tested at a number of case studies in NW Spain (Galicia), Western France (Brittany) and SW Britain (Isles of Scilly).

Keywords: Coastal archaeology; 3D modelling; Structure from Motion (SfM); climate change

Résumé

La vulnérabilité du patrimoine littoral est de plus en plus évidente, en particulier dans des régions telles que les façades atlantiques européenne et américaine, où l'action combinée de la remontée du niveau marin, les dynamiques du milieu littoral et l'action humaine sur l'environnement affectent de manière significative le trait de côte. Dans ce contexte, les techniques d'enregistrement et de modélisation 3D peuvent apporter des solutions à la préservation et à l'analyse numérique des sites archéologiques en danger. Dans cet article, nous discuterons le potentiel de la photogrammétrie à courte distance en tant qu'outil pour l'étude de l'érosion des sites archéologiques du littoral. Cette méthodologie est actuellement testée dans toute une série d'études de cas situés dans le NO de l'Espagne (Galice), dans l'Ouest de la France (Bretagne) et dans le SO de la Grande Bretagne (Iles de Scilly).

Mots clés: Archéologie du littoral; modélisation 3D; Structure from Motion (SfM); changement climatique

Introduction

At present the simultaneous forces of sea-level rise, a visible effect of climate change, and human activity are threatening many coasts and islands around the globe. As a result, the vulnerability of

coastal heritage is increasingly recognised as an issue of high priority, particularly in areas such as the European Atlantic shore line, where the consequences of sea-level rise, coastal environment dynamics and human activity are significantly altering the coastline.

In Europe, Scottish and English archaeologists were among the first to warn of the increasing threat to heritage in high-risk areas (Ashmore 1994, English Heritage 1997), and several projects have been initiated focussing on the analysis and preservation of threatened coastal archaeological sites (e.g. Dawson 2013). In the west of France, current estimates indicate that more than 2500 archaeological sites are severely threatened (Daire *et al.* 2012: 169). More recently, other research programmes have been established in other European areas such as NW Spain (Ballesteros-Arias *et al.* 2013). In the Americas, several research initiatives have dealt with the problem of coastal archaeological site erosion and site vulnerability (e.g. Westley *et al.* 2011), and several authors have highlighted the fact that natural and cultural heritage conservation approaches aim to achieve very similar outcomes (e.g. Brum *et al.* 2011: 155-57; Reeder *et al.* 2012: 187-88). The need for a better understanding of this heritage, its setting and its vulnerability is thus becoming increasingly urgent (cf. Erlandson 2008).

Resulting from previous research experience on coastal and island archaeology and on heritage studies, one of the aims of the eSCOPES Project (*Evolving spaces: coastal landscapes of the Neolithic in the European Land's Ends*) is to provide cost-effective tools for monitoring threatened coastal archaeological sites. Research is being carried out on the Isles of Scilly (UK), in Morbihan and Côtes-d'Armor (Western France) and in Ría de Arousa (Northwest Spain) (Figure 1). The project, which began in May 2013 and continues until April 2015, uses Geographical Information Technologies (GIT) and close-range 3D photogrammetric techniques as cost-effective solutions to analyse, record, model and monitor selected case studies within these areas. In this paper we will focus on the methodology and on the first preliminary results of this project.

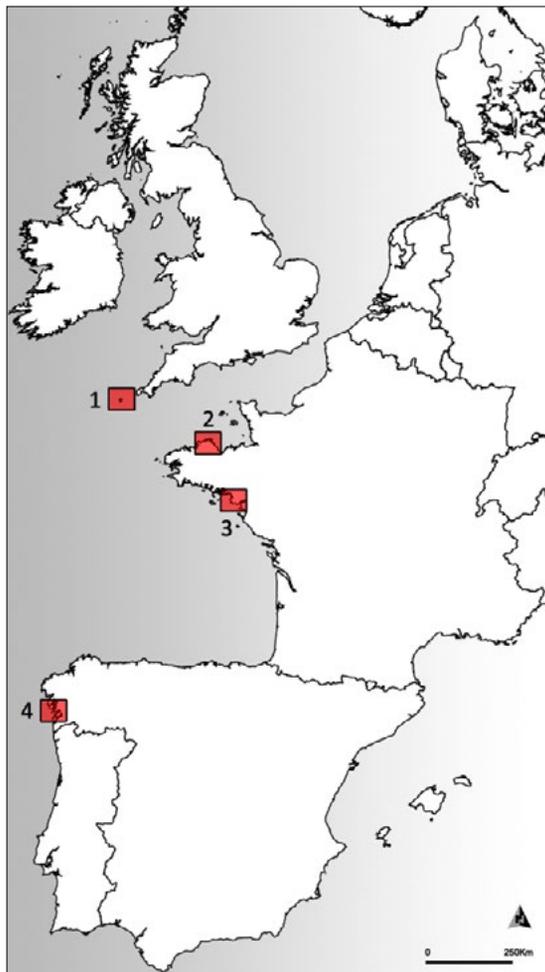


FIGURE 1. LOCATION MAP OF STUDY AREAS: 1. SAINT MARY'S (ISLES OF SCILLY, CORNWALL, UK); ISLE OF COALEN (CÔTES-D'ARMOR, BRITTANY, FRANCE); PÉNESTIN PENINSULA (MORBIHAN, BRITTANY, FRANCE); ISLE OF GUIDOIRO AREOSO (RÍA DE AROUSA, GALICIA, SPAIN).

Materials and methods

3D reconstructions for research and conservation of archaeological sites and objects are becoming increasingly common as laser and photogrammetric techniques become increasingly available and accessible to non-specialists. Several research initiatives have been launched which apply 3D imaging techniques to architectural analysis, archaeological excavation recording, rock art studies, conservation and the display of museum collections. The scale of such applications is varied, ranging from the overall recording of archaeological sites and buildings, through analysis of specific structures within sites, to the 3D modelling of individual archaeological objects.

In order to contribute to heritage vulnerability research, monitoring and management strategies

we are using modern close-range photogrammetric techniques (‘Structure from Motion’) to record, model in three dimensions and monitor changes to the structure and setting of selected archaeological sites in four areas of the European Atlantic shore line: the island of Saint Mary’s (Isles of Scilly, Cornwall, UK), the island of Coalen (Côtes-d’Armor, Brittany, France), the Pénestin peninsula (Morbihan, Brittany, France) and the island of Guidoiro Areoso (Ría de Arousa, Galicia, Spain). These sites have been chosen taking into account their location within different environmental settings, their different structural characteristics and their high vulnerability (Table 1).

Name	Region	Sub-region	Location	Type	Chronology
Coalen	NW France	Côtes-d’Armor (Brittany)	Intertidal area	Passage grave	Neolithic
Le Lomer	NW France	Morbihan (Brittany)	Rocky cliff	Gallery grave	Neolithic
Guidoiro Areoso Monument 3	NW Spain	Ría de Arousa (Galicia)	Dune	Passage grave	Neolithic
Guidoiro Areoso Monument 5	NW Spain	Ría de Arousa (Galicia)	Dune/ Intertidal area	Passage grave	Neolithic
Guidoiro Areoso Monument 4	NW Spain	Ría de Arousa (Galicia)	Dune/ high water mark	Passage grave & shell midden	Neolithic & Bronze Age
Halangy Porth beach	SW Britain	St Mary’s (Isles of Scilly)	Cliff/ pebble deposits	Settlement	Iron Age

TABLE 1. ARCHAEOLOGICAL SITES CONSIDERED FOR THE ANALYSIS.

Two different methodological approaches are being tested to evaluate the scientific value of ‘Structure from Motion’ 3D modelling to coastal archaeological erosion. Firstly, a supervised photographic record using topographic reference points – established during the first field campaign (September 2013) in the vicinity of each site with the help of a total station (Leica TCRP1203) and Differential Geographical Positioning System (DGPS, Leica GPS1200)–, combined with a series of control point measurements (Figure 2). This method is being applied to two archaeological sites located in Guidoiro Areoso (Spain), to one site located in the Pénestin peninsula (France) and to one site located on the island of Coalen (France). Secondly, a photographic record without the use of precise topographic reference positioning. In this case, the use of poles or a few distances measured in the field between two points provide a metric reference for the sites. The aim of this procedure is to evaluate the potential of integrating 3D models created from image archives that were not initially intended for use in 3D reconstruction into the general monitoring project (e.g. López-Romero 2014). This method is being applied to one archaeological site located in Guidoiro Areoso (Spain) and to one site located on the island of Saint Mary’s (Isles of Scilly, UK).

As for the photographic equipment, in both cases we are using two conventional reflex cameras (Nikon D300 equipped with a GPS receiver and Canon EOS 700D) and a compact camera (Canon G10).

The monitoring procedure involves the comparison of the resulting series of 3D models created for each site studied. The Digital Surface Models (DSM) are created using Agisoft PhotoScan Software,¹ and the editing and quantitative analysis (surface loss, surface gain) is being performed in MeshLab

¹ <http://agisoft.ru/>



FIGURE 2. DGPS POSITIONING OF REFERENCE STATIONS. PÉNESTIN PENINSULA (BRITTANY, FRANCE).

(v.1.3.3),² SAGA GIS (v.2.1.4)³ and Cloud Compare (v.2.6.0).⁴ Some issues with the automatic detection of targets as implemented in the last version of PhotoScan (v. 1.1.0) forced us to use an earlier version (v.1.0.4).⁵

Three fieldwork campaigns have been completed for the sites located in Western France and NW Spain (September 2013, March 2014 and September 2014). Only one has been completed for the site located on the Isles of Scilly (July 2014) but a second campaign and a collection of images dating from prior to 2014 will be undertaken in March 2015. Through this procedure we thus obtain a set of Digital Surface Models that provide a snapshot of the changes that have occurred between a six- and twelve-month time-scale.

Preliminary results

Even though the final results are not yet available, a number of preliminary results have already been obtained that allow us to evaluate the scientific value of our research methodology for digital recording, modelling and monitoring of coastal site erosion.

The planning of the fieldwork is essential, and we have gained a great deal of experience since the first campaign in September 2013. This aspect becomes crucial at sites such as Guidoiro Areoso or Coalen, where access is dictated and/or limited by the tidal regimes.

Over the course of the project, several changes in or around the sites have become evident. Some of these changes were apparent from one fieldwork campaign to the next, whilst others are being uncovered only through the quantitative analysis of the models.

² <http://meshlab.sourceforge.net/>

³ <http://www.saga-gis.org/>

⁴ <http://www.danielgm.net/cc/>

⁵ Targets generated with the latest (v. 1.1.0) version of PhotoScan software contain even number of sectors. Targets generated with previous versions had no such a restriction. Even after activating the “disable parity” option in v.1.1.0 (Agisoft PhotoScan User Manual, page 38) the automatic detection of such targets does not work properly. As all the targets generated for our project were created with previous versions of PhotoScan, and as automatic detection is more accurate than the manual procedure, we decided to use v. 1.0.4.

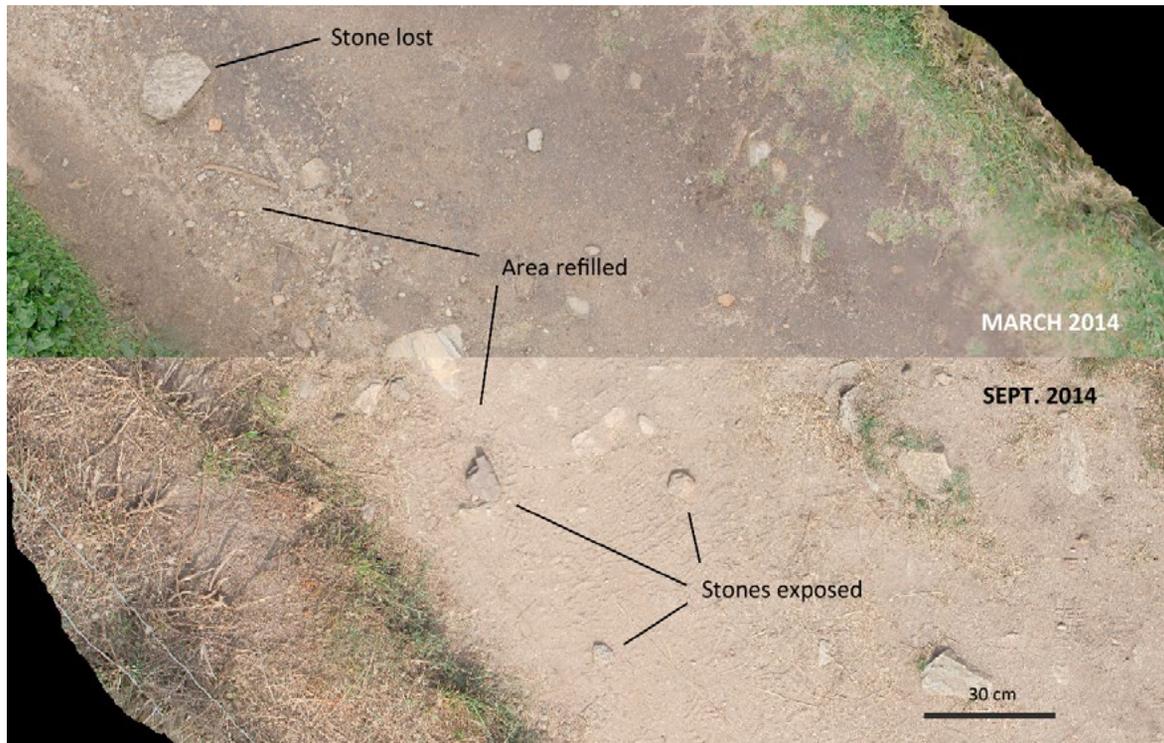


FIGURE 3. COASTAL PATH AT LE LOMER (PÉNESTIN, BRITTANY, FRANCE). COMPARED ORTHOPHOTOS FOR THE YEAR 2014.

In NW France, the site of Coalen in Northern Brittany is affected by daily tidal regimes. As a result of this, the deposition, displacement and redeposition of sediments and small-sized stones has been observed within the one-year record we have compiled. While this could be interpreted as indicative of general stability of both the site and its orthostatic components, the process is actually eroding the remains of the preserved paleosoil. Slow as it may be, this erosion will ultimately result in the displacement and final collapse of the remaining structure. Erosion at the site of Le Lomer, in Southern Brittany, is much more evident. Analysis of the remains embedded in the rocky cliff show a rapid rate of destruction of the remaining structures. This cliff is composed of soft sedimentary rocks, a fact that affects the stability of the archaeological remains. At the top of the cliff a coastal path runs parallel to stone arrangements belonging to the remains of a Neolithic mound monument. While weathering is the main factor behind the erosion of the remains on the cliff, erosion by walking along this coastal path is the main factor in altering the remains at the topmost part of the archaeological site. The combined orthophoto and 3D model (March 2014 – September 2014) is providing interesting evidence about the nature of the erosion, but also of episodes of sediment refilling and compaction (Figure 3).

In NW Spain, the exceptional intensity and duration of the 2013-2014 winter storms put the resilience of the archaeological remains located in Guidoiro Areoso to the test. This situation was exacerbated by the fragility of the dune environment (Figure 4). At Monument 4, where the responsible authorities (*Dirección Xeral do Patrimonio Cultural de la Xunta de Galicia* and *Servicio Provincial de Costas de Pontevedra*) built a dry-stone wall in 2011 to protect the visible remains, a significant amount of aeolian sediment has been lost since the project began, and a Bronze Age shell midden associated with the monument has become exposed. Similarly, the stone structure covering the earthen mound has suffered erosion on the north western side of the monument. At Monument 3, the loss of dune sediment is equally visible but has not yet been quantified as we are currently finalising the processing of the 3D model from the last fieldwork campaign (September 2014). Finally, although



FIGURE 4. GENERAL VIEW OF GUIDOIRO AREOSO (RÍA DE AROUSA, GALICIA, SPAIN), SHOWING THE LOCATION OF MONUMENT 4.

Monument 5 was destroyed before the project began, we have been able to collect a series of images of this site through a public archaeology initiative, which has allowed the creation of a 3D Digital Surface Model of this monument (as of 2011). This initiative is being coordinated by three of the authors (ELR, PMB, AGF) and by Ignacio Vilaseco Vázquez (Grupo de Estudos para a Prehistoria do NW Peninsular, Universidade de Santiago de Compostela). We have been able to collect (as of 28/01/2015) more than 280 images of this islet from the general public and from colleagues across the region. The objectives were to obtain images from private collections, dating prior to 2013, to provide answers to the public interest on the heritage of the isle and in doing so, to integrate the public into the research process. A series of tools have been created for this: a HistoryPin project,⁶ a blog and information website,⁷ a Facebook page,⁸ a Google+ page⁹ and a dedicated contact email address.¹⁰ With this information and tools, we are building an image archive that will contribute to the long term analysis of the erosion in Guidoiro, making visible the problem of coastal heritage erosion and more accessible to non-specialists.

In SW Britain, the site of Halangy Porth, St Mary's, Isles of Scilly, lies on a small eroding cliff and is also severely affected by invasive vegetation. The visible structures are complex and include archaeological remains such as fish bones, cattle bones and pottery. The eroding section was photographically recorded by a team from Cardiff University in 2005, and was compared at the time to a section recorded in the 1980's. As a result of this work, it was estimated that about 1m of coastline was lost over that period (Mulville 2005; Johns and Mulville 2011). More recently, in early 2014, a thorough photographic record of the visible structures was made by local researchers and by members of the Isles of Scilly Museum (K. Sawyer, pers. comm.) following the winter storms of that year. We performed a first photographic campaign in July 2014, resulting in an initial 3D model. The level of detail attained from this allowed us to precisely model some of the archaeological material that was visible within the eroding profile. A second fieldwork campaign is scheduled for March

⁶ <http://www.historypin.com/channels/view/54782>

⁷ <http://guidoirodixital.wordpress.com/>

⁸ www.facebook.com/guidoiodixital

⁹ <https://plus.google.com/118411261666364325005/>

¹⁰ guidoirodixital@gmail.com

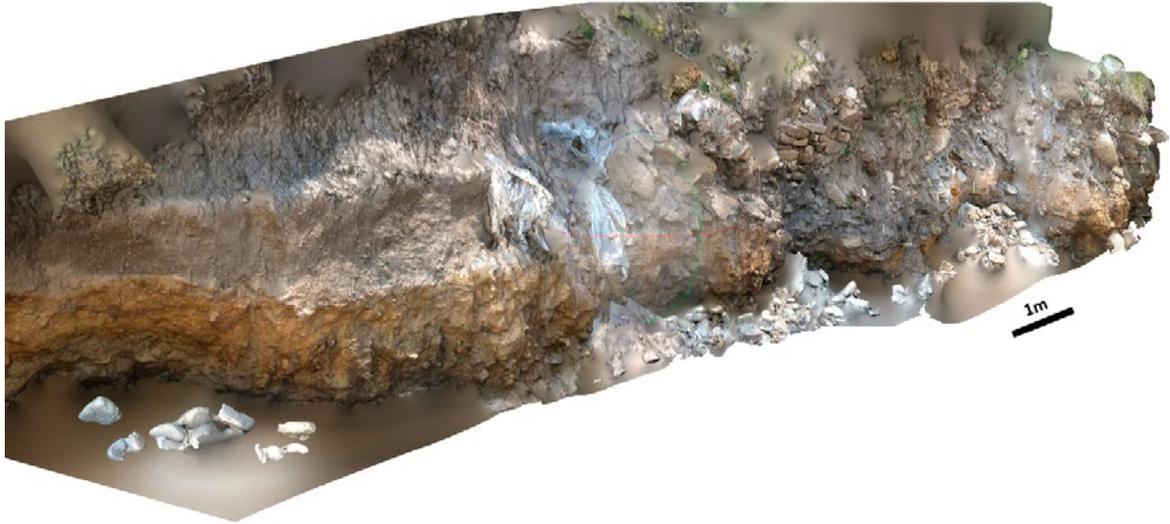


FIGURE 5. HALANGY PORTH (SAINT MARY'S, ISLES OF SCILLY, UK).
3D MODEL OBTAINED FROM PHOTOGRAPHS TAKEN IN JULY 2014.

2015. As for Guidoiro Areoso Monument 5, no topographic reference points have been recorded (Figure 5).

Seasonal changes in the vegetation cover at all the sites but one (Coalen gallery grave, located in the intertidal area) are equally apparent. These changes in vegetation have the double (and difficult to evaluate) effect of preventing some sediment loss but, at the same time, eroding specific areas across the sites.

Discussion

The use of modern close-range photogrammetry (i.e. Structure from Motion) appears to be a cost-effective way to efficiently monitor coastal archaeological site erosion. The simplification of the modelling procedure, when compared to classic photogrammetry techniques, makes it accessible to non-specialists. Though complementary to terrestrial laser scanning (3D-TLS, e.g. Lim *et al.* 2005), photogrammetry has three main advantages over that technique: it is considerably cheaper, it substantially reduces the amount of heavy equipment necessary for fieldwork, and the modelling is generated from photographs (which, in addition to their inherent scientific value, can be used to perform realistic mapping of the resulting 3D models).

