Best Practices of GeoInformatic Technologies for the Mapping of Archaeolandscapes

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Apostolos Sarris

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Preface

New geoinformatic technologies have recently had a transformative effect on landscape archaeology, particularly by facilitating the high resolution acquisition and analysis of data over large areas. These techniques have fundamentally changed the nature and scope of questions that can be addressed regarding the archaeological record. Despite this stimulating potential, many practising archaeologists were not trained in these methods and so are not fully aware of their capabilities or the most appropriate ways to apply them. This volume collates state of the art research in the fields of geophysics, geochemistry, aerial imaging, dating, digital archaeology, GIS and marine archaeology to present a comprehensive overview of the specialised techniques which can contribute to landscape scale archaeological investigations. It is hoped that it will serve as a 'best practice' guide for their use and encourage their widespread adoption by the archaeological community.

Geophysical survey has been revolutionised by the wide scale availability of high quality positioning systems such as differential GPS and the introduction of fast sampling multi-sensor arrays. These have freed geophysicists from traditional small and regularly spaced grids and allowed them to collect high density data over large areas extremely quickly. This significant increase in areal coverage, does not simply increase the amount of data available, but fundamentally revises the way in which these techniques can examine the spatial distribution of archaeological material. It moves geophysics from just being a technique of 'archaeological prospection' to being one that can answer nuanced questions about the interaction between the landscape and humans in ways that are impractical through conventional excavation and pedestrian survey techniques. Not to mention that the playground of the application of these techniques becomes even more challenging when the archaeological context is not the usual one (e.g. off-shore prospection). Another major advance in geophysical survey is the prospects offered by data fusion for quantitatively combining different geophysical data in a rigorous fashion, which is not coloured by preconceptions about the data or study area.

On a much larger scale, aerial and satellite imaging also provide important new insights into archaeological landscapes. A particularly popular approach in recent years is the use of structure from motion photogrammetry to create composite orthophotos and digital elevation models from aerial platforms such as kites, balloons and drones. This has been mainly driven by the widespread availability of cheap unmanned aerial platforms and high resolution, lightweight digital cameras. This advance has been augmented by the widespread availability of high resolution satellite imagery, allowing the subtle surface expression of archaeological features to be mapped remotely. The aerial and satellite perspective of the archaeological sites is particularly suited to the study of the archaeolandscapes as it positions archaeological material in the context of the broader area, including the topography, geomorphology, vegetation and hydrology.

Other spatially based digital techniques such as GIS, visualisation and agent based modelling also provide new tools for the analysis and dissemination of archaeological information. GIS modelling of geomorphic, topographical and geological parameters coupled with the spatial distribution of the cultural residues provide alternative ways to model the interactive responses between humans and environment through time. This is especially obvious when agent based modelling (ABM) is used to simulate the interactions between individual and collective entities in the landscape. Additionally, digital techniques allow the archiving and analysis of historical information in ways that facilitate new interpretations and mixed reality approaches provide stimulating means to reconstruct monuments and interpret and represent sites.

A number of other scientific methods have made an important contribution to the documentation of archaeological landscapes. For example, maritime archaeology has benefited from the wide scale availability of geophysical equipment as well as new technologies that allow the inspection of archaeological features below the depth of conventional SCUBA investigation. This includes diving technology such as the Exosuit and unmanned underwater vehicles. The use of geochemical techniques in archaeology has been facilitated by the use of low cost, high throughput methods such ICP-AES and essentially non-destructive methods such as laser ablation sampling. Also of great interest are new portable field techniques such as pXRF which allow immediate feedback on composition during archaeological investigations and facilitate the informed guidance of sampling for more elaborate analysis. The above techniques coupled with other approaches such as dating methods and provenance studies can create a more integrated framework for the study of the archaeolandscapes.

In conclusion, new geoinformatic technologies provide exciting new tools for the investigation and documentation of archaeological landscapes. This volume summaries the current best practices to enable archaeologists and practitioners to gain a further understanding of the current 'state of the art' across a broad disciplinary range. These methods are rapidly evolving and many new developments are expected soon however it is hoped that this book will serve as an impetus for archaeologists and cultural heritage professionals to integrate these techniques within their own research in a useful and productive fashion.

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Images of the Past: Magnetic Prospection in Archaeology

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Abstract: This chapter introduces near-surface magnetic prospection as it is applied in archaeology. It contains a short overview of the history of the application of this technique to archaeological sites and landscapes, and a brief discussion of the basic scientific principles involved. It is not designed to teach in-depth these principles, but rather to outline the current state of the art, and accepted 'best practice' principles for those wishing to employ magnetic methods in their research. As such, it is vital that practitioners obtain hands-on training on the conduction, processing, interpretation and reporting of geophysical surveys. This document discusses the environments and site-types that are best suited to magnetic methods, and explains how to get the most archaeological information from the surveys. It specifically considers the issues of working in Mediterranean environments, and explores mitigation strategies for these issues. It also emphasizes that magnetometry is one geophysical technique within a wide range available to the researcher, and discourages reliance on magnetics alone for archaeological geophysical prospection. There is also a short discussion of data processing and reporting and archiving for magnetic data.

Keywords**:** *magnetometry, gradiometry, geophysics, magnetic susceptibility, multi sensor surveys, data processing, archaeology, landscape.*

Introduction

It is impossible in a manuscript of this length to cover all but the most essential introduction to the physics behind magnetic prospection in archaeology, or the history of this discipline. Readers are referred to two excellent introductory texts that go into detail on both of these topics (and for other geophysical methods applied to archaeology): 'Seeing Beneath the Soil' (Clark 1996) and 'Revealing the Buried Past' (Gaffney and Gater 2003). This guide also draws heavily on the format and philosophy of the English Heritage best practice guidelines contained in 'Geophysical Survey in Archaeological Field Evaluation', (English Heritage 2008), which were updated in 2008 and a new version of them is also expected in 2015. Technology in this area has moved quickly, and 7 years on, this text will contain specific guidance on working with the most recently developed multi-sensor cart based gradiometer systems.

Magnetic Survey In Archaeology

In short, magnetic prospection in archaeology is the mapping of surface and sub-soil variations in the magnetic properties of soils and buried materials, such as walls, pit and ditch fills, and surfaces like roads. In order for it to be successful, there needs to be a measureable magnetic contrast between the buried material of interest and its surrounding matrix (usually soil, but also for example, sand). In near surface geophysical surveys, two main methods of discovering magnetic contrasts are employed. The first, considered here, is the influence magnetized remains have on the magnetic field of the earth. The second, and related property is that of magnetic susceptibility, which is how magnetized a material becomes in the presence of a magnetic field (see Simon & Moffat, this volume). The physics of magnetic susceptibility is explained below. What follows here is a short history of the use of near-surface magnetic prospection in archaeology.

The first archaeological applications of magnetic geophysics were early instances of metal detectors being employed on archaeological sites, as noted by Hesse (2000), most particularly Mesnil du Buisson, who noticed that the instruments also responded to ceramic tiles, and predicted the future development of a sub-discipline of 'geophysics' dealing with shallow / near surface anomalies, including archaeological ones, as early as 1934. During and immediately following WWII, instances of metal detectors being employed in more or less systematic ways continued, but it is not until the early 1960's that we see the development of magnetometers and their specific application to look for buried archaeological features, in the deployment of proton precession and caesium vapour instruments in the search for Sybaris conducted by the Lerici Foundation (Rainey *et al.* 1967). At the same time, in the United Kingdom Atkinson was developing methods and instruments for electrical surveys in archaeology, which together with the work of the Lerici Foundation prompted a period of exploration of various near-surface geophysical methodologies in the 1950's and '60's. These were largely reported in the (now defunct) journal, Prospezioni Archaeologiche, where the development of the discipline of archaeological geophysics can be traced. This slowed down in the 1980's, and in the UK in particular, the discipline moved out of the research arena and into applied practice, particularly in rescue archaeology. From the mid 1980's onwards, this shift to a commercial footing drove instrument development; since then advances in computing (speed of processors, graphic display capabilities, GPS

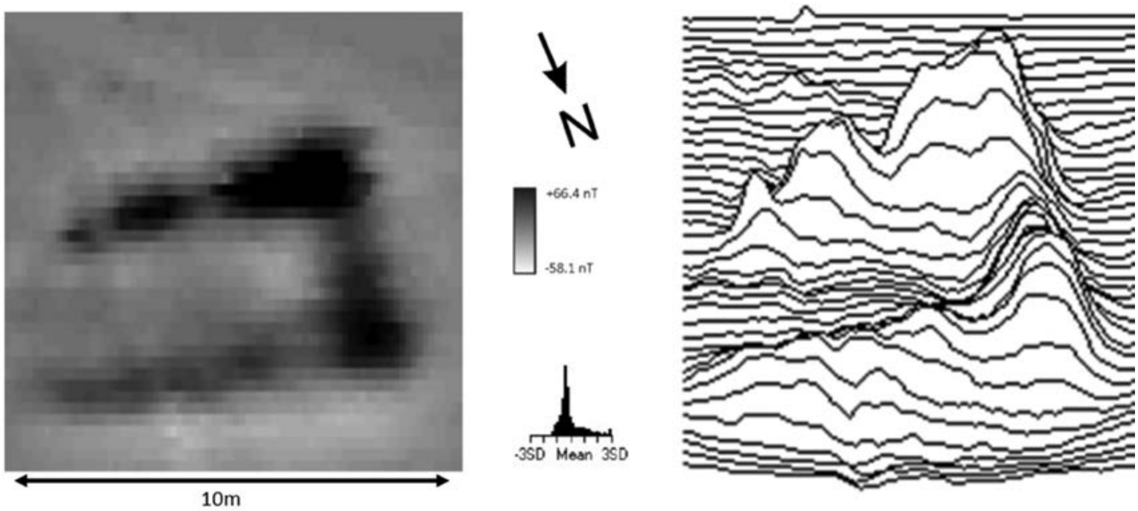

Figure 1. Greyscale raster plot (left) and trace plot (right) of a gradiometer survey over small Bronze Age structure at Contrada Damale, Northern Calabria, Italy. The greyscale data is plotted using 55 shades of grey, with a spread of 3 standard deviations from the mean. The survey was conducted with a resolution of 0.25m x 0.125m.

improvements, and memory capacity) have all allowed the development of instruments and methodologies. The basics physics remains unchanged, but now we use multi sensor platforms, located by differential-GPS or robotic total station, and towed from quad bikes, to cover huge areas: this has been made possible by changes in computing rather than fundamental developments in sensor technology or core methods.

The Physical Principles

Earth has an electromagnetic field that is generated by complex interactions in the molten metals in the planets core. Circular currents exist at the core-mantle boundary and these act as a solenoid, generating the field. Important characteristics of this field are the distinctive changes in the angle of dip between the poles and the equator; which impacts on the magnitude and appearance of anomalies (Clark, 1996:64). In geomagnetic survey, the measurement unit is normally nT – nano Tesla (= $10 \times^{-9}$ tesla), which is a measurement of magnetic flux density, or the strength of the magnetic field. The reason we normally work with such small units is because we are measuring very small changes in the local strength of the magnetic field of the Earth being caused (in archaeological surveys at least) by buried deposits or features that lead to small but detectable changes by one of two mechanisms. The strongest effects on the field come from remnant magnetization: this is when materials have been permanently magnetized by exposure to high temperatures (beyond their Curie point). These effects produce a small local magnetic field, which distorts the field produced by the earth. Typical archaeological examples include kilns and furnaces, but also buildings and features constructed from igneous rocks with remnant magnetism, such as basalt. Deposits with a contrast in magnetic susceptibility also have an effect on the Earths' magnetic field that we can measure, despite being magnetized only in the presence of a magnetic field. In general, areas with enhanced magnetic susceptibility (with respect to the one of the surrounding soil) are represented as positive anomalies, whereas areas with smaller percentage content in iron oxides (i.e. smaller values of the magnetic susceptibility) are represented as negative magnetic anomalies. Both kinds of anomalies are interesting in the process of interpretation of the magnetic data.