Through the careful planning of the photographic recording (sufficient number of images per site, sufficient image overlapping) and of the 3D modelling procedure (geo-referencing, ground control points) it has been possible to create accurate analytical models at relative low cost (2 to 4 people per site per day, conventional photographic and topographic equipment, affordable educational software license and/or freeware). Additionally, once the procedure has been set up at a couple of sites, it is easy to replicate.

The application of this technique to archaeological research goes far beyond the initial expectations. For example, it has been possible to successfully apply the methodology to the analysis of sites where no topographic recording has been performed (Halangy Porth) or even to archaeological sites which have already been lost (Guidoiro Areoso Monument 5). The recovery of scientific information from these sites from the 3D digital analysis of ancient image archives opens new and promising perspectives from which to study coastal heritage at risk. In these cases, it is important to remember

that there is always a possibility of over- or misinterpreting some of the information provided by the models. The higher the quality, coverage and variety of the input images however, the better the quality of the modelled surface and the lower the risk of misinterpretation.

Finally, in addition to our overall results, the secondary outputs (photographic series, 3D models, difference grids) will constitute powerful tools for decision-making processes to inform best practice in managing coastal heritage in the future.

Acknowledgements

This research has been made possible through the eSCOPES Project (Evolving spaces: coastal landscapes of the Neolithic in the European Land's Ends, Marie Curie-IEF, European Commission, PI E. López-Romero). The authors would like to thank Chris Scarre (Durham University), Felipe Criado-Boado (Institute of Heritage Sciences, Incipit, CSIC) and X.I. Vilaseco Vázquez (Grupo de Estudos para a Prehistoria do NW Peninsular, Universidade de Santiago de Compostela) for their support and Loïc Langouet (AMARAI, France) for facilitating additional photographic equipment.

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Fast 3D recording techniques: a low-cost method for the documentation and analysis of scattered architectural elements as a part of the EMCHAHE project

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Abstract

The Marie Curie CIG EMCHAHE project Early Medieval Churches: History, Archaeology and Heritage (2013-2017) focuses on the research of archaeological and historical remains of early medieval rural churches and on enhancing their value for cultural management in Galicia (Northwest Spain), by applying different perspectives. The project aims at studying a large number of churches within their wider context, rather than studying each one in detail. In this paper we propose a methodological workflow for a 3D recording all these buildings in a precise and practical way, thereby creating a 3D documentation that will serve as the basis for their stratigraphic analysis and the dissemination of the results.

Keywords: *Early Medieval period; Galicia; Archaeology of architecture; 3D documentation; Structure from Motion (SfM)*

Résumé

Le projet Marie Curie CIG EMCHAHE Early Medieval Churches: History, Archaeology and Heritage (2013-2017) aborde l'étude des restes archéologiques et historiques des églises rurales d'époque médiévale en Galice (Nord-ouest de l'Espagne), ainsi que celui de sa valeur pour la gestion culturelle, sous différentes perspectives. Ce projet poursuit également toute une variété d'objectifs, dont l'analyse d'ensemble d'un grand nombre d'églises face à une analyse restreinte et détaillée de chacune de ces entités. Dans cet article nous présenterons une démarche méthodologique permettant un enregistrement 3D rapide, précis et efficace de ces architectures, ainsi que les principes d'une documentation stratigraphique tridimensionnelle et sa divulgation.

Mots clés: *Haut Moyen Age; Galice; archéologie du bâti; relevé 3D; Structure from Motion (SfM)*

Introduction

Early medieval churches: history, archaeology and heritage

This work forms a part of the project *Early Medieval Churches: History, Archaeology and Heritage* (EMCHAHE) based at the University of Santiago de Compostela (Spain) and funded by a European Marie Curie Career Integration Grant (Grant agreement – PCIG12-GA-2012-334068, European Commission, FP7). The EMCHAHE project, led by José Carlos Sánchez-Pardo, runs from 2013 to 2017, and aims to analyse, from an interdisciplinary perspective, the archaeology and history of early medieval rural churches and their value in terms of cultural management in Galicia (Northwest Spain) (Sánchez-Pardo & Blanco-Rotea 2014). Specifically, it has two major goals:

- Firstly, to generate new archaeological and historical knowledge on the social dynamics in such a peripheral area of Europe during the period of transformation that lasted from the fall

THE THREE DIMENSIONS OF ARCHAEOLOGY

of the Roman Empire until the peak of the feudal system (5th-11th centuries), by studying the remaining evidence of the religious buildings from this period,

- Secondly, to learn how to re-direct all this knowledge towards a proper and effective management and communication of the important and relatively unknown heritage value of the remains of these buildings at architectural, archaeological, artistic, documentary or even toponymic level.

Both objectives are interrelated, as only an adequate historical knowledge allows for correct heritage management.

The project, rather than focusing on the individual monumental examples of early medieval architecture, intends to study a large number of churches from a global perspective, in order to obtain new evidence of the early medieval churches in this region, to compare construction techniques and chronologies, and to identify their founders as well as the areas in which they are distributed. An initial collection of data for the project recorded 265 churches with possible early medieval archaeological evidence in Galicia. However, given the impossibility of studying this number of churches, 3 case-study areas were chosen (Figure 1):

- Area of Lugo (2943 km²) which contains 61 churches to survey,
- Area of Iria-Deza (1082 km²) with 31 churches to survey,
- Area of Ourense (1820 km²) with 36 churches to survey.

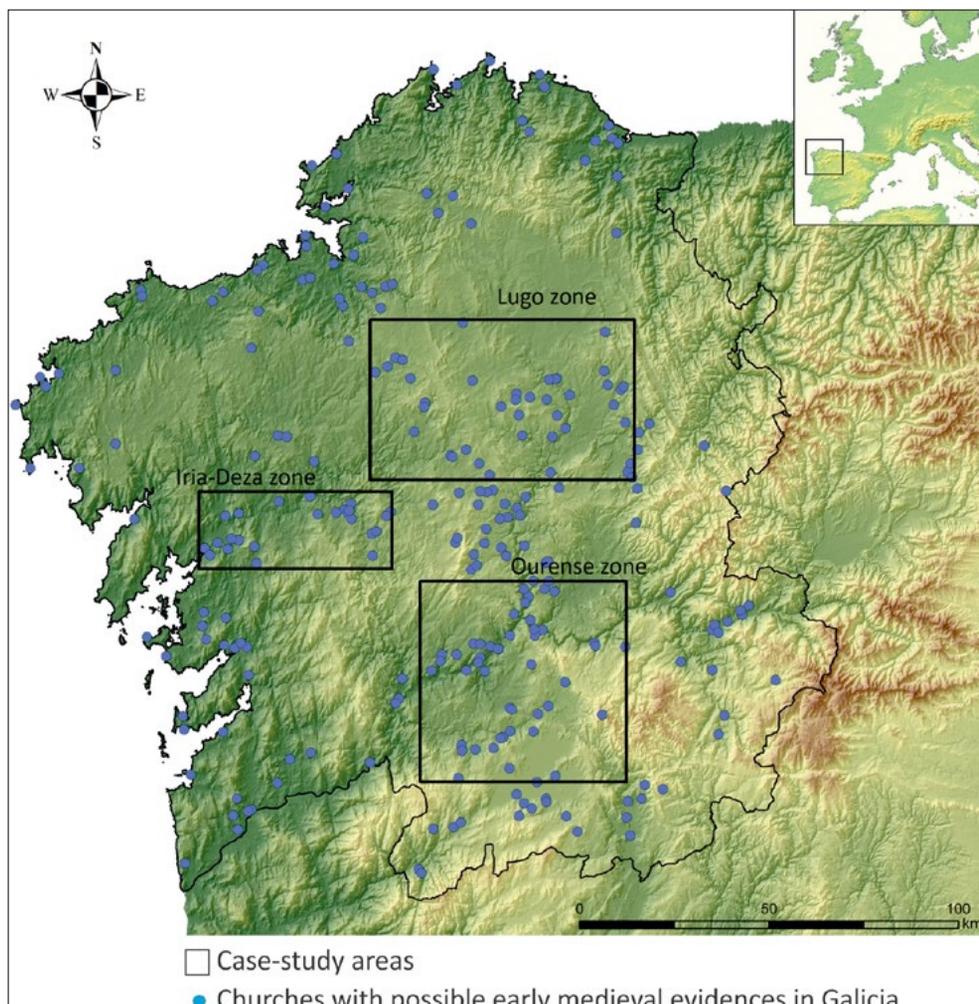


FIGURE 1. EMCHAHE CASE STUDY AREAS IN THE NW IBERIAN PENINSULA.

One of the main challenges facing the project is to propose a suitable methodology for achieving these ambitious goals. In this paper we summarise the methodological proposal we have applied, which has to draw on limited resources while being capable of overcoming a series of important methodological hurdles.

One of these hurdles is the territorial scale, which implies the analysis of a large number of sites scattered throughout three rural areas of Galicia. This dispersion increases the difficulty and cost of accessing and studying each church. Another is the difficulty related to identify and analyse evidence of early medieval churches, which is even more problematic due to the existence of several architectural modifications and reconstructions. Therefore, it was necessary to apply a technique for accurately documenting churches in the field including graphic and geometric information to then carry out a detailed study (including the stratigraphic analysis of walls, the identification of construction techniques, etc.) at the lowest cost.

At an archaeological level, the project is characterised by a wide perspective, strongly linked to the approaches used in Landscape Archaeology but combined with the stratigraphic analysis of both buried and standing remains of early medieval churches.

Approaches to the study and geometric survey of early medieval churches

A workflow has been designed which makes it possible to analyse this large number of cases in a fast, systematic way, with enough detail to identify the elements that characterise the possible early medieval evidence. To achieve this, the EMCHAHE methodology is based on the application of two successive working phases:

1. A prospection phase (extensive strategy, Figure 2) in which religious buildings are identified which show signs of having originated in the early Middle Ages, such as their toponyms and the presence of isolated elements or phases from this period in the structure itself. During this stage, the analytical methods and strategies applied are:
 - a. Reviewing documentary sources: examining books and documents to identify churches from this period (Sánchez Pardo 2012a; 2012b).
 - b. Creation of a GIS: georeferencing the documented evidence.
 - c. Selection of study areas: taking into account the results of the two previous strategies, the scope and resources of the project.
 - d. Architectural survey: carrying out prospection work in the selected areas to identify churches possibly containing remains earlier than the 11th century and other archaeological elements associated with them, such as necropoleis or individual sarcophagi. This methodology was developed by Blanco-Rotea (2003; 2008; 2009; 2011), López Cordeiro (2009), Quirós and Gobbato (2004) and Sánchez Zufiaurre (2004; 2007).
2. An analytical phase (intensive strategy, Figure 2), in which each case is analysed in detail with the aim of carrying out a comprehensive study of early medieval churches. This phase includes the following steps:
 - a. Documentation of early medieval remains: recording and analysing early medieval elements which are decontextualized or which have been re-used in later churches or buildings in the surrounding area.
 - b. Geometric documentation of individual elements and churches: 3D registration of the churches and elements analysed using a technique that is cost-effective and sufficiently accurate (Blanco-Rotea *et al.* 2014).
 - c. Stratigraphic analysis of walls: a methodology related to the archaeological prospection work, carried out in order to identify the construction sequence for the selected buildings and to identify the presence of any early medieval element.
 - d. Cluster analysis: identification of patterns and a chrono-typological analysis of the built structures.

Study approach in EMCHAHE

The methodological strategy in EMCHAHE is based on the application of two successive work phases:

- **Prospecting phase (extensive strategy)**

- Revision of documentary sources
- Creation of a GIS
- Selection of study areas
- Architectural survey

- **Analytical phase (intensive strategy)**

- Comprehensive study of the early medieval churches :

- Documentation of the early medieval remains
- Geometric documentation of individual elements and churches
- Stratigraphic analysis of paraments
- Cluster analysis
- Analysis of mortars and bricks
- Analysis of lapidary inscriptions and markings
- Territorial analysis

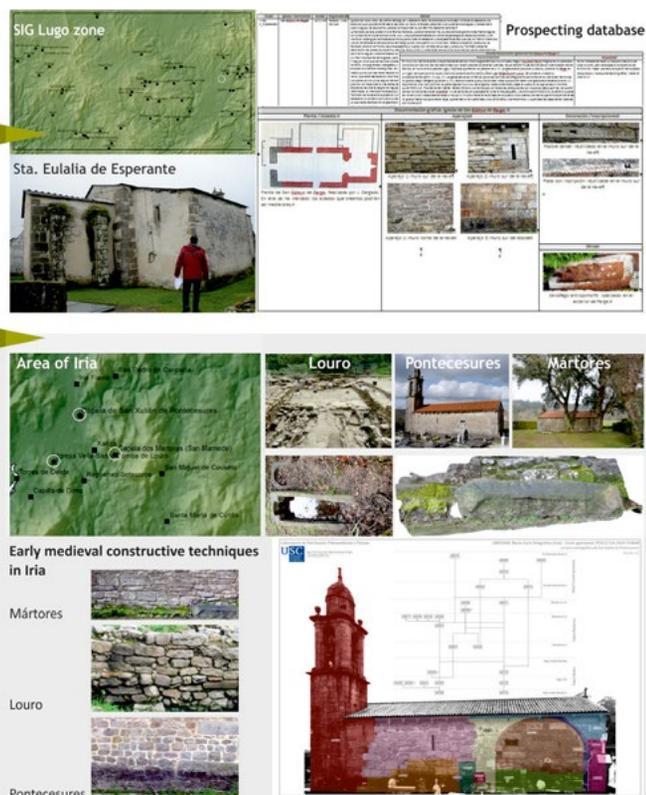


FIGURE 2. SUMMARY OF THE DIFFERENT TECHNIQUES APPLIED IN THE PROSPECTIVE AND ANALYTICAL PHASES OF EMCHAHE.

- Analysis of bricks and mortars: characterisation and dating of mortars using optically stimulated luminescence, and of bricks using thermo-luminescence (Blanco-Rotea *et al.* 2009; Sanjurjo-Sánchez *et al.* 2010).
- Analysis of lapidary inscriptions and markings: a series of lapidary inscriptions have been found, some of which are unpublished, which will be studied as their dating will serve as a chronological indicator for the stratigraphic analysis.
- Territorial analysis: the study of the churches will be compared with an analysis of the surrounding territory, in order to see how they are related to the processes of forming medieval landscapes (Blanco-Rotea 2011).

A 3D recording of the elevations of the selected churches was carried out (Figure 3). A detailed analysis of a large number of churches was needed, which included recording elevations and drawing ground plans, identifying changes in materials, specific elements, boundaries of stratigraphic units, etc. In order to choose the most appropriate methodology we considered the requirements of our project:

- Great portability of the equipment due to the dispersion of the sites and constraints in terms of time and money;
- Easy integration into the fieldwork and possibility to be carried out by one person without additional resources;
- Precise representation of the churches' elevations and volumes, with a precision to the centimetre range.

Close range photogrammetry, specifically the Structure from Motion (SfM) technique (Agarwal *et al.* 2011; De Reu *et al.* 2013; Verhoeven 2011), resulted to be the most suitable methodology as it

Geometric Survey for a 3D Record

Challenges and Requirements:

- Detailed analysis of a large number of churches: to represent elevations and plants, identifying demarcation of materials, specific elements, contours of stratigraphic units, etc.
- Great agility is required due to the dispersion of the sites and the time and economic constraints.
- We need a technique that does not involve additional resources and that can be easily integrated into the fieldwork by the archaeologist
- A technique that allows to correctly represent the elevations and volumes of the studied churches. Moreover, it has to enable centrimetric measurements.

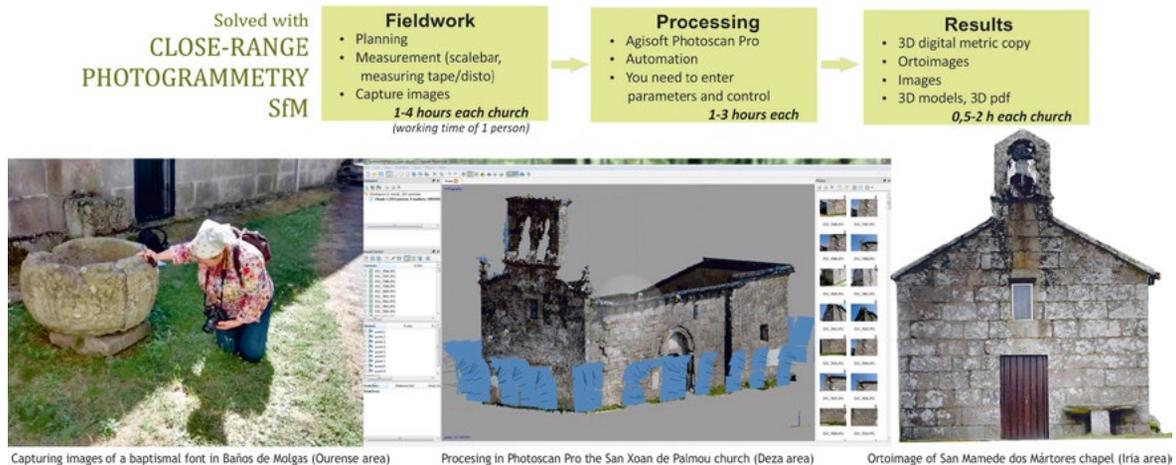


FIGURE 3. SUMMARY OF THE WORKFLOW OF THE 3-D RECORDING TECHNIQUE IN EMCHAHE.

provided an portable, low-cost solution for this type of 3D recording. We used the *Agisoft PhotoScan Pro* v1.0 software,¹ which makes it possible to automate alignment, reconstruction and scaling of the 3D point clouds and 3D meshes, in order to obtain metric 3D models, orthoimages, etc.

We chose this technique because it can be easily integrated into the workflow of the EMCHAHE team and into the methodologies used in the project. A precise knowledge of the recorded structure and of the steps needed for the successful application of this technique are required, namely gathering the data, taking the necessary images and measuring the structures using a measuring tape or distance measurer in order to be able to scale the 3D models.

The processing of all these data was carried out in an automatic way, although in some particularly complicated cases it was necessary to intervene in the process, introducing additional reference points and checking the quality of the results obtained. Some of these problematic cases included churches with highly irregular ground plans, buildings where a very narrow field of view made it difficult to obtain the necessary images, and situations in which it was difficult to fit two façades in the same image. In these cases, a discontinuity in the data points and the impossibility to create a closed volume could be encountered, but additional control points were introduced to overcome these problems.

From 3D data acquisition to the results

Close-range photogrammetry is a low-cost technique that allows for a correct, accurate and detailed record of each church, as a basis for the visualization, analysis and reconstruction of the buildings.

¹ AgiSoft LLC. 2014, <http://www.agisoft.com/>

After several months of fieldwork and post-processing, we documented a large number of churches, and were able to speed up the fieldwork in several ways in comparison to the previous method of quick documentation (creating photo-mosaics of every wall, taking all measurements with a tape in every churches and significant elements, etc.) and make the results more accurate. The most essential result for the analytical phase is the creation of orthoimages of the walls (Figure 4). These images are used as the basic graphic element to identify and analyse the different construction phases of the building, as well as to draw the result of the stratigraphic analysis (Figure 7). The orthoimages make it possible to represent the geometric shape and appearance of the analysed churches, as well as the materials used to build them, since the whole of the surface is represented unobstructed and with a real texture, orthographically and at the same scale, without any of the deformation, errors or effects caused by lenses or perspective found in photography. In order to use the orthoimage as a map with metric value, it must be scaled. In this project, this has been achieved by means of a number of measurements taken in every church. Then, other extra measurements were taken to verify if the orthoimage was correctly scaled. Moreover, the creation of orthoimages makes it possible to review the analyses carried out in the field and to take new measurements without having to return to the site.

The application of this technique also allows the creation of 3D models (Figure 5), which makes it possible to record the entire geometry and analyse in the office properties of the structure such as its volume, texture, its relationship with the environment, etc. Such 3D models increase the possibility

San Mamede dos Mártores chapel



FIGURE 4. DIFFERENCES IN THE SOUTHERN ELEVATION OF THE CHAPEL OF SAN MAMEDE DOS MÁRTORES: TOP, A PHOTO OF THE ELEVATION WITH A TREE THAT HIDE S PART OF THE SURFACE, AS WELL AS SUFFERING FROM THE TYPICAL DEFORMATION SEEN IN PHOTOS; BOTTOM, THE ORTHOIMAGE OF THE SAME ELEVATION, WITHOUT ANY DEFORMATION OR THE TREE IN FRONT OF THE FAÇADE.