This means that as we move over a magnetic anomaly we see a change in the local field strength. This can be either measured directly, with a magnetometer that measures the total field, or with a gradiometer which measures the difference in field strength over a fixed distance (in other words, the gradient): this is because the steepness of the magnetic gradient is affected by the magnetic anomaly. Gradiometers have frequently been employed in archaeological surveys as they are cheaper to build than total field strength magnetometers, and have some other useful advantages, to be discussed below. Typically, whichever instrument is used, readings of either the gradient or the total field strength are taken along transects and displayed to show the relative changes over the survey area. These measurements can be presented as raster data, or less commonly, as trace plots of each traverse (Fig. 1).

There are multiple factors that have an influence on the final appearance of the anomaly in the data; the depth of burial, the type of magnetization, the instrument properties, the degree of contrast between the anomaly and the soil matrix, and the local topography all play a part. What is important to recognize here is that the dimensions and position of the anomaly in the data cannot be assumed to have a 1:1 relationship with a buried archaeological feature. In geophysical survey we map anomalies, which then need to be carefully interpreted as features using a combination of knowledge and experience. Practitioners should consult the following references for the applied archaeological perspective on magnetic prospection: Clark (1996 Chapter 3), Gaffney and Gater (2003, in particular pages 36-42). The Gaffney & Gater volume in particular has a very useful section full of examples of surveys of different types of sites, which despite a slight bias towards the UK, gives a good idea of the range of responses that can be expected. For more discussion of the physics behind the detection of these anomalies, the geological literature should be consulted. In this respect, a useful volume is Kearey *et. al.* (2002), which has a chapter dedicated to magnetism.

Instrumentation

Two general families of magnetometers are usually employed aiming toward the measurement of the total intensity of the magnetic field or its vertical or horizontal components. Proton magnetometers calculate the total field intensity through the measurement of the free-precession frequency (Larmor precession frequency) of protons aligned in a direction perpendicular to the Earth's magnetic field. Proton magnetometers may be used either in differential mode (using one rover and one base station sensors) or in gradiometer mode and have a sensitivity of about 0.1 nT.

As a further development of the proton magnetometers, modern total field instruments use alkali vapour based sensors. These are composed of a system of a vapour chamber, a photon emitter and detectors. Light excites the caesium atoms and polarises them. Changes in the local magnetic field will cause changes in the polarisation, allowing the atoms to intercept photons and this 'dimming' will be picked up by the detector. The detection is omni-directional, allowing the total field to be measured. In practice, this means there is a period where the lamps need to warm up and allow the vapour to become fully polarised. Commonly, two sensors are used together, either arranged one above the other (allowing the calculation of the gradient of the field), or side-by side to allow more dense coverage or to measure the horizontal gradient. The sensors can be carried by an operator or mounted onto a cart.

Fluxgate gradiometers are widely employed in archaeological surveys for a number of reasons, but primarily because they are considerably cheaper than alkali vapour sensors (Fig. 2). Highly magnetically susceptible cores (often mumetal) are wrapped in two coils, a drive coil and a detection coil. The drive coil rapidly cycles, driving the solenoid effect and bringing the core in and out of saturation. Every time they come out of saturation, external fields (i.e. the field of the earth) can enter them, causing an electrical pulse in the detection coil. Two strips are used, with the cores wound in such a way that the drive coil has no net magnetic effect on the detector coil. The fluxgate can only measure the field parallel to the axis of symmetry of the core. Any tilt will cause a large change in the observed readings. For this reason, the cores are always used in pairs, mounted a fixed distance (usually either 0.5m, 0.75m or 1m) apart. One measurement is subtracted from the other, giving the gradient of the vertical component of the field. It isn't possible to measure the total field strength with a fluxgate instrument. Greater sensor separation in theory increases the depth of investigation, but again in practice this is a minor distinction. For both methods, the typical depth of investigation for features with archaeological signal strengths (typically 5-20nT for anything other than remnant objects) is 0.5m to 1m (Clark 1996).

The two models of handheld gradiometers commonly used in archaeology (Geoscan FM series, Bartington Grad601 / DualGrad601) need to be hand trimmed prior to each episode of survey, to ensure the optimal alignment of the two sensors. Small changes from heating caused by operation or temperature shifts in the environment can cause 'drift' in the positions of the cores/coils and so the data. Mounting multiple gradiometers onto a cart system allows for very rapid area coverage while maintaining dense traverses. The mounted sensors cannot be manually trimmed like the handheld sensors: instead special tensor-alignment is required and a software routine calculates the adjustments needed to the readings to 'balance' the signal.

In theory, alkali vapour instruments are more sensitive than fluxgates, but actual field conditions mean this is rarely achieved, though a study by English Heritage did show they were better at detecting low amplitude (less than 0.5nT in peak amplitude) on soils with good magnetic contrasts (Linford *et al.* 2007). The main difference between the two instruments is that total field measurements cannot be made with a gradiometer, and in some situations these are necessary or preferable. There are also advantages to the fluxgate systems. Operating as a gradiometer, rather than measuring the total field, it is less subjected to the diurnal variations of the total magnetic field or to the geological trends caused by the bedrock (though igneous geology causes problems generally for magnetic data). These issues complicate the interpretation of total field data, but can be dealt with by the use of a base station magnetometer (in the case of diurnal shift) or with filtering (in the case of gradual background changes in geology). Instrument choice is therefore governed by the budget, by the size of the survey area, and by the terrain: cart systems cannot be used on steep slopes or where there is significant ground vegetation. They are also difficult to use on soft ground and ploughed fields, whereas instruments held by a walker are more versatile.

Where and how is magnetometry useful?

First of all, before deciding to use magnetometry as a geophysical method on your site, you need to consider what type of archaeological features you expect. Broadly speaking, you will be conducting research on a site where archaeological remains are known or suspected, to find out more about them (site elaboration surveys), or, perhaps

Figure 2a. Left: A SENSYS 8 fluxgate gradiometer array cart system, navigated by DGPS (see below), and set up with a 4m survey swath, with 0.25m traverse separation. Right: Bartington DualGrad 601, 1m sensor separation fluxgate gradiometer with 1m traverse interval for hand held surveys

Figure 2b. Left: Pair of Geonics G-858 cesium vapour magnetometers set up as a 1m vertical gradiometer. Right: Geoscan Research FM256 0.5m sensor separation fluxgate gradiometer (can also be mounted on a frame with a second instrument, with a 1m traverse interval) for handheld surveys.

in a Cultural Resource Management (CRM) context, you need to check whether archaeology is present in an area, prior to some destructive or disruptive activity (site detection surveys). In both cases, because of the wide variety of archaeological features that cause magnetic anomalies, magnetometry is a good 'first pass' technique, but it should not be used as a sole method, especially in CRM site detection surveys.