Santo Tomé de Tordea church

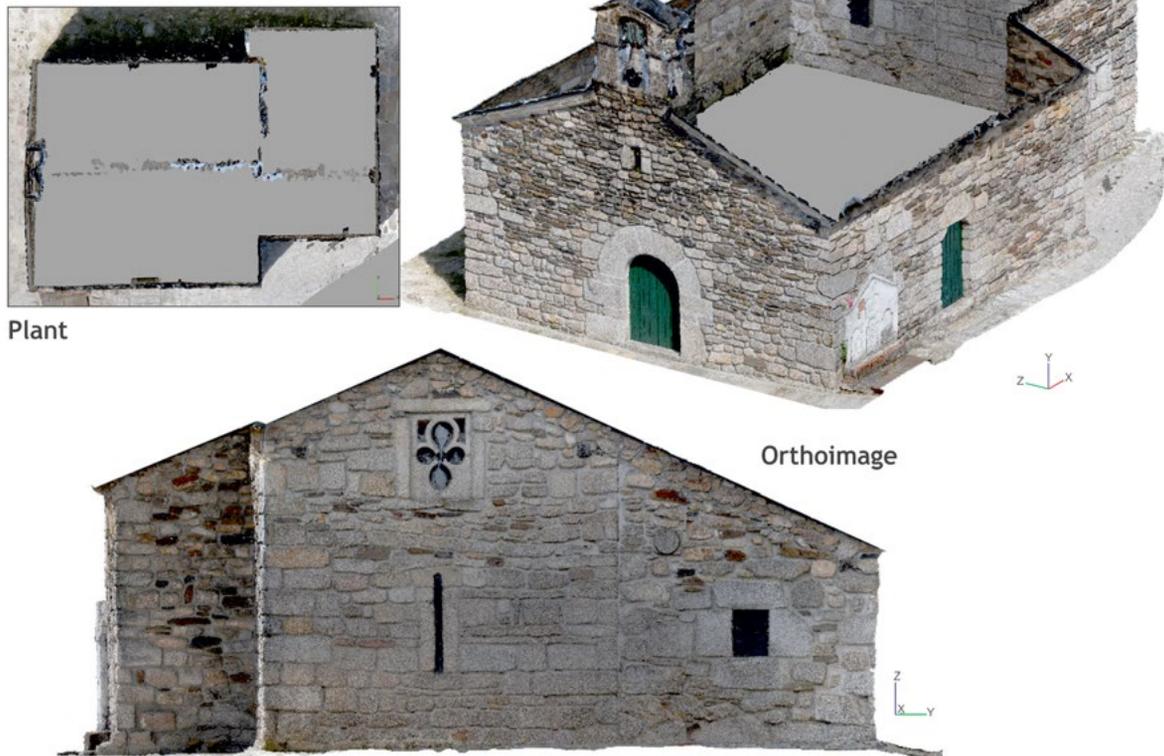


FIGURE 5. DIFFERENT VIEWS OF THE 3-D MODEL OF SANTO TOMÉ DE TORDEA CHURCH.

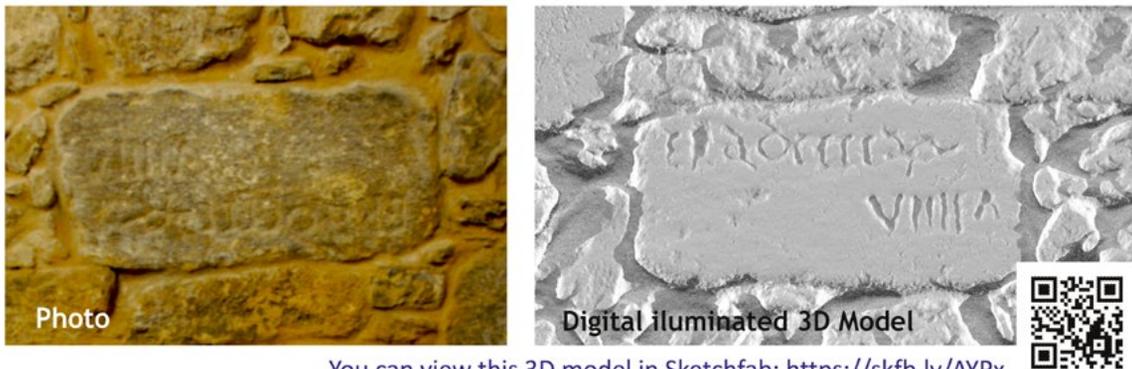
of representation not only because elevations, plans, sections, perspective views and interactive 3D models can be obtained, but also because the construction phases of the buildings can be represented in 3D and 3D reconstruction hypotheses can be created.

A challenge of the application of terrestrial photogrammetry is related to the necessity to cover the entire geometry of the building with pictures. Elements that are too high (such as bell towers or roofs) are not properly represented with photographs taken from the ground and therefore raised elements such as drones or scaffolding have to be used in order to properly record the parts that are not visible otherwise.

Another important aspect of this technique is the possibility of achieving a high level of detail. While carrying out the project, we documented a number of individual elements in detail (Figure 6), as they allow us to date the construction phases of the building in which they are found, or provide us with information about previous periods. This is the case of elements such as inscriptions, decorations, windows, baptismal fonts or sarcophagi. In this case, therefore, close-range photogrammetry makes it possible to document entire buildings or specific elements at different scales using the same equipment and workflow.

The advantages of using this technique relate to (1) the rapidity of the recording (e.g. in the case of the sarcophagus from San Mamede the photos were taken in 20 minutes and one hour was spent for the editing process); (2) the high level of detail that can be achieved (details such as inscriptions, reliefs, prints, erosion, that cannot be observed in reality can be better appreciated in the 3D model);

Inscription in San Martiño de Armental church



You can view this 3D model in Sketchfab: <https://skfb.ly/AYPx>

Sarcophagus cover in San Mamede dos Mártores chapel



You can view and download this 3D model in pdf here: <http://hdl.handle.net/10347/11401>

FIGURE 6. EXAMPLE OF THE HIGH LEVEL OF DETAIL THAT CAN BE ACHIEVED USING THIS 3-D RECORDING SYSTEM; 3D MODEL IN SKETCHFAB: [HTTPS://SKFB.LY/AYPX](https://skfb.ly/AYPx); 3D MODEL IN PFD: [HTTP://HDL.HANDLE.NET/10347/11401](http://hdl.handle.net/10347/11401)

(3) the simplification of the dissemination process since formats such as 3DPDF or platforms such as Sketchfab make it possible to publish and interact with the model.

In order to achieve a satisfactory result, a good data recording in the field is necessary (high-quality images, sufficient overlapping, correct lighting, etc.). As a final note, it must be stressed that, although the recording phase is quite fast, the post-processing phase implies an effort that must be taken into account: the photographic record has to be revised in order to eliminate poor quality photographs; the process of creation of 3D information has to be controlled before extracting the results. Although Agisoft PhotoScan software helps to automate and speed up the photogrammetric process, it is necessary to invest some effort for proper results. In our case, we estimate that for each registration hour, around five hours are needed for processing the results (depending on the available computer equipment).

Conclusions

Initially, EMCHAHE did not envisage the use of any geometric documentation method for heritage assets other than conventional photography, as the wide-scale focus of the project was directed towards the understanding of churches within a larger context rather than the detailed study of each one.

However, the complexity of the stratigraphy documented in many of the buildings and the need to individually understand the characteristics of construction phases, bonding materials, decorative

items or typologies employed in these first Galician churches, required a more detailed study of the buildings. This meant that it was necessary to find a way of representing them using a system that was fast, cheap and easy to use.

The project is still ongoing, but we have obtained a number of methodological conclusions and benefits from this workflow. Firstly, the photogrammetric methodology developed has proved to be very effective and practical for the needs of a large-scale study like this one. It is a portable working method to be used in the field, involving very light recording equipment (reflex camera, scale bar, distance meter, etc.), and makes it possible to record all of the most essential information in just a few hours in order to obtain a suitable 3D record of the churches being analysed.

This technique also has the necessary flexibility to adapt to the characteristics of each church that needs to be documented, both because the same technique can be used to document the entire building and specific details, and because it can be adapted to more complex conditions (restrictions in documenting parts that are not visible from the ground, dark areas etc.) although in these cases more on-site work is required.

Another important aspect for the project is that this is a low-cost technique in comparison with other geometric documentation methodologies. It can be used in this case because the requirements of the project in geometric terms are quite basic: it is necessary to obtain models where the elements and surfaces of the exterior elevations can be measured on a centimetre scale, as well as to represent elevations where it is possible to be able to perform the analysis of each building.

A clear idea about the requirements and the outcome of the geometric documentation project makes it possible to identify and apply the necessary technique, and therefore to adjust its costs, especially when the resources are limited. The costs will rise if it becomes necessary to georeference the buildings or to obtain records on a millimetre range (which would require a topographic survey using a total station or a GPS), or to record both the interiors and exteriors of the buildings. The buildings

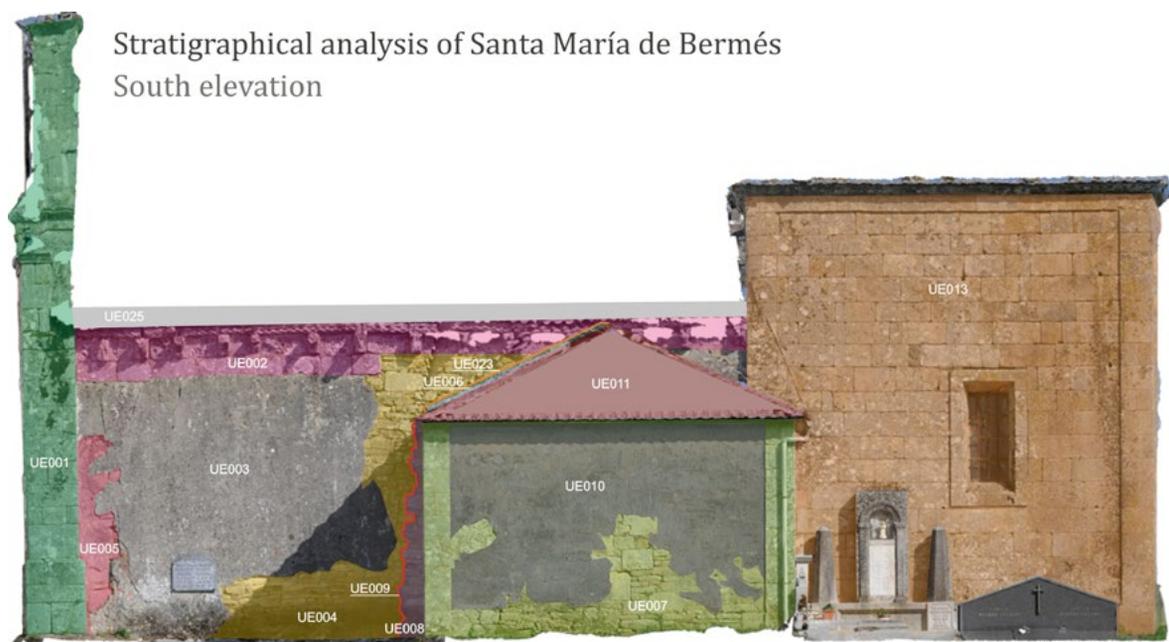


FIGURE 7. WE USE THE RESULTS OF PHOTOGRAMMETRY NOT ONLY TO SHOW THE CHURCHES, BUT ALSO TO ANALYSE AND PRESENT THE RESULTS.

selected for this project are small; therefore their complete elevations can be documented taking photos from ground level, except for bell towers, spires, and sometimes their roofs and elements in high positions. The roofs have only been represented in a few cases. To obtain such information, it would be necessary to use other devices such as UAV (Peinado *et al.* 2014), scaffolding or even Terrestrial Laser Scanning, which make it possible to record higher zones in detail without losing any precision because of the height of the building.

The digital copy of the building that is created using photogrammetry can then be used to make decisions or recover information without returning to the site, such as obtaining measurements of specific elements, or analysing the details of certain constructive or decorative elements. It can also be used as the basis for the final phase of the project, which involves presenting the results of the research and proposals of reconstructive hypothesis that not only evaluate the stratigraphy in 2D, but also make it possible to reconstruct the volumes of ancient buildings that have survived in the interior of the preserved churches selected for this research. This quick 3D record therefore improves the heritage outreach in presenting the results and reconstructing hypotheses, a fundamental aspect of a project that focuses on communication via the social networks² or via electronic publications.

Technical Sheet EMCHAHE project

EMCHAHE: “Early Medieval Churches: History, Archaeology and Heritage” (2013-2017), Marie Curie Career Integration Grant (Grant agreement – PCIG12-GA-2012- 334068)

- Director of the EMCHAHE Project: José Carlos Sánchez-Pardo (USC);
- PI of the EMCHAHE Project: Marco V. García Quintela (USC);
- Director of archaeological works: Rebeca Blanco-Rotea (USC);
- 3D Documentation support: Patricia Mañana-Borrazás (Incipit, CSIC).

The poster presented at UISPP-Burgos 2014 can be downloaded here: <http://hdl.handle.net/10347/11404>

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² The project has a Facebook page at <https://www.facebook.com/EMCHAHE>.

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Using airborne laser scanning and historical aerial photos to identify modern age fortifications in the Minho Valley, Northwest Iberian Peninsula

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Abstract

We present a trans-disciplinary research project to study fortified landscapes from the Modern Age (17th century) on the Galician-Portuguese border, in the north-west of the Iberian Peninsula. We use different geospatial techniques, in particular aerial photogrammetry, airborne LiDAR and GIS, for landscape analysis. This approach has allowed us to locate and document some of these fortifications, to assess their conservation status and to understand their relationship with other fortified elements.

Keywords: *LiDAR, Photogrammetry, Landscape Archaeology, Modern Age Fortifications*

Résumé

Dans ce travail nous présentons une approche transdisciplinaire pour l'étude des paysages fortifiés de l'époque Moderne (17ème siècle) au long de la frontière galicienne-portugaise. Notre approche est basée sur l'utilisation de différentes techniques géospatiales, plus notamment la photogrammétrie aérienne, le LiDAR aéroporté et les Systèmes d'Information Géographique, pour l'analyse du paysage. Cette approche nous a permis de trouver et de documenter certaines de ces fortifications, d'analyser leur état de préservation et de comprendre leur rapport avec d'autres sites fortifiés.

Mots clés: *LiDAR, photogrammétrie, Archéologie du Paysage, fortifications de l'époque Moderne*

The project: modern age fortified landscape in Galicia

Modern Age Fortified Landscapes is a transversal and self-sustained project from the Institute of Heritage Sciences (Incipit) of the Spanish National Research Council (CSIC), with the collaboration of the Laboratory of Heritage, Palaeoenvironment and Landscape (University of Santiago de Compostela), directed by Rebeca Blanco-Rotea. The project investigates Modern Age Galician fortified landscapes from the perspective of Built Heritage Management, combining several links in the Cultural Heritage Value Chain. This is an interpretative chain which establishes a series of successive instances, from the identification of cultural heritage through to its reception by society. Information from different archaeological projects has been incorporated. One of the initial projects on this topic was FORTTRANS, the Executive Plan for Trans-frontier Fortresses in the Lower River Miño in 2003, sponsored by the General Directorate for Cultural Heritage of the regional government of Galicia and directed by the architects Antonio Hoyuela, Fernando Cobos and Jaime Garrido, in which our team carried out the archaeological work (Cobos & Hoyuela 2005; Vecoña 2006; Blanco-Rotea & García Rodríguez 2005; Blanco-Rotea 2013).

Taking Blanco-Rotea's PhD thesis "Architecture and landscape. Border fortifications in Southern Galicia and Northern Portugal" (Blanco-Rotea 2015) as a starting point, we continued to investigate

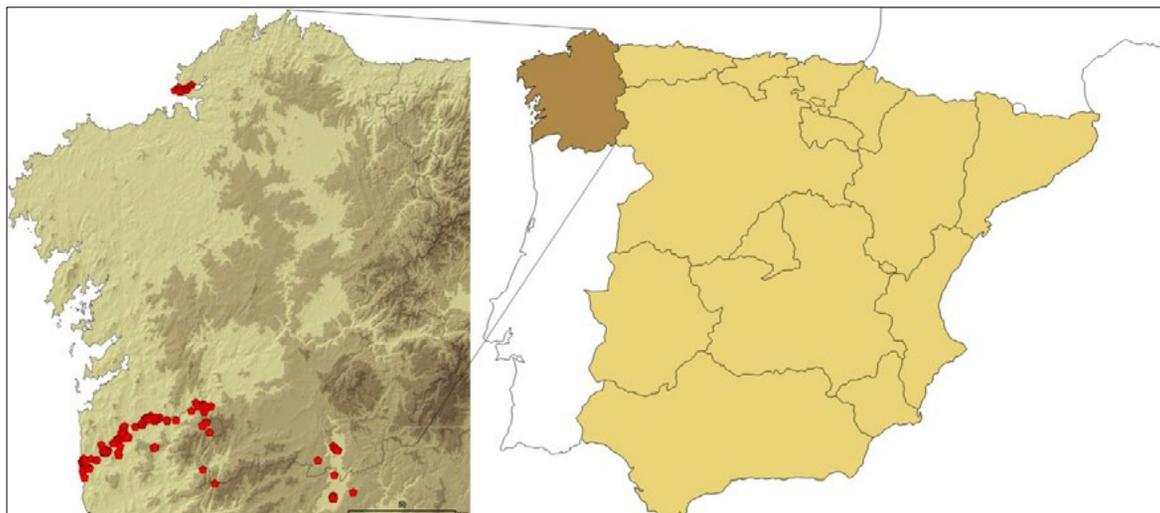


FIGURE 1. AREAS STUDIED AS A PART OF THE MODERN AGE FORTIFIED LANDSCAPES PROJECT (NORTH-WEST IBERIAN PENINSULA), SHOWING THE DIFFERENT FORTIFICATIONS.

the relationship between the fortified architecture of this period and the construction of a cultural landscape that has now become a milestone of the Galician cultural heritage (Figure 1).

Many of the fortifications built in this period have a number of specific characteristics that hinder their visibility and detectability in the field. Therefore we have combined methodologies from different disciplines such as the Archaeology of Architecture and Landscape Archaeology, so that we could explore different tools that would allow us to locate these fortifications, make them visible, identify their structure and geometry and characterize them archaeologically at a micro and macro level (Figure 2).

Study approach

From the architecture to the landscape

Our methodological approach for with the study of fortified landscapes is based on three main stages (Figure 2). The first stage, involving the planning of the work, which involves analysing the characteristics of the study we are going to carry out and defining the working schedule, thereby identifying aspects such as the scope of the study, the type of archaeological elements with which we will be working to define the conceptual model of entities of the reality to be studied, or the most suitable methods for carrying out the identification, characterisation and evaluation of the elements.

The second stage, which we will elaborate on in this paper, consists of the identification, characterization and evaluation of the archaeological and heritage elements that comprise the fortified landscape, on three spatial scales: macrospatial scales (the landscape), semi-microspatial scale (the fortification and its surroundings) and the microspatial scale (the inside of the fortification and its component elements). The scope of this analysis is determined by the previous stage, namely the characteristics of the project. The aim of this stage is to produce an inventory of the archaeological and heritage elements that are included in each of these three spatial levels, meaning it is necessary to identify, characterise and evaluate them at each level.

Our methodological approach is tailored to the specific type of heritage under study. Our starting point in developing the methodology was the interdisciplinary, multi-scale approach of Landscape

From the architecture to the landscape

Analysis of archaeological and patrimonial entities

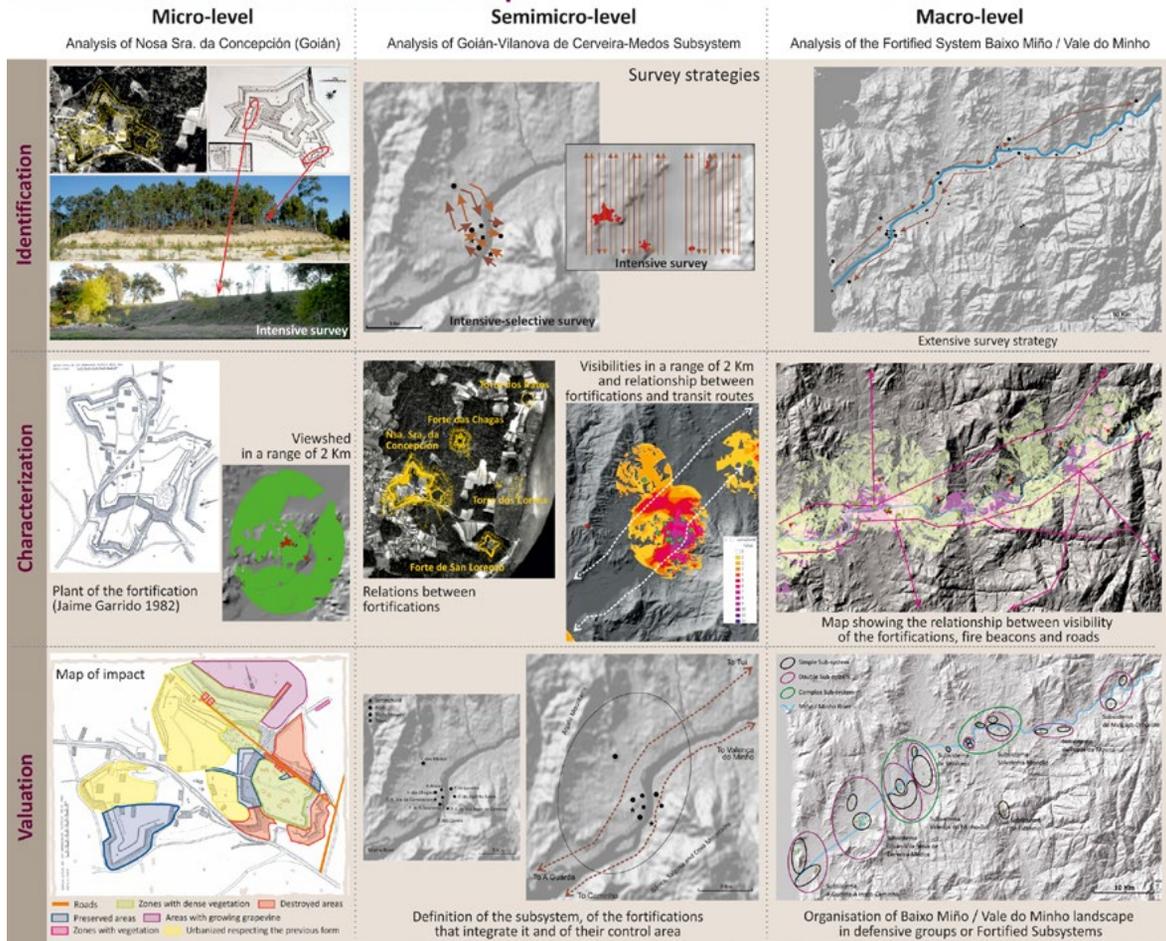


FIGURE 2. SUMMARY OF THE ANALYSIS OF ARCHAEOLOGICAL AND HERITAGE ELEMENTS.

Archaeology (archaeological survey, formal analysis of architectural space, analysis of mobility) and Archaeology of Architecture (stratigraphic reading of walls, space syntax, analysis of the historical mapping). This allowed us to identify the constructive process of the fortifications, to study the relationships between the parts of a fortification and identify the reason why it was built, taking into account the art of fortification in the Modern Age. However, we were also interested in a larger scale, namely in the relationships between fortifications and groups of fortifications, or between groups of fortifications and their surrounding landscape. Therefore, it was essential to integrate the three spatial scales: micro, semi-micro and macro. The approach also had to define the elements which would be studied in each of the three scales, and the tools that would be used to analyse them.

In other words, the identification, characterisation and assessment of the elements can vary in each of the analytical scales, as the type of entities comprising them and the relationships between them also vary, meaning that the methodologies used to suitably characterise and evaluate them may also be different.

As can be seen in Figure 2, the analysis of the archaeological and heritage elements is also divided into three stages, which are repeated in each of the three analytical scales. The Identification stage consists of identifying the entities, in this case, which comprise the landscape being studied, in order to produce an inventory. One of the methodological tools used in this stage was archaeological

survey,¹ carried out intensively on the microspatial scale, with which we have been able to identify the fortifications in the field and preserved parts; intensively-selectively (this technique consists of the recognition in the field of selected parts inside the area of study in which it is of interest to carry out a survey of greater intensity. In this strategy the visibility is not necessary between the members of the team and the trajectory goes towards elements emphasized in the landscape) and intensively (in contrast to the previous one, in this strategy the intervisibility is necessary between the members of the team, and the trajectory is organized/structured to include visually the totality of the surface to survey) on the semi-microspatial scale, allowing us to identify the groups of fortifications and the relationships between them; or extensively on the macrospatial scale (this technique consists of a general recognition of the area of study to identify the visible heritage entities), which allows us to observe the relationships between the groups of fortifications (we identify a group between those fortifications that have a spatial relation of visibility or functionally) and between them and the territory. The characterisation stage is aimed at “achieving a classification of the components of a landscape on all working scales, from the internal structure of each component (if it is viable to define it) through to the organisation of all of the components of a larger study unit” (Barreiro 2000: 32). At micro level, two of the tools used were geometrically documenting the elements and analysing their visibility from their surroundings, the analysis was made in situ and there was done a theoretical calculation of the visual basin on the digital elevations model; at semi-micro level, the tools used were geo-referencing the ground plans of fortifications, analysing aerial photographs and analysing the visibility of the fortifications from their surroundings and between the forts, as well as their relationship with transit routes. In this case, we did a study of the historical transit routes from Medieval Age until the end of the 18th century, to observe its relationship with the fortifications. The georeferencing of the routes has allowed us to observe its spatial relationship with the forts, as well as the visibility from the fortifications towards the routes. Finally, the evaluation stage is aimed at attributing the elements included in the inventory with an archaeological and heritage value, by diagnosing their *heritage situation* and *archaeological assessment*. The first consists of determining the current state of preservation of the element, while the second consists of determining its quality, i.e. its archaeological value as an instrument for the reconstruction of history (Barreiro 2000: 37) based on a summary of the evidence, an analysis of the surrounding area and defining hypotheses about the significance of the evidence within its surrounding area. To establish these hypotheses we have taken into account different aspects such as the position of each fortification within the group, their relationship with other fortifications or with the main fortification within the group, but also the areas of accumulation of visibility, as the road network or the Minho river. All these aspects have been taken together to understand the relationship between the fortifications and between these and the territory. On a microspatial scale, impact maps and maps showing the state of preservation of the fortification were made; on the semi-microspatial scale, the defensive subsystems or ensembles were defined, their component fortifications and the areas they controlled, while on a macrospatial scale, the way in which the subsystems were organised throughout the landscape of the Miño Valley, allowing us to access the landscape itself.

Finally, the third stage, interpreting the fortified landscape, consists of interpreting each of the elements that comprise the landscape on the different scales, from the landscape itself through to the structure, or vice-versa. In order to complete this interpretation, we place the characterised and assessed field data in the historical context in which a fortified landscape is created. This allows us to their interactions with previous or subsequent fortified landscapes, and their transformations. All this has enabled us to define a theoretical model of the fortified landscape of the Minho Valley which represent the principal entities, the relationships between these entities (which are interpreted as groups of fortifications or subsystems), between the subsystems and between these and the territory (which are interpreted as the fortified landscape) (Figure 3).

¹ For this study we have used four complementary techniques of archaeological survey proposed from the Incipit: the extensive survey, intensive – selective survey, intensive survey and of full coverage survey (Amado & Barreiro 2004: 241).

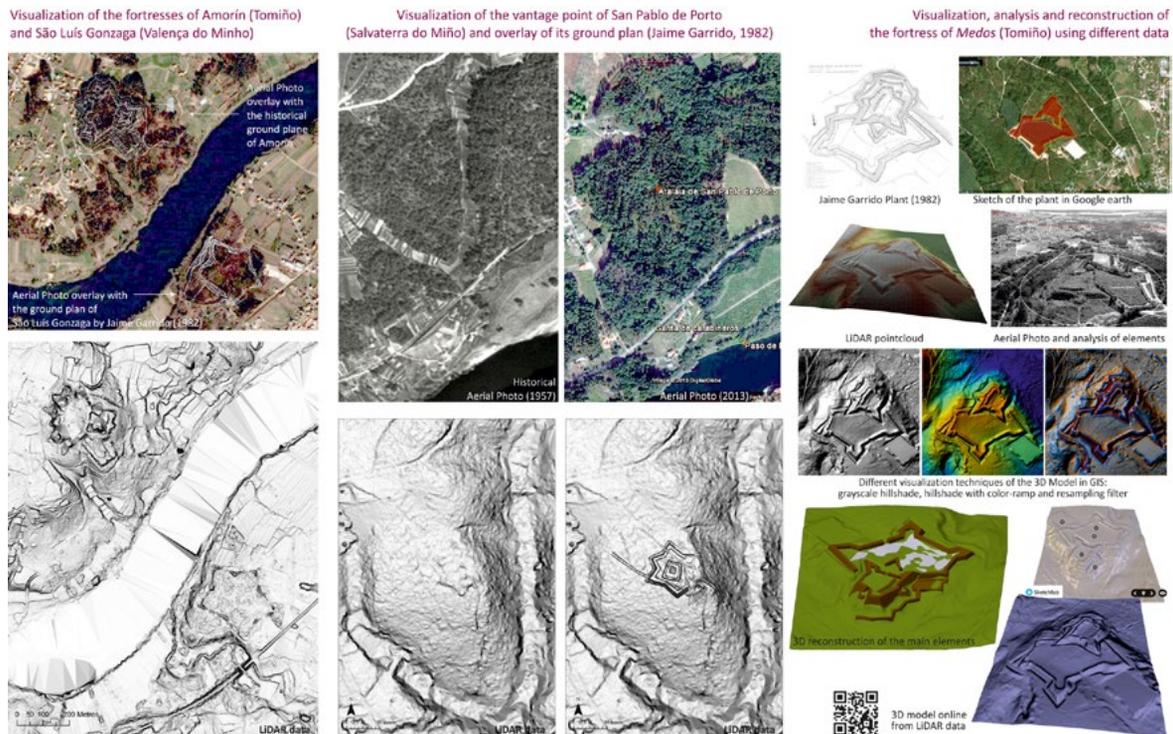


FIGURE 3. APPLICATION OF AIRBORNE LIDAR TO BASTIONED FORTIFICATIONS IN THE BAIXO MINHO; THE FORTRESS OF MEDOS CAN BE VIEWED ONLINE AT SKETCHFAB: [HTTPS://SKFB.LY/YUWD](https://skfb.ly/yUWD)

Problems to identify the fortifications

One of the key issues when working with this type of architecture and its relationship with the landscape is to obtain a correct geolocation and obtain its geometry. In many cases these are complex structures that represent a succession of different geometric shapes including all of the typical elements of bastioned fortifications (bastion, battery, braye, cavalier, couvre porte, crownwork, fort of glacis, furrow of glacis, hornwork, ravelin, redan trace, ...), including subordinate defences. In addition, using the tools we mentioned in the previous section, we must differentiate between elements that are part of defensive systems preceding or following to which we are studying.

In the case of the *Baixo Miño / Vale do Minho*, several aspects have affected the identification and visibility of the fortifications:

- Fortifications using earthworks that sometimes look like natural hills.
- Poor state of preservation due to:
 - Problems caused by the construction materials used (earth);
 - Many of them were intentionally destroyed at the end of the Portuguese War of Restoration (1640-1668);
 - Land use practices that have partially or completely altered the constructions.
- In many cases their geometry and large size make it impossible to obtain an overall *in situ* image, except from elevated positions.
- Many of these structures have become overgrown by vegetation, which means they cannot be seen even from elevated positions.

Archaeological remote sensing

Techniques based on 3D point-clouds for the modelling and documentation of cultural heritage (De Reu *et al.* 2013) and the mapping and archaeological surveying of sites and landscapes (Verhoeven

et al. 2012) have evolved at an astounding rate and are now applied on a widespread basis. For our study, we have used two techniques to visualize and identify the fortifications of this area: LiDAR and Photogrammetry.

Airborne LiDAR

In areas that are usually densely forested, the identification of archaeological features is still very problematic (Doneus *et al.* 2008). The introduction of Airborne Laser Scanning (ALS) or Light Detection and Ranging (LiDAR) has helped to overcome this problem because of its unique capability to penetrate vegetation canopies, making it possible to document the underlying topographic surface and identify any cultural remains on it (Opitz and Cowley 2013).

For the Spanish border, we have a complete LiDAR coverage (http://www.ign.es/PNOA/vuelo_lidar.html), with all the data freely available. The LiDAR data is already classified, so we only have to isolate the ground points from which we have obtained a Digital Terrain Model (DTM). In most of the cases we have used the hillshade as a visual technique, although in some cases we have applied other more complex and advanced visualization techniques, such as the Resampling Filter available in SAGA GIS software, that allow us to represent local small-scale elevation differences, similarly to Local Relief Models (Hesse 2010), in order to highlight the different structures of the Modern Age fortifications (Figure 3).

Aerial Photogrammetry

In order to understand the landscape in greater detail, we have combined airborne LiDAR data with historical aerial photos (Figure 4), which proved to be a valuable tool as each technique revealed different features, making it possible to maximise the results (Crutchley 2009).

We have used Structure from Motion (SfM) photogrammetry to build three-dimensional geometric information with which we have been able to generate new cartography data, namely Digital Surface Models (DSM) and orthophotos. These have then been analysed in GIS, compared with other geometric representations. Finally, 3-D models have been created from these datasets. In particular, we have used historical aerial photos taken by the United States Air Force during the 1950s (Antonio-Pérez *et al.* 2014) to digitally review areas or elements that have now been destroyed or altered.

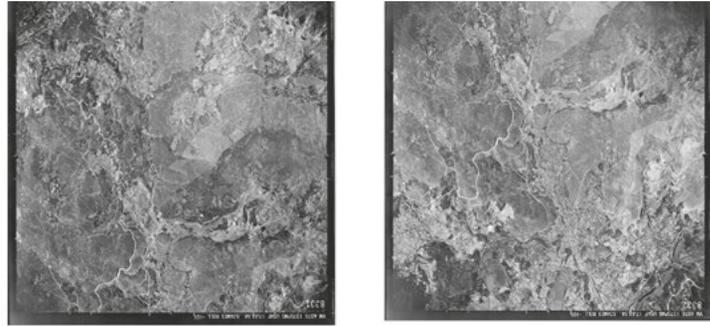
Results

In this publication we present a number of preliminary results related to the potential of combining airborne LiDAR with historical aerial photos in order to investigate Modern Age fortifications in the Minho valley, in the northwestern Iberian Peninsula.

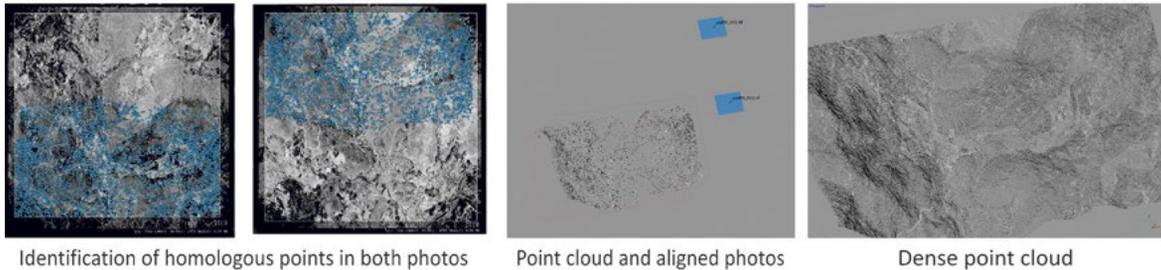
The examples shown in this publication refer to work carried out in the fortresses of Amorín (Tomiño, Spain) and São Luís Gonzaga (Valença do Minho, Portugal), which face each other across the river Miño, and also in the vantage point of San Pablo de Porto, in Salvaterra de Miño, Spain.

In the case of the first two fortifications, Amorín and São Luís Ganzaga, the use of LiDAR data was crucial in assessing their state of preservation. As a starting point we used detailed documentation of the ground plan created by the architect Jaime Garrido Rodríguez in the 1980s (Garrido 1989, 2001); however, today they are completely covered by dense vegetation, which not only makes it impossible to see the structures and verify their presence, but in some areas makes it impossible to enter the fortifications themselves. This same handicap occurred in the use of aerial photography, when the dense vegetation frequently made it impossible to locate the fortifications. Therefore, using LiDAR data became an essential tool in verifying the existence of the fortifications and their precise location by the identification of a pit and parapets, as well as to evaluate their state of preservation.

Based on 2 historical aerial photos USAF58 (1958)

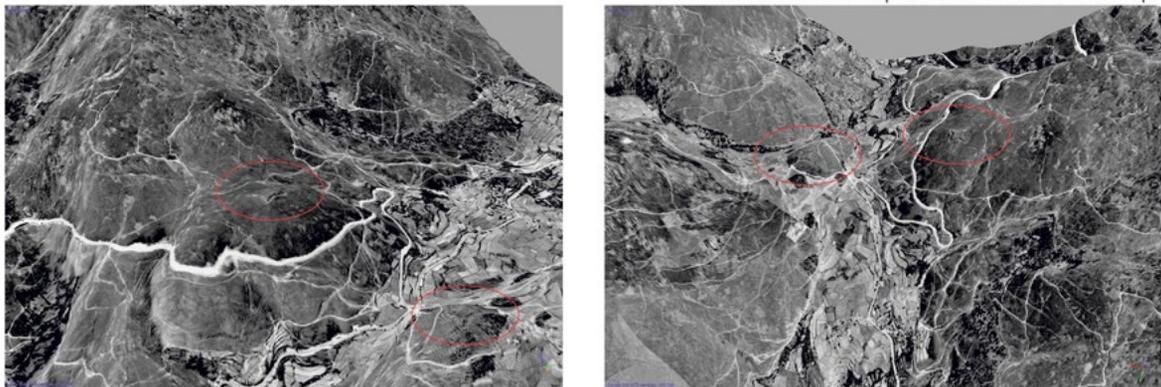


Photogrammetric process with Agisoft PhotoScan



RESULTS: 3D MODELS

that allow to recover lost information (the now vanished fortress of *A Pereira*) and a historical representation of the landscape



Fortresses of *Bragandelo* and *A Pereira* (Extremo, Arcos de Valdevez, Portugal)

FIGURE 4. WORKFLOW OF THE PHOTOGAMMETRIC RECONSTRUCTION OF THE FORTIFICATIONS OF EXTREMO FROM HISTORICAL AERIAL PHOTOGRAPHS (1958) WITH ELEMENTS THAT HAVE NOW BEEN DESTROYED.

In the case of the fortification of San Pablo de Porto the problems we faced were very similar. We had a ground plan also made by Jaime Garrido in 1982, but in contrast to the previous two cases it is virtually impossible to identify today since the vantage point has been seriously levelled due to the replanting of trees. Its position was also approximate, as there is no precise cartographic information that allowed us to identify the remains of the vantage point. Once again, by using LiDAR data it was possible to verify its exact position and assess the state of preservation; at least partially: the structures shown in the plan created by Garrido (Figure 3) have lost their north, north-east and north-west ramparts.

In the case of photogrammetry (Figure 4), this has been especially useful in making reconstructions based on historical photographs, different remains of fortified structures and even entire fortifications, which were destroyed after they were documented. Here we used the Agisoft PhotoScan Pro

software with two photogrammetric pairs of one of the areas for which we did not have LiDAR data, the village of Extremo in Arcos de Valdevez, Portugal. Based on historic documentation on the map titled *Mappa do distrito entre os rios Douro e Minho* from 1813 (Portuguese National Library, <http://purl.pt/22844>) and previous studies (Ericeira 1945, Volume III: 182; Antunes 1996: 233-239) we knew that there had once been two fortifications in this location on the heights overlooking the mountain pass of Extremo. However, today only the Fortress of Bragandelo can be identified *in situ*. Using photogrammetry we were able to reconstruct the location of the other fortification, the Fortress of Pereira, destroyed during the process of building a football pitch. It was also possible to identify the trenches that connected both fortifications, a characteristic communication system of this type of structures with ramparts that has been lost in practically all of the defensive structures documented in the *Baixo Miño / Vale do Minho*.

Conclusions

The use of an interdisciplinary approach using multiple techniques allows improving the analysis, representation and interpretation of cultural heritage elements. These techniques can help to speed up work, to reconstruct the geometry of many of the sites that have been destroyed or which are difficult to access, to facilitate the processes of documentation and on-site registration, and to generate reliable topographical information that allows performing more detailed archaeological and architectural analysis.

Using airborne laser scanning and historical aerial photos has allowed us to complete the archaeological information obtained about the Modern Age fortifications of the Minho valley, many of which, built on earth, were hidden under the vegetation. It has been possible to observe the state of conservation of the fortifications, which in many cases is better than the expected, to analyse its planimetric structure and topographic setting and to compare with the representations made in the historical maps and also to observe the relationship of some fortifications with his counterpart in the neighbouring country. From these data we have carried out a virtual reconstruction of the elements that built the fortresses, such as Forte of Medes, affected by several agricultural and forest exploration. All this has helped to characterize the theoretical model of the fortified landscape of Modern Age of the Minho Valley.

Benefits of LiDAR

- Open access: LiDAR data in Spain is provided freely and with open access, by the Spanish National Geographic Institute (IGN).
- Open source: these models can be generated using freeware (FruyoViewer, LAsTools) and open source software (Quantum GIS, SAGA GIS).
- Low cost: using open access data and free/open source software, it is possible to generate good representations and comprehensive analyses.
- High-resolution data that covers large areas, making it possible to map cultural heritage elements on different scales.