As has been previously stated, magnetometer surveys allow the mapping of materials with contrasting magnetic properties to their surrounding matrix. On archaeological sites, we are typically interested in anthropogenic anomalies rather than natural ones. This includes features with different magnetic susceptibilities as well as remnantly magnetised material.

Anthropogenic features such as pits, ditches, post-holes (if large enough) and building fills often contain material with enhanced magnetic susceptibility, and so show as positive anomalies in magnetometer surveys. The process by which they gain enhanced susceptibility is mostly due to the Le Borgne effect (see Gaffney and Gater 2003:38), whereby repeated heating (in hearths and ovens) converts

Table 1. Suitable and unsuitable geologies for magnetic prospection

Suitable / favourable	Unsuitable/problematic
Sedimentary parents including limestone, most sandstone	Igneous geology
Metamorphic geologies including slate, despite elevated background readings	Waterlogged soils
A few surveys have succeeded on basic igneous parents	Alluvium can be problematic, but depends heavily on local conditions: same for coversands, and clays
	Marine deposits such as old lagoons (good results from relict marine terraces however)

iron minerals into more susceptible forms, but processes of fermentation by magnetobacteria may also occur, particularly in the organic-rich deposits on settlement sites.

Built structures are more often visible thanks to remnant magnetization, either from fired components such as brick and tile, or due to the use of stone with remnant magnetism, such as basalt in Roman roads. Structures built from non-magnetic stone may appear as negative anomalies, in contrast with more magnetic fills and surrounding soils. Industrial features such as ovens, furnaces and kilns respond well to this method, and can produce very distinctive anomalies allowing robust interpretations. Transient occupation sites rarely leave enough contrasts, and dry-stone walls of non-magnetic rock that do not contrast well with the surrounding soils are also problematic. Similarly, field boundaries away from settlement sites will only by detected if the disturbed soil in the ditch fills has developed enhanced magnetic susceptibility: this will not always be the case.

As well as the type of archaeology you need to detect, you also need to know about the geology and pedology of the survey area. Whilst there are always exceptions, generally speaking, the conditions summarized in Table 1 need to be taken into account.

Waterlogging is a particular problem for magnetometry, as wet soils inhibit the enhancement of magnetic susceptibility (Thompson and Oldfield 1986), or in some environments, redistribute magnetic minerals within the soil (Kattenberg and Aalbersberg 2004). Igneous geology is also a major problem, with the remnant magnetism of the parent rocks swamping and overwhelming the responses from archaeological features, but with careful interpretation these environments can produce useful surveys. The English Heritage (2008) guidelines contain a useful detailed matrix of different geologies with suggested survey methods. These guidelines are free to download from https://www.english-heritage.org.uk/publications/geophysical-survey-in-archaeological-field-evaluation/

Magnetometry in the Mediterranean

In their review of geophysical surveys for archaeological purposes in the Mediterranean, Sarris and Jones (2000) identified a series of challenges the Mediterranean environment specifically poses for geophysical surveys. These all have an impact on magnetic prospection. They are:

- Fragmentation of the landscape
- Terrain
- Effects of weather and climate
- Geology
- Site longevity

Mediterranean landscapes are often characterised by *fragmentation*, either by the physiography of the region, with coastal zones that transition rapidly to mountainous interiors, or by social factors such as inheritance practices, which have led to a patchwork of smaller fields and terraces. Mixed crop regimes mean that even in flat areas, large contiguous fields under the same cover are rare. The mountainous *terrain* of the Mediterranean region doesn't just fragment the landscape, the steep and often rocky ground also poses logistical and practical problems for surveys. Larger cart-based systems can operate on rough and sloping ground, but only up to a point: then, handheld instruments must be used, costing time. The steep terrain also means terracing is common. Terraces are both difficult to survey and difficult to interpret because of the way slope-processes and terraces combine to simultaneously erode and bury layers following the original slope profile.

The ruggedness of the *terrain* in Mediterranean landscapes also causes other problems. Typically, settlements tend to be *long lived* due to the scarcity of suitable land near cultivable soils. This means that archaeological sites are often within or in close proximity to modern settlements, and often exist as palimpsests of traces built up over millennia. This causes a number of problems for magnetic prospection. First of all, modern buildings and urban areas disrupt magnetic surveys a great deal, thanks to the use of large amounts of metal in construction and utility pipes and cables. There comes a point where an area is too built up for magnetic surveys to be useful, as the noise from the modern materials drowns out any useful archaeological response. Secondly, magnetic surveys lack a depth element. They record only two-dimensional information. Where there is a palimpsest of features, sorting out the tangle of responses from different depths and phases of the site becomes quite difficult, rendering archaeological interpretations uncertain.

The Mediterranean *climate* is favourable to magnetic surveys in terms of the formation of magnetic contrasts. The humid winters give rise to reducing conditions, and the hot dry summers to oxidizing conditions, meaning that soils in the region generally have a high in-situ conversion rate for the iron oxides (i.e. they have high magnetic susceptibilities), leading to strong contrasts that are readily detectable, especially on well drained limestone geologies, which occur over much of the region (Sarris and Jones, 2000:23). However, in some areas, the natural soil enhancement can reach a similar or larger magnitude than the archaeological features, especially on more ephemeral sites. This can cause problems for survey interpretation. Furthermore, the dryness of the soils for much of the year causes problems for electrical and ground penetrating radar surveys, which rely to some degree on moisture contrasts. This means it can be difficult to obtain comparison data from other methodologies to improve interpretations and check the magnetic surveys didn't miss something crucial due to a lack of magnetic contrasts.

In the field: preparation, survey and common pitfalls

General principles

All instruments require different set up procedures. Ensure you are familiar with the process for your specific instrument, and the detection implications of any options you select (such as the sensitivity settings, and any pre-processing of the signal). Remember that different soils and site-types might require different settings and approaches. A key element in obtaining good data is to be flexible and responsive to the specific conditions of your site, rather than following a 'one size fits all' approach. Bearing this in mind, what follows are general principles for obtaining the best data possible, regardless of instrument type or site type.