Benefits of Photogrammetry

- Possibility of retrieving geometric information from historical photos.
- Possibility of recovering missing landscapes and structures.
- Low cost: geometry can be created from multiple aerial photos, with software becoming cheaper or even free.
- Affordable technique in areas with no LiDAR data.
- Easy to combine with other techniques such as LiDAR.

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You can download the poster presented at UISPP 2014 in Burgos, Spain from this link:
<http://hdl.handle.net/10261/101376>.

Devilish details – fine-tuning survey techniques for ephemeral sites

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Abstract

The Rural Life in Protohistoric Italy project investigates small surface scatters from the Bronze and Iron Age, found during field walking surveys in Calabria, Italy. In this article we argue that detailed, multidisciplinary investigations of such ephemeral sites are crucial for our understanding of protohistoric rural society and land use. We illustrate our methodology of integrated surface recordings, geophysical methods, small test pits and laboratory studies with the case study of the Late Bronze Age site T231. The implications of this case study for regional settlement models are discussed.

Keywords: *Archaeological methodology, rural landscapes, near-surface prospection, protohistory, data integration.*

Résumé

Le projet Rural Life in Protohistoric Italy (Vie rurale en Italie protohistorique) étudie la distribution de matériels de surface des âges du Bronze et du Fer, trouvées lors de prospections pédestres en Calabre (Italie). Dans cet article nous soutenons que les recherches détaillées et multidisciplinaires de tel sites éphémères sont cruciaux pour la compréhension de la société rurale protohistorique et l'utilisation des terres. L'étude de cas du site T231 daté du Bronze final illustre notre approche méthodologique des enregistrements intégrés en surface, des méthodes géophysiques, des petits sondages et des études de laboratoire. La discussion porte sur les implications de cette étude de cas pour des modèles d'habitat régional.

Mots clés: *Méthodologie archéologique, paysages ruraux, prospection près de la surface, protohistoire, intégration de données.*

Introduction

Ephemeral protohistoric surface sites are detected in almost all field walking surveys in Italy; they bear witness to rural land use that stretches from coastlines to marginal areas in the mountainous interior. However, our understanding of protohistoric society is hampered by a lack of studies targeted at small sites: Italian protohistoric research remains, until today, largely focused on “central places”. In this paper we will present our current investigations into small Bronze Age surface scatters in Calabria (southern Italy), and argue that a systematic, detailed, and interdisciplinary approach will result in a new level of insight, with the integration of high resolution datasets as the key to success. We will illustrate our approach with a case study: the Late Bronze Age (LBA) structure at site T231.

Protohistoric research in the Sibaritide

The Plain of Sibari and its surroundings in northern Calabria have been the subject of a long tradition of protohistoric research, yet most intensive investigations were dedicated to large, central places interpreted as the top rung of settlement hierarchy: Torre Mordillo, Broglio di Trebisacce, and Timpone della Motta (Figure 1). Although small protohistoric scatters have been recorded in the area since the 1960's (De Rossi *et al.* 1969), and the dynamics between “major” and “minor” sites were studied by the La Sapienza University research school of Renato Peroni in the 1980's and 1990's, none of the smaller sites have been studied in detail. Moreover, neither single farms nor other limited

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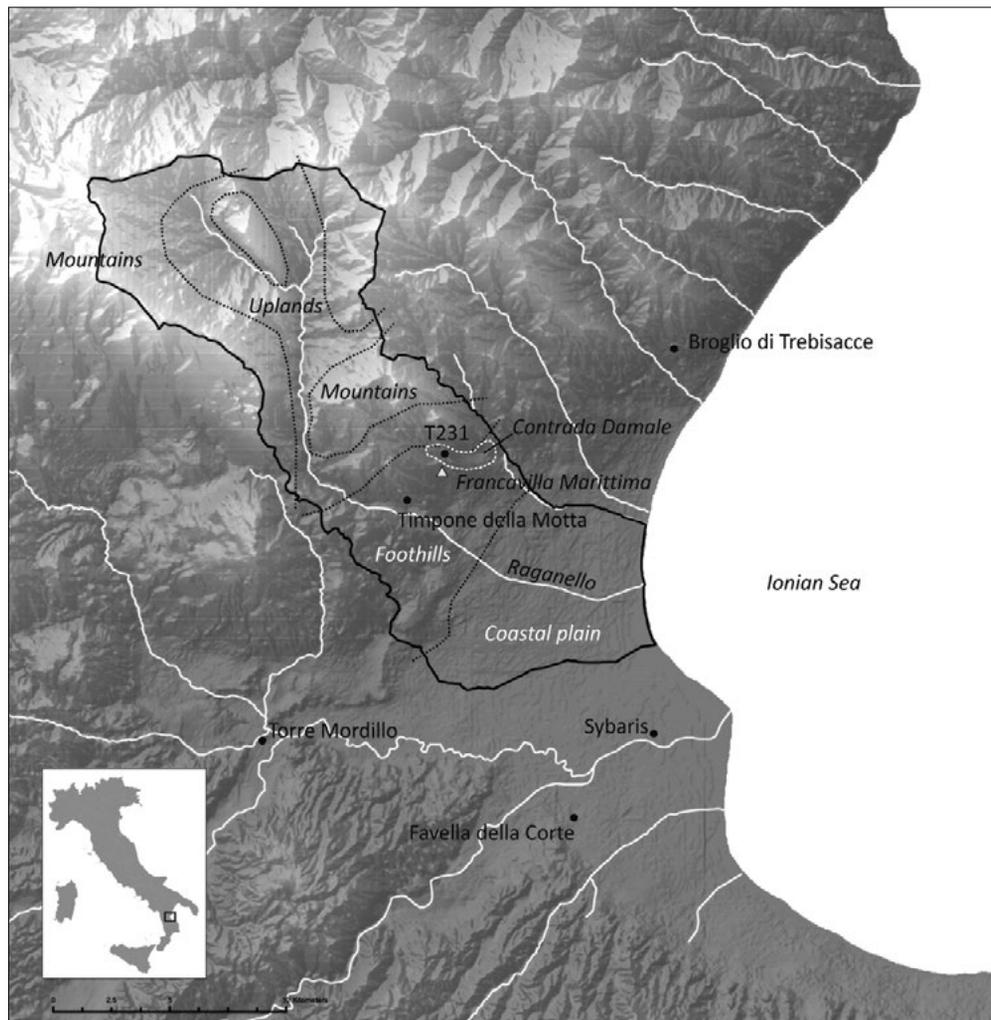


FIGURE 1. THE SIBARITIDE IN NORTHERN CALABRIA (ITALY), WITH ARCHAEOLOGICAL SITES MENTIONED IN THE TEXT. THE RESEARCH AREA OF THE RAP AND RLPI PROJECTS IS OUTLINED IN BLACK. THE FOUR LANDSCAPE ZONES USED IN THE SITE CLASSIFICATION ARE INDICATED WITH DASHED LINES (MAP W. DE NEEF/GIA).

activity locations feature at all in Peroni’s model of protohistoric settlement dynamics and increasing social complexity in the Sibaritide (Peroni & Trucco 1994: 832-879, Vanzetti 2013). In fact, Peroni’s theory is based on the unsystematic topographical recording of a mere 36 sites, occupied during at least one sub-phase of the 800-year span between the Middle Bronze Age and Early Iron Age (1700-900 BC).

Studies by the Groningen Institute of Archaeology (GIA) in the Raganello basin add a significant dimension to this existing framework. Originally a side project to explore the surroundings of the GIA excavations on the Timpone della Motta near Francavilla Marittima, the surveys grew into a large independent research project mapping diachronic settlement remains between the coastal plain and the inland mountains of the Pollino range (Attema *et al.* 2010: 6-7). More than 10 years of systematic field walking by the Raganello Archaeological Project (RAP, 2000-2010) resulted in the mapping of 255 surface scatters in this river basin in the northern part of the Sibaritide, dating from the Bronze Age to sub-recent threshing floors. The majority of these remains, 160 sites, date to the protohistoric period. Since they are typically only a few meters in diameter, we assume that we have

recorded the base of the settlement hierarchy consisting of short-lived, rural activity foci. They occur throughout the research area, and testify to protohistoric presence in all landscape components, from the gently rolling foothills to slopes in the uplands and mountains. The coastal plain, formally part of the research area, remains uninvestigated due to the heavy alluvial sedimentation, covering antique land surfaces under several meters of soil. Archaeological remains outside our research area, such as the Neolithic village Favella della Corte and the Archaic Greek colony of Sybaris, indicate that the coastal plain was occupied as well.

Our present research project, the Rural Life in Protohistoric Italy project (RLPI, 2010-2015), is aimed at a better understanding of the protohistoric record presented by the RAP and other Mediterranean survey projects. The interpretation of ephemeral protohistoric remains encounters several problems. First, most of the scatters are small and they often consist of poorly preserved handmade ceramics which cannot be dated closely. This means that it is difficult to assess what they represent in terms of function, chronology, and possible structural remains. Moreover, since they are located in an area which was until recently under intensive agricultural exploitation, covering diverse geological zones characterized by pronounced relief, natural and anthropogenic post-depositional processes deeply influence their preservation and detection. And finally, we are aware of the fact that their detection may have been subject to several research biases, caused by the survey strategy, accessibility, and visibility.

To tackle these problems, the project aims are threefold. Firstly, we focus on establishing whether buried remains produce the materials on the surface. Secondly, we map the natural and anthropogenic processes that influence the preservation and detection of these remains, so that we can assess which parts of the landscape are likely to produce surface scatters, where they may have been destroyed, and where they may be buried beyond the reach of the plough. For this we build on a previous research project directed by Van Leusen, the Hidden Landscapes Project (HLP, 2005-2009), in which landscape classifications at different scales and an erosion model were developed for the Raganello basin (Feiken 2014). Finally, we test, evaluate, and combine survey and prospection methods, in order to mitigate detection biases. Now, with the fieldwork phase of the project closed, we can present preliminary results of our efforts and propose strategies that may clarify ephemeral protohistoric presence in similar Mediterranean landscapes.

Methodology

Our field research follows a stratified sampling approach guided by a classification of the 160 protohistoric scatters in the Raganello basin. This site classification is emphatically not based on any preconceived site types known from other research, but is based on unambiguous properties of local topography and material assemblage (De Neef, forthcoming). In order to prevent the classification from becoming too detailed, a broad division in four general landscape zones was used: the coastal plain, foothills, upland valley, and mountains (Figure 2). The site classification allows us to study land use and settlement dynamics on a regional scale by extrapolating from detailed investigations of representative examples from each class. With the fieldwork phase of the project finished, we can conclude that the proposed site typology “works”, albeit with a few corrections.²

The selected protohistoric sites were investigated with a range of methods: a close (re-)study of the material assemblage, high coverage repeated surveys, geophysical surveys, manual augering, and test pits (De Neef & Van Leusen forthcoming). In continuation of geophysical pilots conducted in the HLP (Van Leusen *et al.* 2014), a number of geophysical techniques were tested, including total field magnetometry, magnetic gradiometry, magnetic susceptibility (MS), electromagnetic surveys, ground penetrating radar (GPR), and electrical resistivity. Of these, the magnetism-based techniques gave the best results under the specific geo-pedological circumstances; we applied magnetic gradiometry and MS measurements on all selected case studies and total field magnetometry on a

² Not all site classes could be studied due to fieldwork permissions or other logistical reasons.

		A S S E M B L A G E				
L A N D S C A P E		Simple impasto		„Rich“	Storage	Funereal
	Plain	-		-	-	-
	Foothills	Small scatter in foothills (44)		Rich foothill sites (4)	Storage vessel sites (24)	Funereal sites (3)
				Rich assemblage with storage vessel (4)		
	Uplands	Small scatter in uplands (20)		Rich upland sites (2)	-	
	Mountains	Scatter in restricted areas (10)	Cave sites (10)	-	-	
		<i>A-typical sites (8)</i>				

FIGURE 2. THE CLASSIFICATION OF PROTOHISTORIC SITES.

subset of these. Aside from these site oriented measurements we also applied a non-site, landscape prospection approach to test how many magnetic features occur without an associated archaeological surface manifestation (Armstrong & Van Leusen forthcoming). Nevertheless, we are aware of the “non-response bias” of archaeological remains not detectable by magnetic contrast, and argue that more research is needed in this field. In addition to the on-site measurements, information about the geological and soil background was obtained by manual augering and soil pits. Augering was also applied to map soils and slope processes on both landscape and site scale, to explain the presence or absence of archaeological remains on the surface (Sevink *et al.* forthcoming). Finally, we were able to investigate the associations between surface material, geophysical features, soils, and archaeological stratigraphy by excavating small targeted test pits. Full excavations were beyond the scope of the project, and not allowed by the fieldwork permit issued by the archaeological authorities.

Our interpretations and research conclusions are highly dependent on the accurate integration of these various invasive and non-invasive datasets, which implies that reliable positioning in the centimeter range is of the utmost importance. This is especially critical for invasive research targeted at single geophysical anomalies, but also for the association between surface and subsurface remains. Maintaining measurement systems in diverse locations, across different research teams, over a number of years proved not to be without problems. Yet in spite of the practical problems of field research in the mountainous inlands of Calabria, we are confident that our approach contributes to a more complete picture of the archaeological record of the Bronze Age. That this is underpinned by the detailed integration of high resolution datasets will be illustrated below with the case study of site T231.

Investigations at T231

Surface scatter T231 is an example of how the combined effort of intensive archaeological re-survey and magnetometry can result in the detection and assessment of previously unknown sites. In the summer of 2011 we produced a new distribution map of protohistoric surface material around the near-by LBA site T94, reaching the highest spatial resolution by recording each individual artefact with a Total Station. This re-survey was accompanied by magnetometer survey using a Bartington Grad601 dual sensor array, conducted in rectangular grids tied into the local measurement system. The magnetometer survey recorded a rectangular, strongly positive anomaly of approximately 8 x 4 m, some 100 m SE of site T94. The distribution map of surface artefacts revealed a diffuse scatter of Bronze Age material, fanning out downslope from this anomaly (Figure 3). This scatter had not been detected in the original RAP survey of the field, conducted with crew members walking at 10m intervals. Like T94, the new scatter was classified as a “protohistoric site with LBA storage vessel in the foothills” on the basis of its material assemblage and location, and named T231.

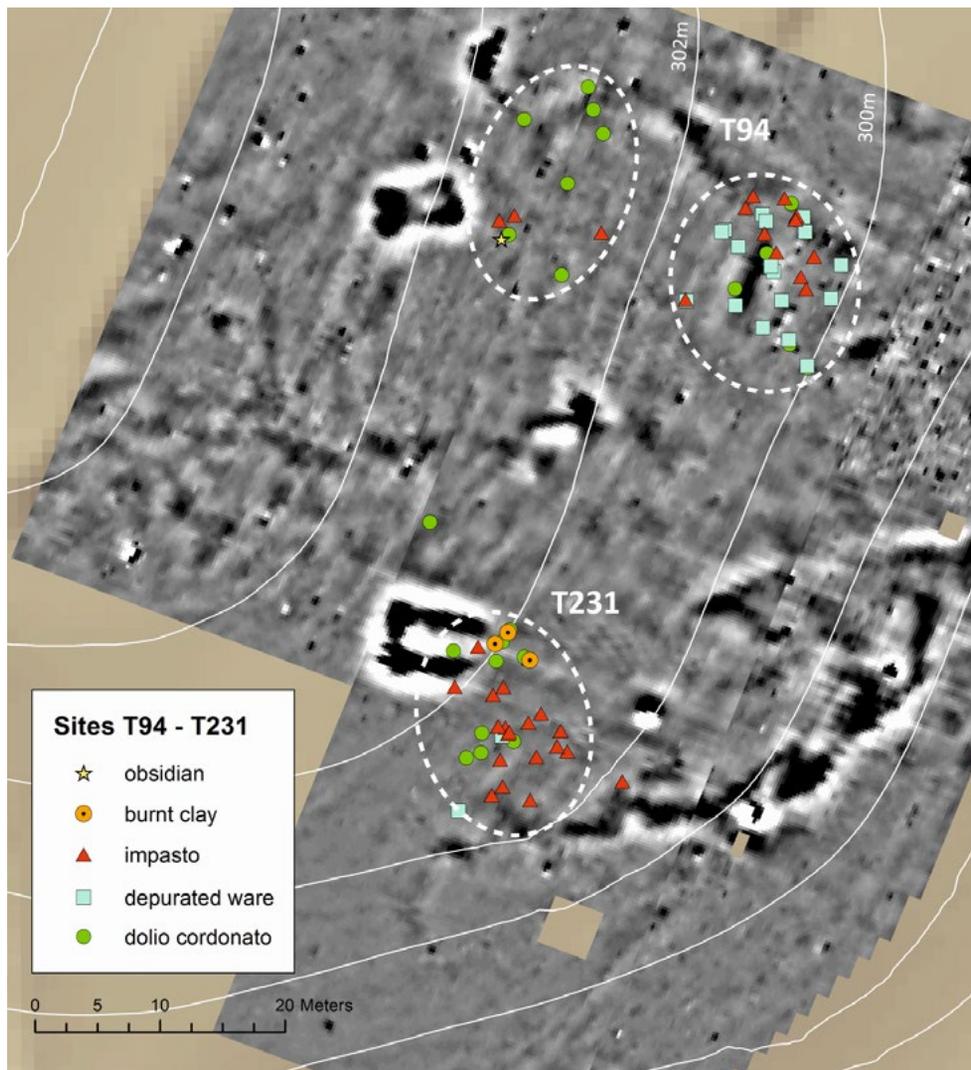


FIGURE 3. SITES T94 AND T231, CONTRADA DAMALE (CALABRIA, ITALY). RESULTS OF THE MAGNETIC GRADIOMETER SURVEY ($\pm 10\text{NT}$) AND THE DISTRIBUTION OF SINGLE ARTEFACTS RECORDED BY TOTAL STATION (MAP W. DE NEEF/GIA).

Although associations between magnetic anomalies and surface scatters may seem obvious by sheer spatial proximity, we insist that invasive research is necessary to establish whether scatter and anomaly are produced by the same subsurface deposit. Moreover, invasive investigations contribute to understanding site formation, post-depositional history, and the precise origin of geophysical anomalies. In the case of T231, we were allowed to strip away the plough layer over an area of 10 x 10 m covering both the rectangular anomaly and the surface scatter, and to excavate two narrow trenches. These immediately confirmed that the magnetic feature is caused by structural remains dating to the LBA. Thus we can confirm a spatial and temporal link between surface material, buried features, and geophysical response.

Stripping away the plough zone yielded the outline of a rectangular structure with a straight short back wall, slightly in-curving side walls, and an open end facing downslope (Figure 4). The walls coincide with lumps of hard, red clay, which were visible primarily near the open end of the structure. It appears that the building was progressively damaged by ploughing on the downslope end, whereas the strong magnetic signal at the rear end suggests that this part of the structure is buried more deeply and therefore better preserved. This was supported by repeated magnetometry and MS measurements on the stripped surface. The MS measurements, conducted with a portable Bartington MS2D loop sensor, showed high values on the exposed clay lumps but not on the rear end of the building, whereas the repeated magnetometry measurements showed the opposite effect.