First of all, some (usually fluxgate) instruments require a balancing routine, whether manual or software driven. This should be done in an area of the site which is known or reasonably assumed to be free of large magnetic contrasts. The better an instrument is balanced, the better the initial result will be, reducing the need for data processing. Balancing and zeroing a machine over an anomaly can skew the results of the survey so badly as to render it uninterpretable. Handheld instruments can be used to 'scout' for quiet spots even before the have been balanced. Larger systems usually need to be balanced 'blind' without a scouting phase. In this instance, be sure to select a location away from modern disturbances (such as the fieldwork van and other instruments in use) and away from any known archaeological remains, on flat ground.

Whether working in grids, or using ungridded methods, you should aim to hit known linear archaeological features at an angle. On sites with orthogonal remains, such as urban area with gridded street plans, this means approaching them on a diagonal, to avoid traverses running along linear anomalies. The reason for this is two-fold. First, it prevents linear anomalies falling between traverses and remaining undetected, and generally allows them to be better visualised. Secondly, some commonly employed filters (especially for gridded data) can process out anomalies that run along a traverse. Where the orientation of the archaeology is unknown, it is better to plan the grids (if used) and traverses to allow maximum coverage.

For hand held instruments, operator gait is very important. New operators should be monitored, their data frequently checked and fed back to them to improve their technique. Operators must be always checked to be magnetically clean (not having any metals on them during the acquisition of the measurements). Ideally, the instrument should move very little relative to the soil surface, and the pace should be stable for the entire traverse. The operator needs to be careful to avoid orientation errors (twisting the instrument), particularly at the starts and ends of lines. Further, for gridded surveys the operator needs to be able to calculate accurately the dummy readings needed to navigate obstacles in the survey, and how to correct their mistakes.

When surveying on sloping sites, additional care must be taken. It is usually best for traverses to run up and down slopes, especially when using multi-sensor equipment, rather than along contours, to ensure both/ all sensors remain a consistent height above the soil surface. If your are using a gridded methodology that relies on operator pacing for the reading locations, and you are zig-zagging back and forth, taking data in both directions, on steep slopes it may be worth switching to parallel traverses as the difference in pace on the up and down traverses can be difficult for even experienced operators to compensate for, leading to staggering errors in the data. See the section below for further information.

In general, the larger the area that can be surveyed the better. If time and budget constraints allow for it, always capture more than the immediate area of interest. This has several advantages. First of all, it allows for clearer interpretation as the difference between on-site and off-site signals will be clearer. It is very hard on certain types of site to distinguish anomalies of interest from the background if you don't have a clear idea of what the undisturbed background looks like. Furthermore, site extents can be difficult to ascertain a-priori and it is better to maximise the probability that you have covered the entire site. Given what we have said about the Mediterranean landscape above, this can be tricky given field divisions and terracing. It's therefore important to also maximise the coverage by surveying right up to these boundaries, working in irregular areas, even on gridded surveys. Only surveying in square/rectangular blocks leaves large amounts of the landscape uncovered at the edges of irregular fields and terraces, and it is well worth the extra time it takes in the field to obtain the most comprehensive coverage possible.

This gives a much greater chance for the recognition of features that cross underneath modern landscape divisions.

On a similar principle, where possible work outside walls, ditches and other obvious site boundaries as well as on the interior as useful information can be recovered about extra mural activities. It is possible that obvious surface boundaries only reflect one particular phase of a site and that information will be lost if the survey is confined to just that area.

Finally, as with the point above about instrument settings, always adapt your survey strategy (including resolutions, see below) to the specific case at hand. For example, a compromise may have to be made between approaching the archaeology at a specific angle and adapting to a steeply sloping site. Record the choices you make (perhaps with the help of a form) and explain them in your reporting so subsequent users of your data can follow your reasoning.

Gridded vs ungridded

The choice between gridded and ungridded methods will usually be instrument based. Handheld fluxgate systems (at time of writing) require grids to be set up in advance of the survey, whereas cart-based systems are typically located by GPS or robotic Total Station, allowing 'freeform' surveys. Caesium and other alkali vapour systems can use a variety of navigation methods, depending on the manufacturer and the instrument settings. This is a general discussion of the specific considerations for the two approaches, regardless of manufacturer or intended processing software.

Gridded methods

On flat sites, use a Total Station or GPS system to set out grids wherever possible. You should know the absolute location of the grid pegs to within 10cm, so navigation grade GPS is not accurate enough and another method must be used. For small sites, setting out the grids using optical squares, or with lines and tapes using Pythagorean triples to create right angles is acceptable, but the resulting grid pegs must then be recorded with high accuracy. If this method is used, then grids should not be set out more than two steps away from the original baseline, to avoid error propagation. Tapes and Pythagoras or optical squares is actually a better method for setting out grids on steeply sloping sites. Where there is a significant slope, the on-the-ground distance can be considerably more than the planar distance used by a total station or dGPS, creating larger grids in terms of the area to be walked than the planned grid sizes. Running tapes along the ground surface cancels this effect, but the resulting pegs must be correctly recorded and the data fitted to them. Measurements of anomalies should be made on data that hasn't been 'squeezed' to fit a flat surface, such as in a 2D GIS representation of the data.

Instruments designed for gridded surveys (particularly Geoscan instruments and the Bartington Grad601 systems) come loaded with firmware that presupposes the data will be collected in grids, and specific modifications must be made to collect data in other ways. The firmware typically contains navigation aids that tell the operator where they are in the grid (i.e. what line, and which position or reading they are about to obtain or have just obtained). The firmware also allows for some mistakes during the acquisition of the data to be corrected, such as being able to delete a line and re-take the data if a pacing or heading error occurred. The firmware also usually allows dummy data points to be inserted at the time of the survey, such as when there is an obstacle within the traverse or the grid is incomplete due to a field boundary. Usually with such systems, a whole grid of data (including any dummy readings) is assembled and stored during the survey process, allowing the data to be downloaded and immediately visualised with no or limited pre-editing. Data is typically stored on resilient flash memory systems in real time, and survives accidental switch-offs and other operator errors, but the specific manufactures instructions should always be adhered to prevent data loss. This does mean however that if a mistake is made (such as a missed traverse) it isn't usually possible in the field to manually go in and add in the missing data; instead, data must be deleted back to the relevant point and then re-collected. For this reason, frequent checks on the position the instrument shows and the real position in the grid are vital as they allow errors to be corrected easily and efficiently. Finally, bear in mind that some processing software (and instrument firmware) assumes a particular and consistent approach to the grid, for example, assuming that all surveys begin in the bottom left hand corner of the grid (based on the direction of the first traverse). Check the instructions for your chosen software and hardware carefully when planning and setting up the grids, as this constraint on starting corner affects choice of grid layout and traverse direction. Typically, with gridded surveys you want your 'starting' baseline to be the most complete edge of your grid (if the grid is partial or disrupted). This means that sometimes, the optimal gridding approach can only be decided in the field after a site inspection, to take into account slopes and obstacles. This should be taken into account when pre-digitising grids using aerial photographs or topographic maps for set out with differential GPS or Total Station.

Ungridded surveys

Typically, survey systems that allow the use of GPS for locating the data points will have a navigation system to monitor the survey tracks and instruments swaths in real time, to allow monitoring of the coverage obtained. If this isn't the case, some control system to space the traverses should be adopted, such as a tape at each end of the survey area with a sighting pole or flag, to allow straight traverses with correct spacing to be maintained. Follow the manufacturer's instructions to obtain best possible position solutions and ensure you have correctly understood and accounted for any offset between the sensor(s) and the antenna. Make frequent backups (i.e. as one contiguous area is finished) of the survey data.

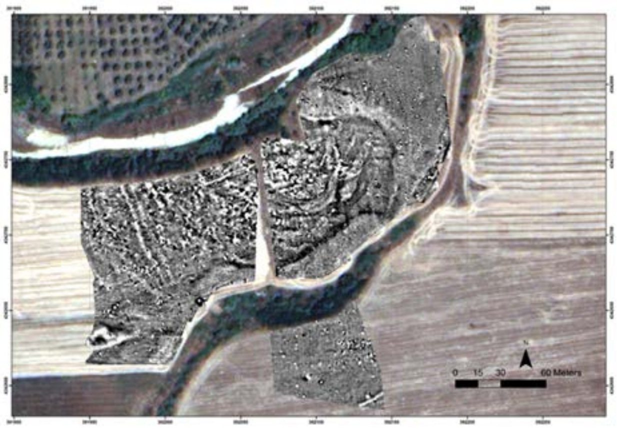

Figure 3. Geomagnetic data collected with the multi-sensor SENSYS system. The eight sensors were separated with 0.5 meters, but along transects the data is collected with high spatial frequency (~10 cm) resulting in a dense point cloud of magnetic readings.

One of the main advantages of an ungridded survey is that minimal time is spent for the survey logistics (e.g. setting up the grids, strictly following transects, etc). Especially, if a multi-sensor system is used in an ungridded fashion survey coverage increases drastically. In one of such instances, at Karatsangliou —a Neolithic site in Thessaly, Greece—, researchers were able to survey 1.5 hectares a day in high resolution (Fig. 3). Correct this sentence to read: Achieving the same coverage with a gridded survey would have required setting out 38 20m x 20m grids, in addition to the extra time needed for surveying with fewer sensors.

Resolutions and Thresholds

Unless your survey is heavily time constricted and looking for large targets only (roads, public buildings of classical or later date), you should use a maximum of 0.5m transect separation and 0.25 in-line or better sampling resolution. Older guidelines and manuals suggest 1x1 or 1x0.5 is OK but this is due to historical processor & memory constraints, which meant that survey resolution was a trade-off between obtaining enough detail without creating unmanageably large datasets. Processor speeds and hard-disk sizes have improved to the point where this is no longer an issue. In almost all cases, the higher resolution data you are able to collect the better. However, for most archaeological features, transect separations of 0.25m or smaller are only useful where very fine detail is needed (and you expect the site to produce good enough contrasts at that scale), either for complex architecture, or on more ephemeral sites where small features like postholes are anticipated.

Surveys with a large difference in the resolution between transect intervals and reading intervals (such as 0.5 x 0.125) can run into problems when processing data due to the difference in detail obtained on the y and x axis, with anomalies appearing to be elongated over the traverse and truncated between traverses. Also, bear in mind that although magnetometry (especially GPS located multi-sensor systems) is the fastest method in terms of area coverage, some targets may be poorly defined: therefore a 'negative' result should always be checked with another (non-magnetic) method like earth resistance or GPR.

Most instruments have a setting that governs the sensitivity of the readings taken. Generally speaking you should use the most sensitive option possible, as the less sensitive options are designed for use in highly magnetised environments with a large range in the expected values (say, on igneous geology). Similarly, there is usually a threshold setting, at which values that exceed a set range will either be recorded as dummy values or as the maximum or minimum set. This can be useful in noisy environments, constraining the dataset to a reasonable range of values which minimises the amount of processing needed to remove large responses from the dataset during processing, as these are rarely archaeological in origin. On most soils and sites, a typical sensitivity is 0.1 nT (recording variations of 0.1nT in amplitude and higher – the limit of most fluxgate systems), with thresholds of 1000 nT above and below the background. Most archaeological anomalies should be observable at this sensitivity and within this range of values.

Geolocation and topographic information

As well as the actual data, other information should also always be recorded for every geophysical survey. For gridded surveys, the location of all grid pegs must be recorded with a method that allows for better than 10cm accuracy on the ground. You need to be confident that you could return to site and re-establish the exact same grid, or navigate to a known anomaly or point with centimetre accuracy. This can be achieved using standard survey methodologies using local grids or surveying directly into projected systems, such as UTM. Whether the survey is gridded or not, major topographic features should be recorded (if gridded, in the same system as the grid pegs); this should include (but is not limited to): standing archaeology, field boundaries, breaks of slope, changes in the surface conditions (e.g. ploughed/unploughed) and any obstacles to the survey. This can greatly assist with the interpretation of the data, and placing any findings in their topographic context. Sketch maps of the site with major buildings, roads, surface changes should also be made, along with a record of what order the grids were surveyed (using a standard reference) and by whom. These sketch maps should also note any vegetation, the field state, weather conditions and any other pertinent facts about the survey. The use of standardised forms for this is encouraged for projects that involve multiple surveys. If the survey is gridded, sketch the grids and record the point ID's for surveyed pegs, and note the order of grids in instrument.