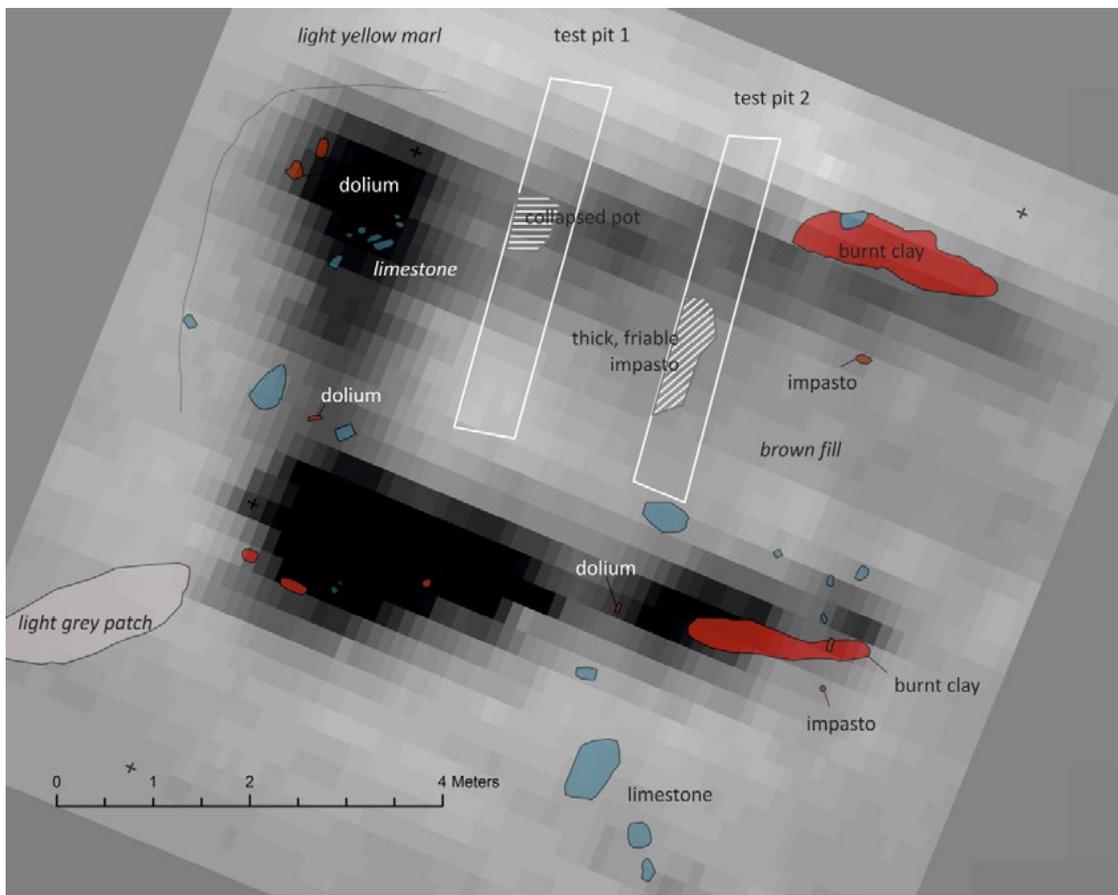


FIGURE 4. SITE T231. RESULTS OF REPEATED MAGNETIC GRADIOMETER SURVEY ON THE EXPOSED SURFACE AFTER TOPSOIL STRIPPING. THE TWO TEST PITS ARE OUTLINED IN WHITE. LOCATIONS OF BURNT CLAY AND CERAMIC FRAGMENTS ON THE STRIPPED SURFACE ARE INDICATED, AS WELL AS THE COLLAPSED POT AND THE FRIABLE THICK IMPASTO IN THE TEST PITS (MAP W. DE NEEF/GIA).

In the end, the cause of the magnetic signal could be established by excavating two parallel slot trenches across the northern long wall. These were placed on either end of a profile baulk which was left standing to document the full soil stratigraphy from the plough layer down. The preserved part of the wall does indeed consist of the hard, orange-red clay seen on the stripped surface. At a depth of approximately 80 cm, a hardened floor was encountered on which large fragments of charcoal and lumps of very thick, friable ceramics were preserved. The pieces of ceramics consist of typical handmade protohistoric pottery, *impasto*, and may be parts of the sort of food ovens known from other nearby Bronze Age settlements such as Torre Mordillo. In one of the slot trenches, we also found piled-up fragments of a large *impasto* vessel which probably collapsed *in situ*. Diagnostic rim fragments place this vessel in the LBA, which coincides with the ceramics found in the surface scatter. Both the hardened floor and the red clay wall were dug into the natural, light-coloured marl, so that we can conclude that the structure had a lowered floor and adobe walls. The lowered part of the building was covered with a fill of brown soil mixed with small charcoal fragments and occasional ceramic sherds. This fill most likely formed after the building's collapse.

Magnetic susceptibility measurements taken on sections in both trenches reveal that the walls in red clay produce high values, in contrast to the relatively low values recorded in the brown fill and the topsoil. MS values of the hardened floor are elevated, but less so than those of the clay wall. Therefore the strongly magnetically enhanced properties of the red clay deposits cause the rectangular feature in the gradiometry data, overpowering the enhancement of the floor and the brown fill.

Intentional fire?

Geophysical analysis of soil samples taken from the slot trenches yielded additional information for the reconstruction of the building's history. The samples were processed and analysed by dr. K. Armstrong in the soil laboratory of Johann-Gutenberg University in Mainz (Germany), with support of the archaeological prospection research group directed by dr. D. Jordan. The MS properties of the samples, established with fractional conversion tests using a hysteresis loop, suggest that the red clay in the wall of the building was heated to exceptionally high temperatures over a sustained period (Armstrong & Van Leusen forthcoming; Crowther 2003). Experimental fires in reconstructed Iron Age huts in Lejre (Denmark) and Butser Hill (UK) indicate that such long duration fires can only be reached by controlled, intentional action, in contrast to intense but short accidental fires (Rasmussen 2007; Harrison 2013). This suggests that the walls of the building at T231 were fired on purpose, and possibly repeatedly.

As to the reasons *why* the building was fired we can only speculate. Intentional firing after abandonment is a tradition which has been suggested for Neolithic and Early Bronze Age dwellings in Calabria (Schaffer 1993; Robb 2007). However, although large charcoal fragments were found on the hardened floor, further burning traces such as ashes or collapsed building components are absent in the interior. An alternative option is the firing of the clay found *in situ* as a foundation for adobe or wattle-and-daub walls, but we have no excavated parallels for this: at nearby Broglio di Trebisacce rectangular store huts dating to the LBA have been found, but these have stone foundations. So far we do not have evidence for stone foundations at T231.

The spatial offset between the rectangular structure and the surface artefact scatter still needs to be clarified. We see such offsets between magnetic anomaly and surface distribution in many other LBA sites. Although we are confident that both manifestations belong together, the test pits have not established how the buried building remains produce the surface scatter. The scatter may be caused by the gradual exposure of buried deposits along the slope by mechanical ploughing, by which the open end of the rectangular structure is progressively damaged. Yet the distance between the magnetic anomaly and the surface ceramics is several meters, and no ceramics occur over the anomaly itself. Several studies of artefact movement in plough soils were conducted when archaeological field walking was a relatively new phenomenon (Cavanagh & Mee 2007: 11-12); now that artefact

survey is an established method, experiments and discussion of artefact displacement seem to have died away without coming to a satisfactory conclusion. Experiments in the 1980's have shown that artefact displacement depends on category, size and slope angle: small ceramic fragments and lithics can move several meters along slopes and plough furrows, whereas larger sherds have been reported to travel up to 20 m. Keeping in mind that the mechanical plough was introduced in this part of Calabria in the 1980's, it is conceivable that finds have been displaced several meters. An alternative explanation for the offset at T231 would be that the surface scatter is not produced by the structure at all, but by an external feature such as a midden, pit, or hearth. In any case, further invasive research to make statements about this was beyond the scope of the project.

Site monitoring and settlement models

Zooming out from the single site to the whole site class, it becomes evident that T231 is not unique: neither in its detection history nor in its preserved remains. This previously unknown site was classified as a "LBA foothill storage vessel site" by its location and finds assemblage, of which class we have now investigated 15 examples by integrated non-invasive and invasive research. Re-surveys of RAP field units and additional surveys in previously non-investigated areas have increased the number of storage vessel sites from 40 to 63. Furthermore, the positioning procedures for our current dataset are much more precise, so that we can effectively monitor changes to the known scatters and test anecdotal theses like Barker's remark that surface sites "can come on and off like traffic lights" (Barker 1995: 49). One of the conclusions of our methodology evaluation therefore is that even the intensive survey strategy of the RAP, with a 20% surface coverage in 50 x 50 m units aimed at mapping diachronic settlement remains, is not suitable for detecting the smallest protohistoric remains.

More-over, our understanding of the concept "site" has changed by consistently integrating different datasets. In the RAP surveys, we used the word for local increases in finds density relative to a background "noise". After four years of intensive non-invasive and invasive research in the RLPI project, we now see a variety of "site" manifestations: pottery scatters of different densities without apparent geophysical signal, scatters associated with a rectangular magnetic anomaly, scatters associated with an undefined magnetic anomaly, but also strong (rectangular) magnetic anomalies and buried archaeological deposits without a surface manifestation. One unintended consequence of our work is thus that we have become aware of the problematic use of the concept "site" in landscape archaeology.

So far, we have detected 16 rectangular magnetic anomalies, of which 9 can be associated with a ceramic scatter containing storage vessel fragments of a specific type, the LBA *dolio cordonato a fasce* (Figure 5). Based on their magnetic intensities, we can assume that most of the detected rectangular structures have a similar formation process involving firing at high temperatures. Both the rectangular anomalies and the storage vessel site class occur non-clustered and only in a specific part of the foothills, a gently undulating agricultural area of 1.7 km² called Contrada Damale, located the foot of a limestone mountain and boasting wide views over the coastal plain (Figure 6).³ Since the *dolii cordonati* are well datable by typo-chronology, we can now postulate that the Contrada Damale features a true settlement boom of small, dispersed habitations in the last phase of the LBA (the Final Bronze Age, ca. 1100-950 BC). We tentatively propose a model of an "open, non-clustered village" consisting of separate farmsteads, the inhabitants of which nevertheless maintain a stable social cohesion – much like the Contrada Damale was some 50 years ago.

This remarkable development has gone unnoticed by traditional scholarship focusing on "central" places and landmark locations. Apart from a few stray observations without clear context, the *dolio cordonato* storage vessels are known primarily from such large, centralized settlements – a research

³ The Contrada Damale is part of the municipality of Cerchiara di Calabria (province of Cosenza).



FIGURE 5. TWO COMPLETE LATE BRONZE AGE STORAGE VESSELS OF THE DOLIO CORDONATO O A FASCE TYPE, EXCAVATED IN BROGLIO DI TREBISACCE (ON DISPLAY IN THE ARCHAEOLOGICAL MUSEUM OF SIBARI). THE VESSEL ON THE LEFT IS APPROXIMATELY 1.3 M HIGH (PHOTO R. FREIBOTHE).



FIGURE 6. VIEW OVER THE CONTRADA DAMALE, THE TOWN OF FRANCAVILLA MARITTIMA AND THE PLAIN OF SIBARI (CALABRIA, ITALY), TOWARDS THE SOUTH-EAST. THE LOCATION OF SITE T231 IS INDICATED WITH A WHITE STAR. THE IONIAN COAST CAN BE SEEN ON THE LEFT; THE BROAD VALLEY OF RIVER RAGANELLO IS ON THE RIGHT (PHOTO W. DE NEEF).

bias which features prominently in Peroni's model of increasing social complexity in which craft specialization and produce redistribution play a large role. The occurrence of this specialized product class in a rural setting, in small dispersed structures such as T231, not only shows that the idea of a strong polarization between major, long-lived centres and minor, short-lived settlements should be reduced, but also that the inhabitants of small LBA rural sites had access to, and a need for, containers with large storage capacity. What was stored in these vessels remains largely un-investigated; residue analysis at Broglio di Trebisacce points to hazelnut or olive oil, but other produce cannot be excluded. The relationships between the inhabitants of large settlements such as Broglio di Trebisacce and Torre Mordillo and those of sites such as T231 remain obscure, but the rural population in the Sibaritide must have been a considerable component in the LBA economy.

Conclusions

Contrary to a persistent belief seen in many survey projects in Italy, we argue that intensive, interdisciplinary investigations into ephemeral protohistoric surface scatters do yield new insights in rural settlement and economy. Even very diffuse ceramic concentrations such as T231, which are regularly found in field walking surveys, can yield new information with the integration of different high-resolution datasets – in this case of surface recording, magnetic gradiometry, magnetic susceptibility, small test pits and laboratory analysis. On a regional scale, investigations of settlement dynamics and land use are enabled by a systematic approach based on extrapolation from site classes.

Although we still do not understand the use of the storage vessel sites and their interdependence, it is evident that the Contrada Damale was intensively used in the last phase of the Bronze Age. We also know now that the inhabitants of sites like T231 had access to a vessel class which was very likely produced by specialized craftsmen; a material category which until now has appeared to be reserved for the emerging elites of the LBA. Looking beyond the individual site, our investigations of the rural landscape contribute to the unraveling of a biased view on protohistoric societies.

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Geophysical survey on “El Mazo de la Castañera” (Cantabria, Spain): looking for open-air domestic remains

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Abstract

In this paper we present a geophysical survey conducted on El Mazo de la Castañera (Cantabria, Spain). The archaeological site, which has preserved remains from the Palaeolithic to the Early Middle Age, is located in a temperate and humid region, with permanent vegetation coverage that hinders observations of superficial evidence. Common methodological approaches, as pedestrian survey or aerial photography, do not yield good results in Cantabria. In consequence there is a lack of open-air habitats: a problem linked to the low visibility of archaeological remains. For this reason, different prospection methods should be used. Geophysical survey allows the detection of non-visible archaeological evidence. Electromagnetic induction survey provides surface maps where we have found anomalies that can be interpreted as archaeological features. In order to check the accuracy of our data processing and interpretations a sondage was conducted in 2014, the results of which were positive.

Keywords: Domestic structures, electromagnetic induction survey, Neolithic to Early Middle Age, Cantabrian Region, Spain

Résumé

Ce travail analyse une prospection géophysique réalisée dans le Mazo de la Castañera (Cantabrie, Espagne). Le gisement est localisé dans une région tempérée et humide, avec une couverture végétale permanente qui limite l'observation superficielle des évidences archéologiques. Les méthodologies habituelles n'ont pas eu de bons résultats en Cantabrie.

En fait, il y a un vide de sites d'habitat en plein air: un problème en relation avec la mauvaise visibilité des restes archéologiques. Par cette raison, d'autres méthodes doivent être utilisées. La prospection géophysique permet de détecter et trouver des évidences archéologiques non visibles. Notre recherche a fourni des cartes de surface où les anomalies électromagnétiques qui peuvent être interprétées comme des structures archéologiques ont été détectées. Afin de vérifier la fiabilité de la méthode, un sondage a été réalisé en novembre 2014. Les résultats obtenus ont été positifs.

Mots clés: Structures domestiques, prospection d'induction magnétique, Région Cantabrique, Espagne

Introduction

This paper presents a geophysical survey conducted at El Mazo de la Castañera (Cantabria, Spain), a hill (Figure 1) where 7 caves are located with archaeological remains from the Paleolithic to the Early Middle Age (Gomarín Guirado 1972-1973; Rincón Vila 1985; Ruiz Cobo 1996; Serna Gancedo *et al.* 2001). In one of these, El Abrigo de la Castañera, an excavation has been conducted, directed by one of us (CVM). This site is the only one with well-contextualized data, which testify of an intensive occupation during the Chalcolithic and Bronze Age. The mentioned research project aimed to explore the potential archaeological record located in the near surroundings of El Abrigo de la Castañera. A special focus was placed on locating open-air habitats, because there is a notorious

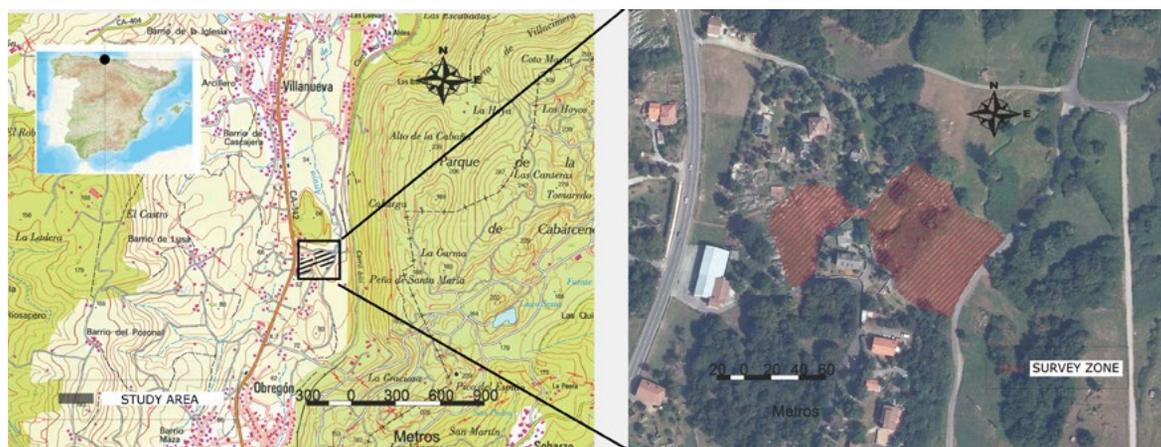


FIGURE 1. LOCATION OF EL MAZO DE LA CASTAÑERA.

absence of this kind of sites in the Cantabrian region. The lack of habitats is linked to the low visibility of archaeological remains of peasant communities from Neolithic to Early Middle Age (post holes, pits, thin deposits, etc.). These kinds of remains are difficult to detect with traditional survey, as pedestrian survey or aerial photography, because the environment has permanent vegetation coverage, caused by specific climatic circumstances of the region. The Cantabrian Region is a strip of land of approximately 350 km long and 30-50 km wide, located between the Atlantic Ocean to the north and the Cantabrian Mountains (with peaks of about 1500-2600 m above sea level) to the south. These orographic conditions cause the “Foehn effect” that reduces the Atlantic climatic conditions in this narrow strip of land.

Material and methods

In order to achieve this goal an electromagnetic induction survey was commissioned to GIPSIA SL. The aim of this method is to detect abnormal accumulations embedded into natural sedimentary soils. We worked on a 9 ha area divided into six different zones (M1 to 6) (Figure 2). The processed data and its interpretation are presented by georeferenced surface maps.

To obtain optimum quality and data density, we covered the study area by perpendicular tracks with an interval of 1 meter, obtaining a mesh of each zone. The purpose was to explore only the superficial layer where archaeological evidences were expected. Basing ourselves on available data about the local archaeology and geology, we worked with a frequency that allowed collecting data to a depth of 2.5 meters. The selected frequency was 47.175 Hz, both electric and magnetic.

Results

The results are presented in two types of georeferenced surface maps: electric conductivity (EC) and magnetic susceptibility (MS) which show several potential archaeological features: anomalies with a geometrical design and sedimentary deposits with an archaeological potential. The detection of non-angular, low-intensity structures is problematic; to observe these traces, we had to present the results at high contrast.

The results vary between the different zones. The most interesting features were detected in M1, M4 and M6. They show circular anomalies of different dimensions clustered in specific areas. Thick sedimentary packages with a high archaeological potential were also documented in three cave mouths. Below we will summarize the results for each of the survey zones.



FIGURE 2. SURVEYED ZONES IN EL MAZO DE LA CASTAÑERA.

Zone M1

M1 shows several anomalies with geometrical shape (Figure 3); besides thick sedimentary accumulations near the rock shelter of Abrigo de la Castañera were detected. The most striking anomaly is a circular zone with a dark perimeter and with a small anomaly in its centre: a dwelling?

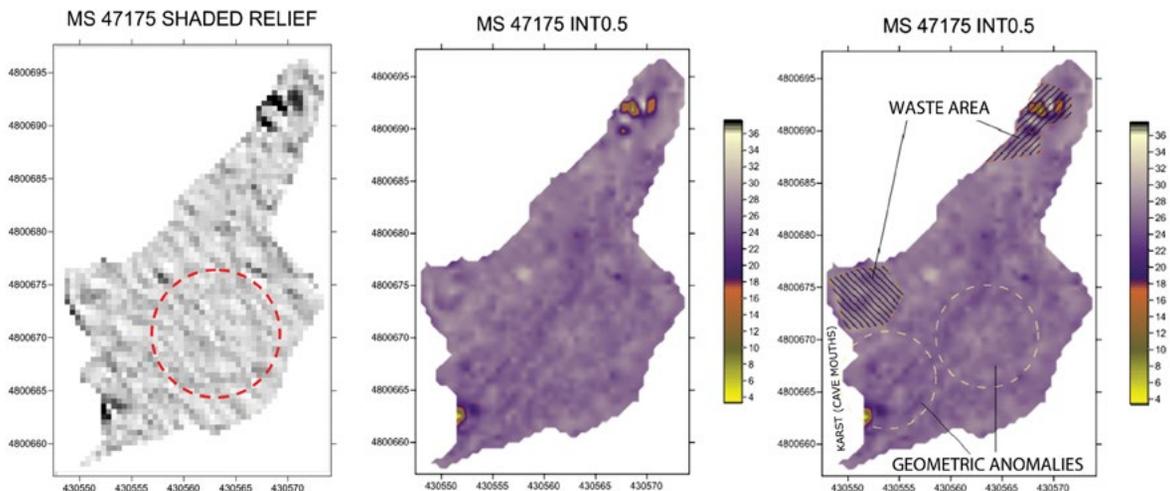


FIGURE 3. SURFACE MAPS FROM M1 ZONE: ELECTRIC CONDUCTIVITY (EC) AND MAGNETIC SUSCEPTIBILITY (MS).

Zone M2

There are no archaeologically relevant MS readings in M2 (Figure 4), apart from several little basins filled with sediments. Bedrock is close to the surface in this area.