The geolocation of any observed anomalies is only going to be as good as your recording of the survey location, either directly, when working ungridded, or indirectly with gridded surveys. Furthermore, with gridded surveys, the location of the data points relative to the grid pegs depends entirely on good survey practice and the skill of the operator in being able to position themselves and thus the readings consistently along the traverse. The use of survey lines with navigation markers (typically at 1m intervals) is strongly recommended, even for experienced surveyors. The use of sighting flags for paced surveys is only advisable for experienced operators working on flatter sites with consistent ground cover.

Zig-zag traverses in gridded surveyors can be problematic. Even experienced surveys can have problems shifting between the up-and down lines in terms of instrument positioning. This can lead to 'stagger' errors in the final dataset due to mismatches in the assumed locations of the readings along the traverses. The corrections needed for these errors can shift the apparent location of an anomaly, enough to cause problems for targeted corings or test pits if the corrections are not properly understood. Therefore, the zig-zag approach should only be used by experienced operators, and even they may be better using a parallel method on steeply sloping sites, or sites with difficult/ rugged terrain. Your aim should always be to collect the best raw data possible, rather than relying on processing to clean up or compensate for poorly acquired datasets.

After the field: processing, intepreting, reporting and archiving

Data processing

Despite the fact that different geophysical methodologies investigate different physical characteristics of the phenomenon they also have considerable common points in their workflows. In this respect, magnetic prospection is not an exception. Without going into details, we provide a typical workflow one might follow after collecting magnetic data. Good data processing is a mixture of technical skill / understanding and experience, and should only be carried out by sufficiently experienced operators.

1. Downloading data from the instrument: Most sensors keep data in their internal memories. Therefore, it is necessary to download data to dedicated computers for processing, interpretation, and archiving. In some cases, sensors might be directly connected to computers, and thus, data is transferred to these computers on-the-fly during the survey. Regardless of the way data is collected, it is strongly advisable that a backup copy of the data is retained in the original format. Standard operating procedures should be adopted in the field to reduce the chances of data loss, such as retaining the data on the instrument until a backup has been made of the initial download.
2. Conversion of data formats: If the researcher does not have access to dedicated processing software or he/she wants to use another platform, it becomes necessary to transform data from its native format. It is of vital importance that metadata should be also transferred with the new format and that the raw and meta data are securely archived.
3. Creating mosaics: Whether data has been collected on grids or following an ungridded method, it is usually desirable to create mosaics of magnetic data. Obtaining a larger coverage within one data file not only provides a more representative picture of the anomalies in their wider contexts, but also helps researcher to accomplish a better data processing routine.
4. Data processing: Processing magnetic data usually requires specialized software, often provided by the vendor of the instruments. Proprietary geophysics software is becoming more accessible to archaeologists and more user-friendly day by day. However, they also remain, to some extent 'black-boxes' and only in some rare cases give the user full access to the parameters of routines and functions. Therefore, it is still necessary to have some degree of specialty in data processing. Without paying special attention to underlying principles of the process, erroneous results can be easily reached. In some other cases, researchers may need to develop their own specialized software. In such cases, it is important that developer pays particular attention to assumptions behind methodologies and that the new software/routine-package is bug-free as much as possible.

Geomagnetic data processing usually involves algebraic and statistical methods in order to improve data quality and make interpretation easier. As for other geophysical data processing techniques, the basic rule of thumb for magnetic data processing can be stated as 'if the anomaly is not immediately visible in the raw data, do not create it.' Data processing can be simplistic; just to 'clean' data or it can attain sophisticated levels. Considering the variety and complexity in magnetic data processing, we will only here briefly evaluate the four most common techniques.

1. Spike removal: Magnetic data may include artificial data spikes due to instrumental noise, or modern ferrous material may interfere with the readings and suppress signals from archaeological features. To reduce (or even sometimes cancel out) these noises, a basic statistical method can be used. The idea is based on comparing each data value with a threshold value and replace data which are falling above (or below) this with statistically sound data. Generically, the determination of the threshold is based on the distribution of data and replacement is provided after an evaluation of data values around the 'spiked' value.
2. Destaggering: Staggering is observed if the instrument data logs are not well aligned with predetermined spatial markers of the survey area. This is especially the case when the survey is conducted in a zigzag mode; the user may experience a systematic displacement at each transect. This problem can be solved by determining a representative value of displacement and iterating survey transects according to this value. Almost all

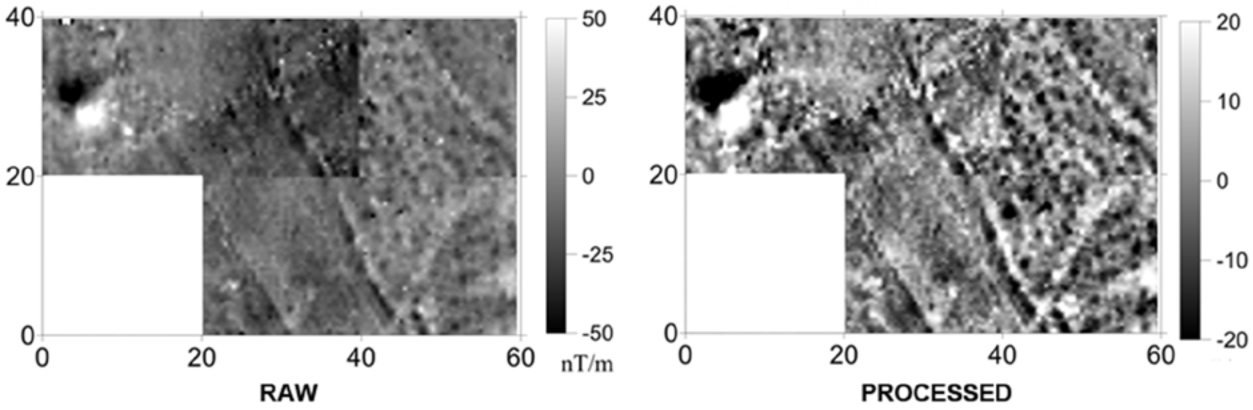

Figure 4. Geomagnetic data collected with Geoscan FM256 on 5 grids with dimensions 20x20m.

geophysical data processing software provides a solution for this as a built-in function.