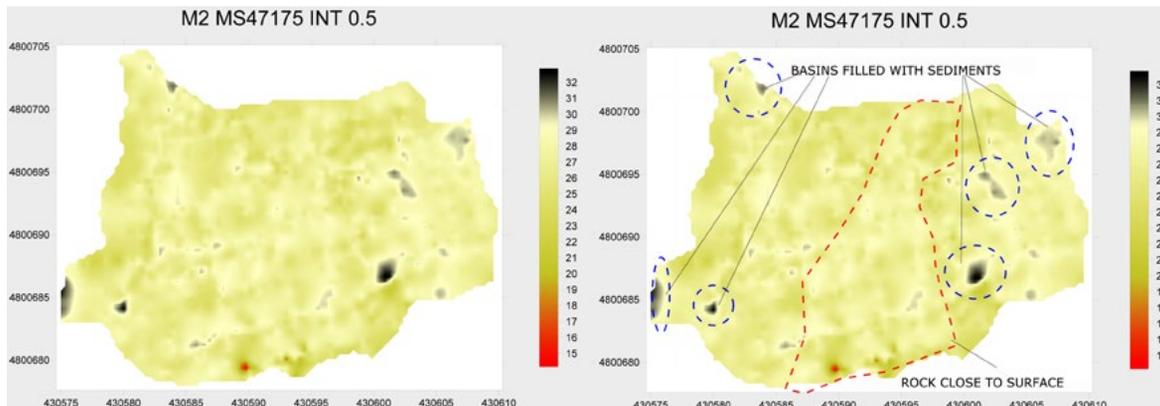


FIGURE 4. READINGS AND INTERPRETATION OF MAGNETIC SUSCEPTIBILITY FROM M2 ZONE.

Zone M3

Area M3 is a strip close to the mouth of a cave (Figure 5). The EC data show a considerable accumulation of sedimentary fillings which contrast with surrounding clays. The deposits come from the cave.

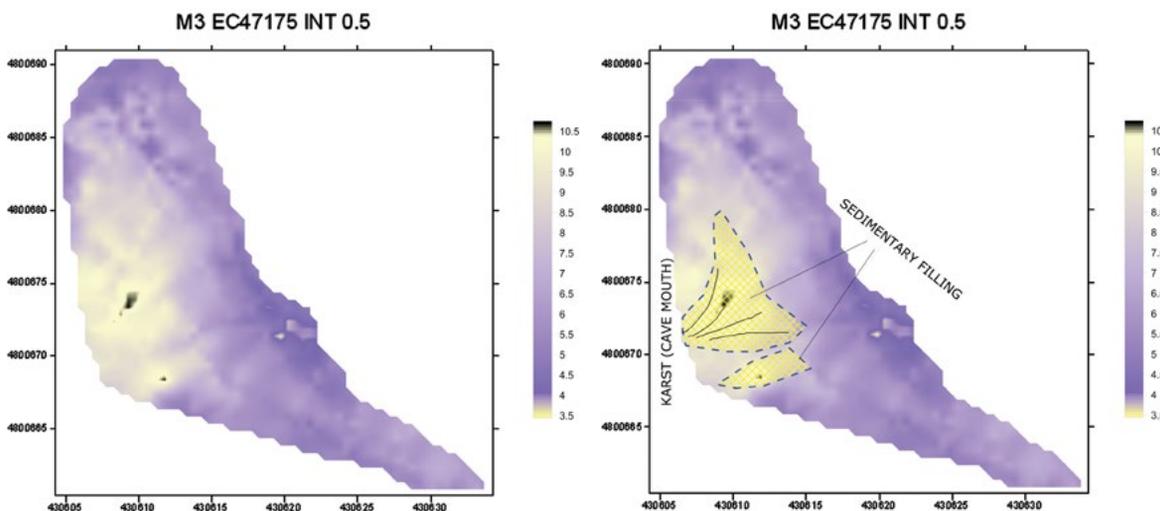


FIGURE 5. READINGS AND INTERPRETATION OF ELECTRIC CONDUCTIVITY FROM M3 ZONE.

Zone M4

Zone M4 has clear data. Readings (Figure 6) show a sedimentary continuity without clear signs of anthropic activity. In consequence, despite a low contrast of readings, we can identify a few features

in this area. Indeed, an interesting and isolated area of high resistivity and susceptibility is observed in both maps, more or less homogeneous, which would be related to an accumulative deposition or specific sedimentary packages. Also, several subzones with anomalies are documented.

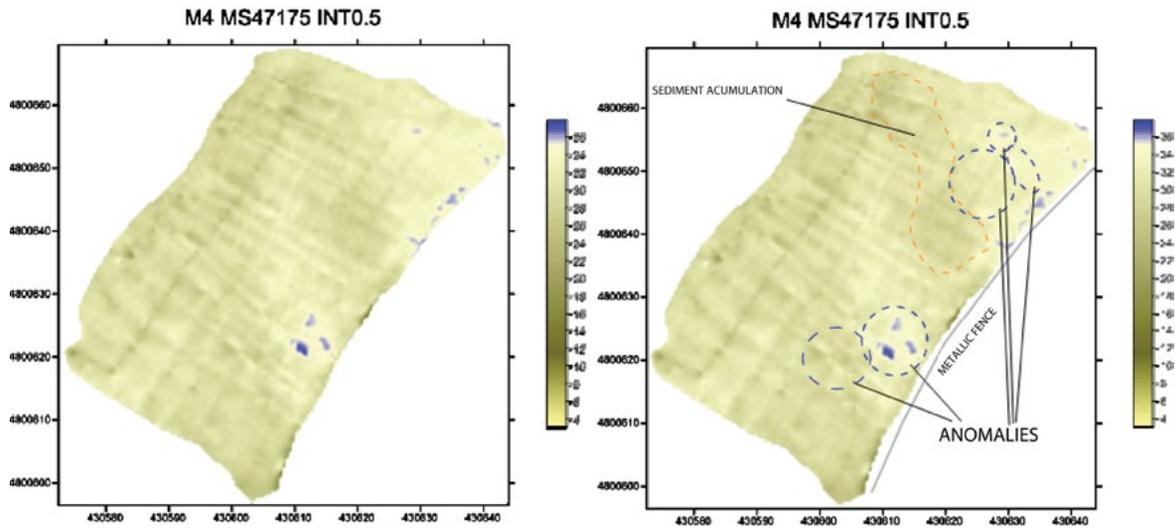


FIGURE 6. READINGS AND INTERPRETATION OF MAGNETIC SUSCEPTIBILITY FROM M4 ZONE.

Zone M5

As in M2, the bedrock is very close to surface here (Figure 7). However, some potential anomalies and some places with sedimentary fillings were observed. High MS values appear to be related to sedimentary filling and very low MS can be associated with bedrock emerging.

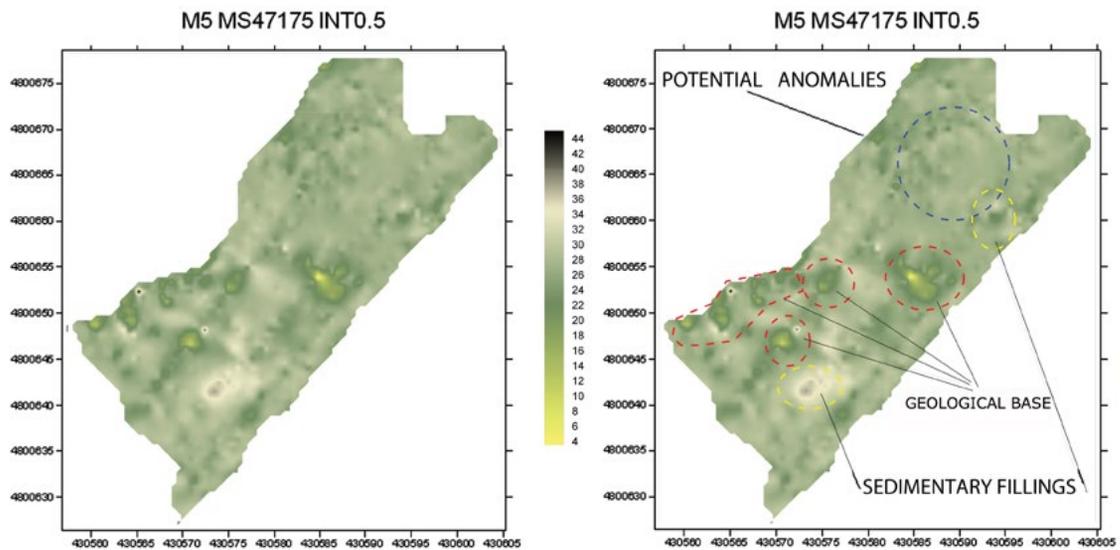


FIGURE 7. READINGS AND INTERPRETATION OF MAGNETIC SUSCEPTIBILITY FROM M5 ZONE.

Zone M6

In M6 there is a significant contrast between data from flat areas, with quaternary fillings, and geological outcrops and areas in contact with them. Here (Figure 8) two different kinds of anomalies can be observed:

- Circular anomalies, characterized by conductivity contrasting with surroundings fillings. There is a big circular trace in a level area near limestone in the northern part of the zone.
- Sedimentary fillings deposited in the mouths of caves.

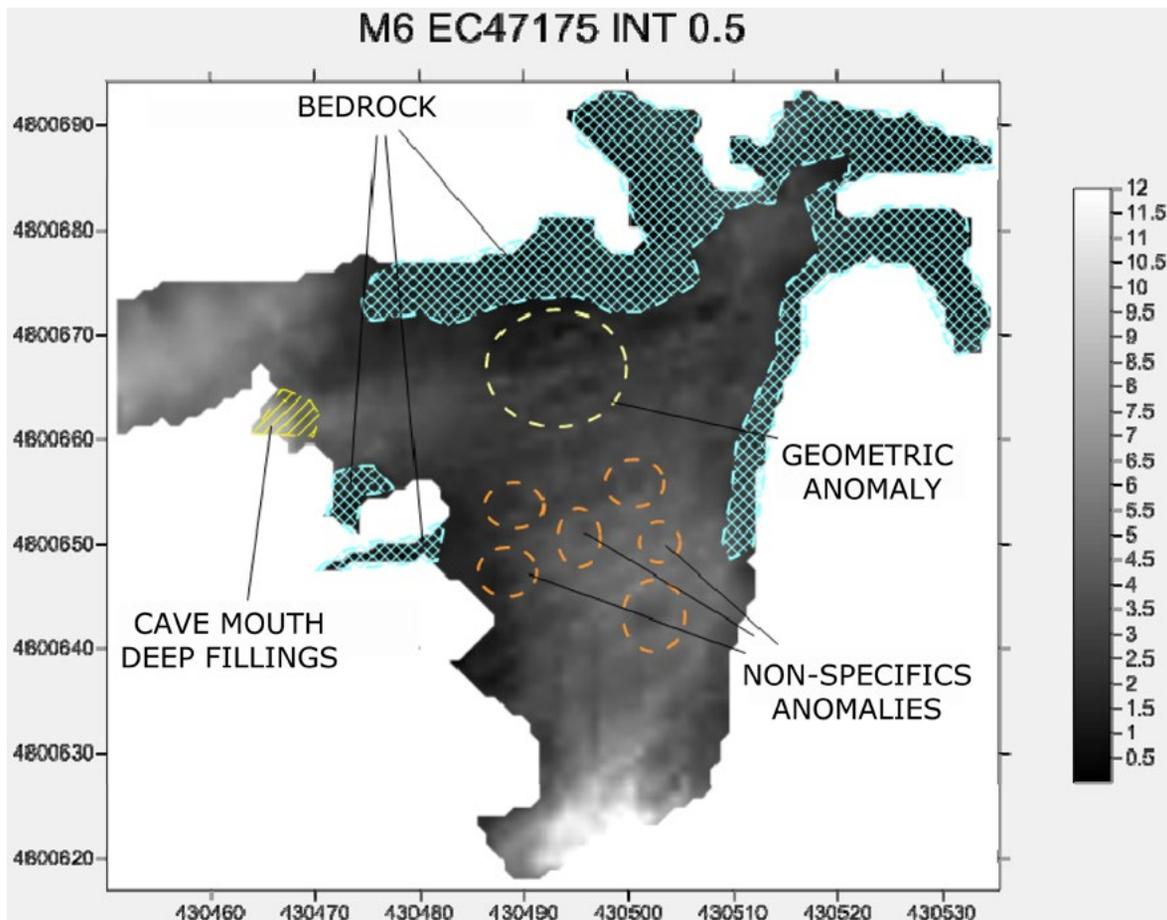


FIGURE 8. READINGS AND INTERPRETATION OF ELECTRIC CONDUCTIVITY FROM M6 ZONE.

Checking the anomalies

The anomalies detected suggest that it is possible to find archaeological structures related to open-air domestic zones. The research has documented several “hot spots” where we have focused the next step of research. In November 2014, two of us (ECB and CVM) have conducted a 10 x 2 m² test pit in zone M1 in order to ground-truth the readings. Under 90 cm of quaternary fillings several features were discovered in a subsquare of 5 x 1 m: a pit, a posthole and a ditch with several planks in vertical position. All of these are covered by a reddish layer with a lot of charcoal. These results confirm that our interpretation of readings provided by geophysical survey were adequate, at least in zone M1.

It cannot be established yet if the archaeological evidence discovered is related to a dwelling or another kind of feature like a fence or an enclosure. At present, the study of archaeological record in zone M1 is ongoing. We are awaiting the results of several analyses (including AMS dating and micromorphology).

Conclusions

The research has demonstrated that geophysical survey provides a more useful approach to detect buried evidences than other surveying methods in Cantabria. The method is particularly useful to help design research strategies. Indeed, the areas where potential archaeological features are located have been greatly reduced. Consequently, the excavation has been limited to one of these "hot spots" the survey detected. The test pit confirmed that in this "hot spot" the detected anomalies are indeed caused by archaeological structures. This does not have to be the case with all anomalies, but at least future efforts can be directed at selected areas.

Acknowledgements

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Electrical resistivity imaging survey around the caves of the Ojo Guareña Karst complex (Merindad de Sotocueva, Burgos, Spain)

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Abstract

Electrical Resistivity Imaging measurements were carried out around Kaite and Palomera Cave in order to identify their detrital infilling morphologies. These two caves are part of the Ojo Guareña Karst complex and contain different archaeological remains dating from the Upper Paleolithic to the Iron Age. At Palomera Cave, the proposed models show complex geological formations that mark the evolution of Palomera Sinkhole as well as the location of interesting infills where archaeological remains may have been preserved. In Kaite, the results suggest the presence of sediments prior to the ceiling breakdown, which, as this is one of the oldest caves in the karstic system (Ortega et al., 2013), may preserve early prehistoric phases of occupation remains. This information adds to a better understanding of the karst formation processes and may be used in the planning of a future excavation.

Keywords: *Ojo Guareña Karst, Electrical Resistivity Imaging, archaeology, speleogenesis*

Résumé

Des prospections géophysiques ERI (Imagerie de Résistivité Électrique) ont été conduites dans les grottes de Kaite et Cueva Palomera, dans l'intention d'identifier la morphologie de ses remplissages terrigènes. Ces deux grottes font partie du Karst d'Ojo Guareña et préservent des restes archéologiques allant du Paléolithique Moyen à L'Age de Fer Les modèles proposés montrent des formations géologiques complexes qui peuvent avoir

identifié, pour Cueva Palomera, l'évolution de la Doline Palomera et aussi la localisation des remplissages susceptibles de garder des restes archéologiques. À Kaité les résultats suggèrent la présence des sédiments qui pourraient appartenir à un moment antérieur à l'effondrement du plafond, or comme c'est l'une des grottes des plus vieilles du système karstique, cela pourrait indiquer l'existence des restes des occupations le plus anciennes. Cette information permet de mieux comprendre les processus de la formation du karst, et peut aider la planification d'une future fouille archéologique.

Mots clés: Karst d'Ojo Guareña, Imagerie de Résistivité Électrique, archéologie, spéléogènes

Introduction

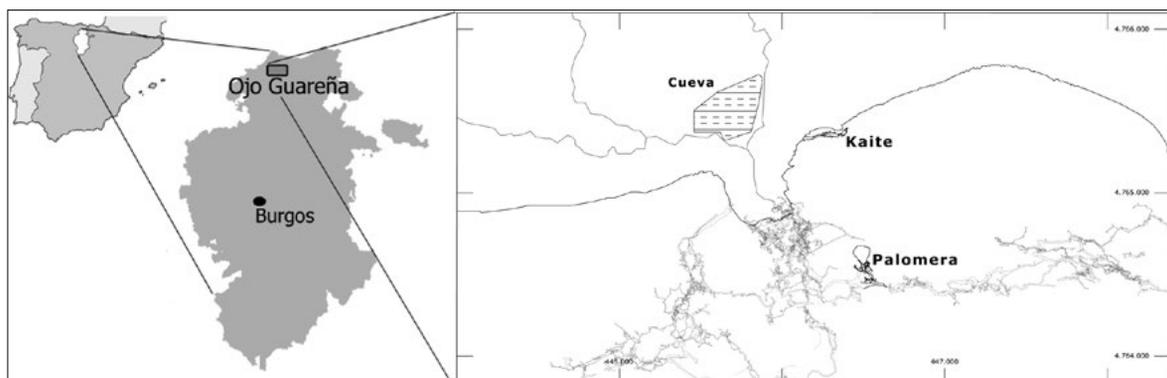
Geophysical prospection is increasingly being used in archaeological research because it allows recognizing buried structures and features without invasive methods. This facilitates the interpretation of sites, excavation planning and conservation policies (Conyers 2012; Bermejo *et al.* 2010; 2013b; Lowe 2012; Cardarelli & Di Filippo 2009; Benech & Hesse 2007; Hesse 1999; Wynn 1986).

Among the geophysical methods, geo-electric surveys, and in particular ERI, are commonly used in the investigation of archaeological karstic sites (Bermejo *et al.* 2014a; Porres *et al.* 2013; Ortega *et al.* 2010; Valois *et al.* 2010; Piro *et al.* 2001). This is because electrical resistivity surveys can determine the size, location and potential of different karstic features with high accuracy (Chalikakis *et al.* 2011; Guérin *et al.* 2009), based on the contrast of the different resistivity values such as between the limestone host rock and the detrital sediments.

The aim of the electric resistivity surveys at the Ojo Guareña Karst complex was to locate sediments that may contain archaeological remains or fills of ancient cave entrances, as well as to find void passages impassable to speleological exploration, which may help understand the evolution and features of this underground environment.

The Ojo Guareña Karst is located in Northern Spain, in the southern spurs of the Cantabrian Range (Figure 1). The Ojo Guareña Karst complex consists of more than 400 cavities with 14 entrances and a network of underground conduits that reaches a total length of 110 km. These caves are developed in Cretaceous limestone and distributed over six overlapping sub-horizontal levels, constituting one of the longest multilevel cave systems in Europe.

The dimensions and variety of these conduits offer countless possibilities for human occupation, as is reflected by the cultural sequence that dates from the Middle Palaeolithic to the Middle Ages (Ortega



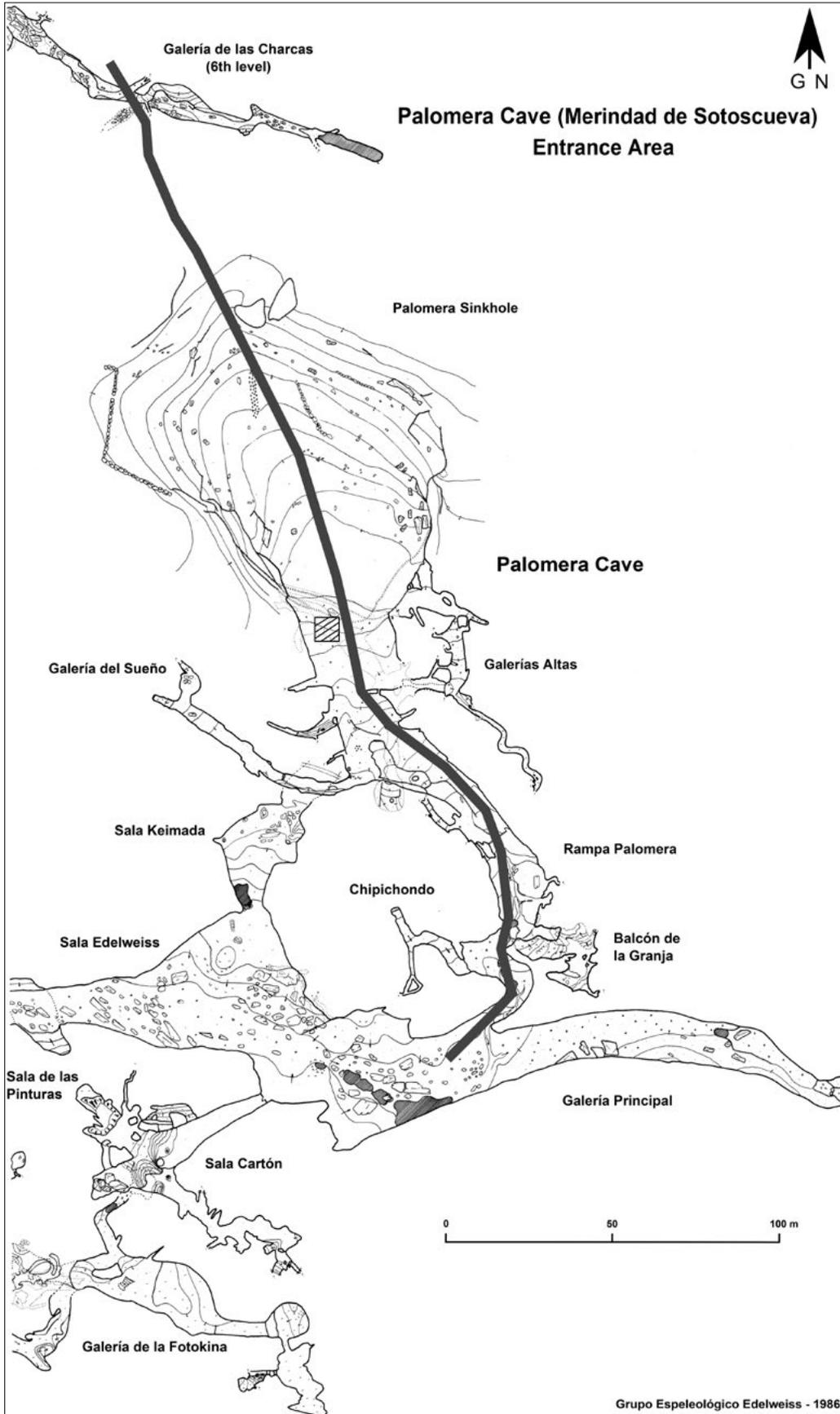


FIGURE 2. PALOMERA CAVE ENTRANCE AREA PLAN. THE ERT PROFILE LAYOUT IS MARKED IN DARK GREY. THE APPROXIMATE LOCATION OF CORCHON'S 1972 EXCAVATION IS MARKED BY A BLACK GRILLE (BASED ON G. E. EDELWEISS, 1986).

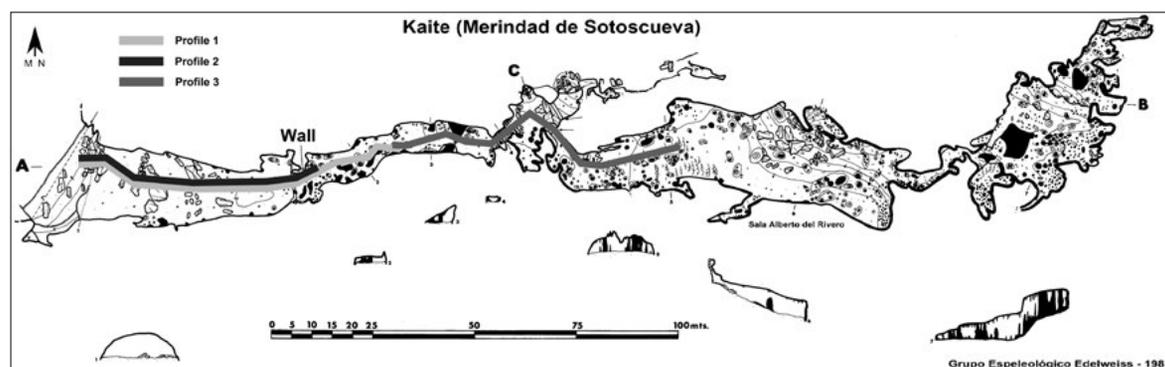


FIGURE 3. KAITE PLAN: A IS THE ANCIENT ENTRANCE; B THE SANCTUARY AREA; C THE CURRENT ACCESS. PROFILE 1 IS MARKED IN BLACK, PROFILE 2 IN LIGHT GREY AND PROFILE 3 IN DARK GREY (BASED ON G. E. EDELWEISS, 1986).

et al. 2013; Ortega & Martín 2011). Kaite and the entrance area of Palomera Cave are among the best-known caves in the complex because of their archaeological records (Ortega & Martín 1986).

Palomera Cave, the main cave of the karstic complex, contains numerous sites dating from the Upper Palaeolithic to the Iron Age. Soledad Corchón's 1972 excavation in the cave entrance uncovered a 5 m deep stratigraphy related to Chalcolithic and Bronze Ages, but did not reach the sedimentary sequence bottom. Therefore, unknown Palaeolithic deposits may still be buried in the lower stratigraphical levels (Ortega & Martín 1986) (Figure 2).

Kaite is a horizontal passage which constitutes an isolated higher level of the Ojo Guareña Karst complex. Neolithic and Bronze Age habitation areas are preserved in its two entrances: a valley facing entrance (A) where a habitation area was demarcated in prehistoric times by a wall; and the current access (C) which is the result of a ceiling collapse (Figure 3). In addition, it preserves sepulchral/symbolic areas inside the cave (B) with semi-naturalistic rock art (Uribarri and Liz 1973; Ortega *et al.* 2013). Its strategic location, perched 140 m above the Sotoscueva Valley, has protected it from the erosive action of the Guareña River and gave it a strategic location for territory control. Therefore, Kaite offers great potential for the presence and preservation of Pleistocene occupation remains.

Methodology

Electrical Resistivity techniques have proven their suitability for characterizing complex karstic environments (Martínez-Moreno *et al.* 2014; Bermejo *et al.* 2013a; 2014b; Cardarelli *et al.* 2006; Zhou *et al.* 2002) even when interpreted through 2D profiles, as they can determine both horizontal and vertical electrical resistivity contrasts.

2D ER imaging renders data compiled by a combination of four aligned electrodes: two of them inject an electrical current into the ground, whereas the other two measure the electrical potential difference. When multiple electrodes are combined along a rectilinear profile, different resistivity values can be recorded at various depths.

Depending on the array geometry, different imaging resolution and penetration depths can be obtained. Wenner-Schlumberger (WS) and Dipole-Dipole (DD) are the commonly used arrays for this type of surveys. WS usually offers good depth determination but poorer spatial resolution, while DD is better at locating vertical and dipping structures but is poorer in depth resolution (Dahlin &

Zhou 2004). Due to the unpredictable nature of the karst subsurface both arrays were used in the present study.

The ER acquisition was performed using a Syscal Pro-resistivity meter (IRIS instruments). In Palomera Cave a single profile with a length of 355 m and 5 m inter-electrode spacing was laid out from Dolina Palomera to Galería Principal, reaching a gradient of more than 80 m (Figure 2). For logistical reasons, the profile was laid out close to the eastern wall of the cave, and in some occasions the electrodes had to be placed on the limestone host rock. In Kaite, three profiles were measured. Profile 1, with a length of 87.5 m and 2.5 m electrode spacing, was placed over the valley-facing entrance area (*A* in Figure 3). In order to gain resolution at interesting features seen at profile 1, profile 2 was arranged in the same area but with less electrode spacing (1.25 m) and was therefore shorter (66.3 m –Figure 3). Finally, profile 3, with a length of 87.5 m and 2.5 m electrode spacing, was laid out over the actual access area (*C* in Figure 3).

In regards with data, effects C and P were filtered using the X2ipi software (© Alexei A. Bobachev) (Ritz *et al.* 1999). Subsequently, data was processed using the Res2dinv software (version 3.59.119, Geotomo Software) to produce a two-dimensional model of the subsurface from the apparent electrical resistivity values, represented in model blocks (Loke & Barker, 1996). Inversions were performed using the Robust option; topographic adjustments were carried out based on the geomorphological maps of the endokarst system provided by the Speleological Group Edelweiss. Special attention was paid to the inversion's absolute error, which is calculated from the difference between the measured and the calculated apparent resistivity values. The logarithmic color scale was designed to display the resistivity values of the geophysical surveys with respect to local geological observations and global knowledge of the karstic system.

Following this process, 225 Ω .m was established as the maximum resistivity value attributed to the different detrital sediments of Palomera Cave. For Kaite, the limit of 350 Ω .m was chosen, as the high resistivity values of the upper layers influence the underlying layers which yielded low resistivity values. These limits are indicated in each profile by a thick black line (Figure 5).

Results and discussion

The model proposed by the ERI profile for Palomera Cave shows a complex geology (Figure 4). In the profile's first 100 m there is a 70 m wide low resistivity anomaly at about 8 m under the subsurface (*a* in Figure 4), with an inclination which coincides with the slope of Palomera Sinkhole. These low resistivity values, which likely correspond to detrital sediments, cannot be attributed to any known cave passage and must therefore be linked to Palomera Sinkhole and/or to the continuation of Galerías Altas level, as they match this conduit's height (Figure 4).

In relation to it, there is a conductive anomaly around the profile's 150 m (*b* in Figure 4) associated to a vertical discontinuity (marked by a discontinuous line in Figure 4) that matches the cave's current entrance cliff. If this is a collapse sinkhole type, it is possible that the former anomalies represent detrital sediments related to the cave's ceiling/walls collapse, whereas the vertical discontinuity may be associated with a fracture that caused this collapse.

The first 50 m from the cave's current entrance reveal a conductive area (*c* in Figure 4) that reaches 15 m in depth. The resistivity values of this area are consistent with the sediments that host the archaeological site of which the upper 5 m are known from Corchón's excavation (Figure 2). Consequently, these may contain remains associated with human occupation.

Finally, the three conductive anomalies (*d-f* in Figure 4) found between the profile's 200-300 m could represent three filled passages with an E-W orientation, related to the fourth level of the karst (Figure 4). This level, the longest one, corresponds to Galería Principal (Figure 2) and is indeed developed E-W, which is the preferential direction of the Ojo Guareña Karst (Figure 1). Contrastingly, the

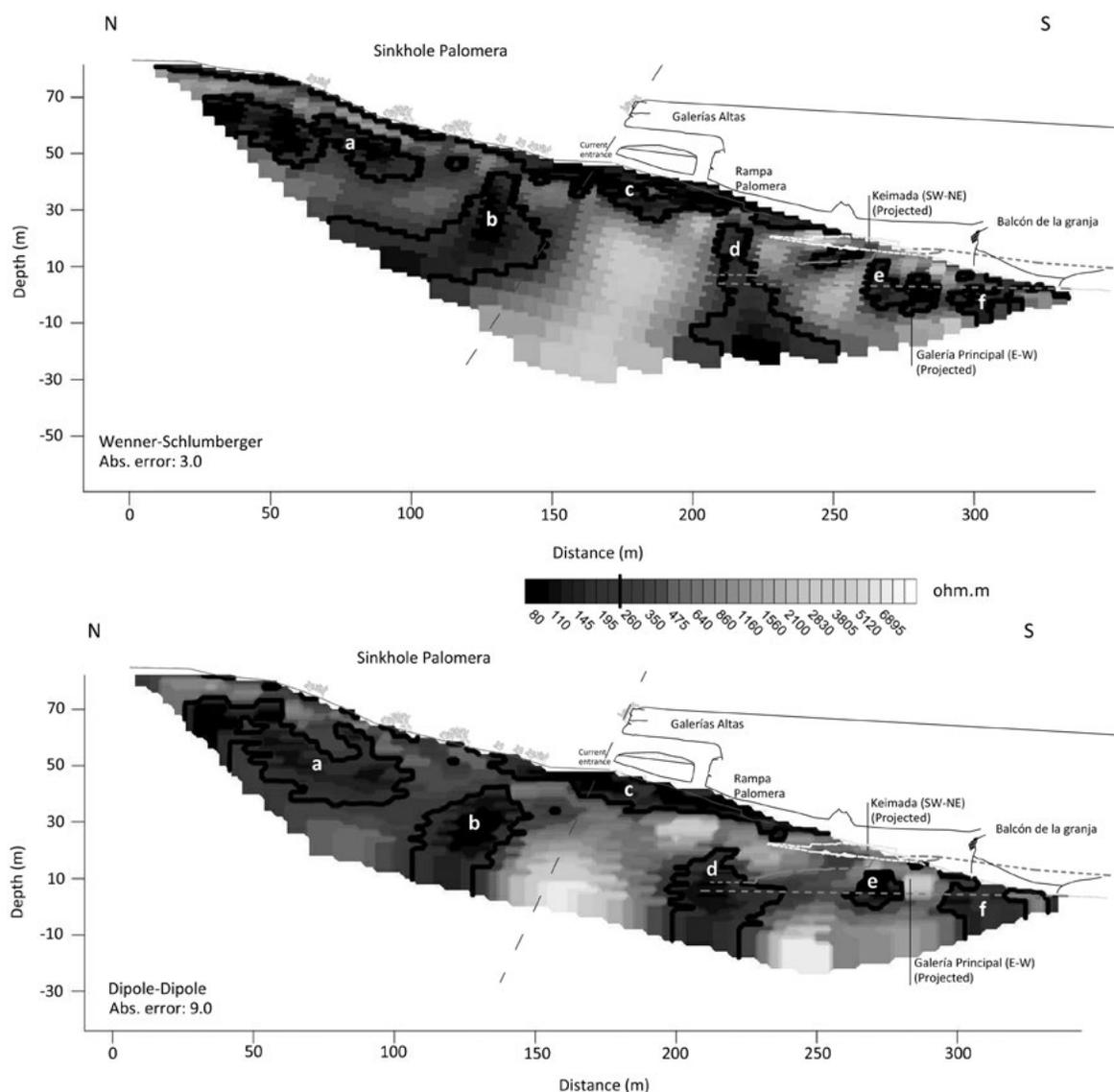


FIGURE 4. PALOMERA'S ERT PROFILE WITH BOTH WENNER-SCHLUMBERGER (WS) AND DIPOLE-DIPOLE (DD) RESULTS.

continuity of Sala Keimada is not visible in the ER survey (Figure 4). This could be due to the fact that the ER profile was placed too close to the eastern wall of the cave, or that the horizontal narrow, visible from Sala Keimada but not accessible to speleological prospection, ends near-by. The last infill (f in Figure 4), at 310 m, is the only one apparently connected with the surface and located near a connection with the Balcón de la Granja passage (Figure 4), a higher level where prehistoric hearths have been identified (Ortega & Martín 1986).

In summary, this latter infill and the one near the cave's entrance are the most accessible for archaeological excavation and may be considered in the planning of future archaeological work. Since the results of both arrays (WS and DD) are similar and their absolute error low, these data can be taken as reliable.

Kaite's profiles 1 and 2 (Figure 3) were laid out over a prehistoric habitation area, delimited by a prehistoric manmade wall (nowadays covered by a thin flowstone), corresponding to the twilight

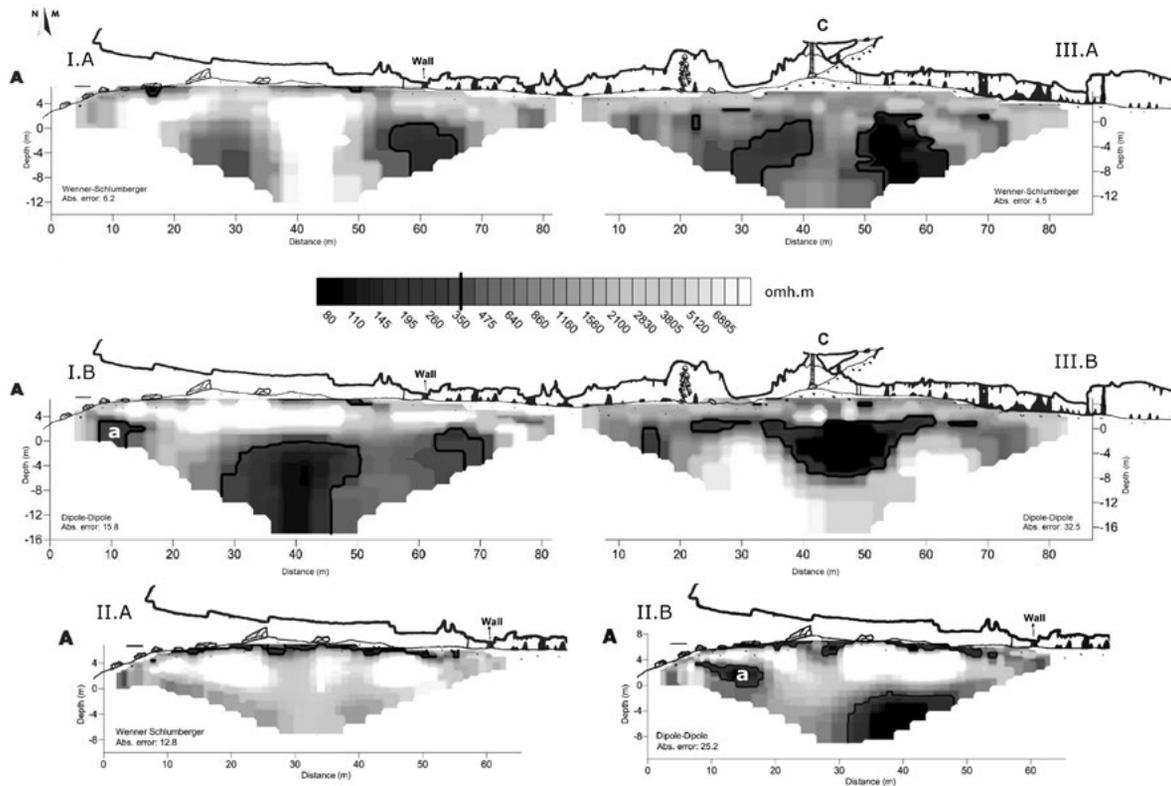


FIGURE 5. KAITE'S ERT PROFILES: I.A – WS PROFILE 1; I.B – DD PROFILE 1; II.A – WS PROFILE 3; II.B – DD PROFILE 3; III.A – WS PROFILE 2; III.B – DD PROFILE 2.

zone, where light is sufficient to permit human vision. In both profiles, the two applied arrays (WS and DD) show low resistivity values in the upper layers, which can be attributed to the sediments visible on the surface. These barely reach one meter deep and disappear laterally before reaching the prehistoric wall, which highlights their relationship to an occupation area (Figure 5 I.A, I.B, II.A and II.B).

The sediments of this upper layer sit on an irregular surface of high resistivity values that reach a depth of up to 7 m. This anomaly may be attributed to the ceiling breakdown blocks, which are visible on the surface and in roof, where the negatives of the blocks can be appreciated (Figure 6). Indeed, they disappear at the profile's 50 m, where the vault morphology changes into a phreatic type (Figure 5).

From this depth downwards it is difficult to make a proper interpretation about the subsurface nature: WS shows high resistivity values (Figure 5 I.A and II.A) whereas DD, at higher absolute error, reveals conductive anomalies consistent with the detrital sediments resistivity values (Figure 5 I.B and III.B). In any case, the conductive anomaly detected by DD at abscissa 15 m in profiles 1 and 2 (a in Figure 5 I.B and II.B) should be considered for a future excavation, as it is close to the surface and therefore easy to gain access to. Moreover, since it is located within the habitation area and below the high resistive anomaly, it is susceptible of hosting a pre-ceiling breakdown occupation. Given the fact that this is one of the oldest caves in the Ojo Guareña Karst complex, these deposits could be Pleistocene.

Profile 3 was conceived as the extension of profile 1, with the aim to cover the cave's length and gain more insight in the cave's current access collapse (Figure 5 III). The results show a very simple



FIGURE 6. DETAIL OF KAITE'S ANCIENT ENTRANCE. NOTICE THE STEPPED CEILING AND THE BIG BLOCKS ON SURFACE THAT MATCH THE VAULT'S NEGATIVES.

geological model that features high resistivity values reaching at least 4 m in depth (Figure 5 III), which can be related to the surface flowstones as well as to the actual access (C in Figure 3) ceiling collapse. In the underlying layers both WS and DD show a conductive anomaly that may indicate the presence of a previously unknown lower karstic filled conduit with N-S orientation. Another possibility is that the anomaly represents the bottom of Kaite's passage, which was filled with sediments and then covered with thick flowstones and/or blocks.

Conclusions

ER prospecting at the Ojo Guareña Karst reveal a complex geology, as can be expected from a multilevel karstic system. In Palomera Cave, anomalies a and b may be interpreted as sediments related to the collapse of Palomera Sinkhole. The conductive anomaly a can be interpreted as the continuation of Galerías Altas passage. Moreover, the vertical discontinuity in both profiles could be linked to a fracture responsible of this collapse.

Inside Palomera Cave, different detrital infills possibly related to human occupation have been identified. The one at the cave entrance and the one related to the Balcón de la Granja passage are interesting for further work because of their accessibility and relationship with other known archaeological sites. In both cases, further geophysical work (including complementary methods such as GPR), together with excavations or archaeological test pits are necessary for a better understanding of the karstic formation processes.

In Kaite the presence of a pre-ceiling breakdown occupation in the valley-facing entrance area is still up in the air, as the different arrays (WS and DD) offer contradictory results. However, the

results show more than 7 m of breakdown potential, which otherwise is witnessed in the geometry of the vault's negatives. Furthermore, the existence of detrital sediments filling an unknown lower karstic level or deposited at the bottom of the conduit, offers new possibilities for the interpretation of this singular cave. Additional geophysical prospection could be helpful in order to plan a future excavation and to elaborate a proper speleogenesis reconstruction of one of the highest and oldest caves of the Ojo Guareña Karst.

The different results obtained in both caves, especially with regards to the cave morphologies, illustrate the potential of ER imaging for archaeological site detection in karstic environments.

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