3. Destriping: Striping in magnetic data is visible when survey transects have significant disagreements for their average values. Striping might have different sources; surveyor might have kept the instrument at alternating levels over the ground, or might have tilted the instrument at alternating transects, etc. Likewise, instrumental drift may cause striping effects in the data. Basic statistical functions, such as pulling the average of magnetic values at each transect to a predetermined value (often zero) can solve the striping effect.
4. Edge matching: If the surveyor is following a gridded survey methodology, it is likely that grids have contrast differences between them. Edge discontinuities will happen if the instrument is aligned at a different base station or instrument drifted significantly during the survey. Dedicated built-in functions usually exist to correct for edge discontinuities. It is also very likely that destriping process provides satisfactory edge matching. In order to avoid edge mismatches, the best practice would be to align sensors after each grid over a magnetically quiet location, preferably returning to the same location throughout the survey.

As an example, magnetic survey at Therasia Island (Fig.4) reveals the power of data processing for a better interpretation of archaeological data. Mismatches between grid edges are immediately visible in the raw data. These mismatches not only create unappealing datasets, but they also make archaeological interpretation harder as some archaeological features may be obscured at the edges. The other problem lies in the range of the data. Through statistical operations, data ranges can be matched in such a way that features become more visible, and thus, their interpretations to become easier. Spike removal in this survey cluster also resulted in an increase in the signal to noise ratio.

Interpretation, reporting and archival of magnetic data

Interpretation: Maybe one of the most important steps in the geomagnetic prospection is the accuracy of the interpretation of data. Interpreting results not only requires knowledge of the archaeology of the area, but also necessitates some working experience with geomagnetic prospection and how each specific instrument behaves under certain environmental conditions. If the magnetic prospection is outsourced, it might be crucial to team up with a geophysicist. Remember that good interpretation relies on both geophysical and archaeological understanding and is rooted in experience. Interpretation of all forms of geophysical data is greatly improved by feedback from archaeological excavations and other forms of ground truthing: seek feedback from the end-users of your data in order to improve interpretations of future surveys.

Reports on magnetic surveys should include as a minimum: Information about the site and its context: date/period, what we already know about archaeology on the site, the land use, geology, and survey conditions; Technical information regarding the instrumentation and settings, with short explanation / justification for the particular methods employed; Raw data & processed data plots with any additional topographical and archaeological information relevant (paths, infrastructure, upstanding remains etc) marked out; Interpretation drawings of any anomalies presented separately from the data, ideally using either CAD or GIS; A discussion of the data obtained, with a clear separation between description of the anomalies and any archaeological interpretation possible / offered; If needed, suggestions for further work.

Metadata and Archiving: Upon the completion of magnetic prospection and interpretation of results, generating metadata and creating an archive is necessary. Accessing metadata (the name of the surveyor, his/her contact address, processing steps, parameters used in the process, and many others) can be of crucial importance if the data needs to be re-examined by future researchers and heritage professionals. Archiving data in both the native format and other basic interchangeable formats will help future researchers to analyze and interpret magnetic data in their own ways. Keeping data only in native format may hinder future use if proprietary software ceases to exist and/ or does not support older formats. Excellent guidelines for the archival of geophysical data have been published by the Archaeology Data Service in the UK, and can be downloaded from http://guides.archaeologydataservice.ac.uk/g2gp/Geophysics_Toc, or in the publication by Schmidt (2013). Bear in mind that there may be local legal obligations for filing reports and / or data with a state archaeological service, within set timeframes.

Concluding remarks

Due to its high efficiency, magnetic prospection is usually considered as the 'first option' among other geophysical survey techniques. In comparison to resistivity surveys, more area can be covered in unit time. Magnetic prospection usually provides better data resolution in comparison to electromagnetic surveys. Finally, these instruments are more user-friendly than GPR. New generation multi-sensor systems, equipped with GPS provide additional capacity though with increased instrument cost. Thanks to its historicity there are now well-established algorithms, routines, and data processing workflows for geomagnetic data. Easy-to-use software also increases the number of researchers who are willing to adopt magnetic prospection in their studies. The transition from gridded to ungridded surveys has been an added value for this technique.

Despite such advantages, magnetic prospection usually fails in urban environments where metallic clutters distort data. Fences, power lines, underground pipes also cause problems in collecting and interpreting geomagnetic data. Therefore, researchers are usually advised to employ other techniques alongside magnetic prospection to fully exploit the arsenal of archaeogeophysicists.

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GPR:
Theory and Practice in Archaeological Prospection

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Abstract: Ground Penetrating Radar (GPR) is a near surface geophysical method that has proven to be an appropriate tool in archaeological prospection. There is a large number of studies in literature where authors manage to map buried antiquities like roads, paths, public and residential buildings, graves and many other features. The operating principle of GPR lies in the interaction of electromagnetic (EM) energy with the subsurface targets. When the conditions are ideal (low conductivity environments, flat surface, lack of vegetation) GPR can provide highly detailed and accurate results, otherwise it can still perform well as a complementary method to the rest of the geophysical techniques applied. For all the above reasons, GPR has evolved as one of the main prospection methods used in archaeological prospection. A number of examples are presented in the particular article to emphasize the importance of the usage of the GPR in archaeological landscape studies. These examples address the potential of GPR techniques in mapping the underground features of ancient cities (Demetrias and Mantinea) and Neolithic mounds (magoules Almyriotiki and Perdika 2).

Keywords: GPR, Archaeology, near surface, Mantinea, Demetrias, Thessaly, Neolithic tell, Magoulas.

Introduction

Ground Penetrating Radar (GPR) is a non-destructive electromagnetic (EM) geophysical technique that uses radio waves, in the frequency range of 10MHz to 2GHz, to map the subsurface. The first reported attempt of using radio wave signals to measure subsurface features was by El-said (1956) who tried to image the depth of a water table. The development of the method accelerated considerably after 1970 as a result of the tremendous progress that took place in electronics and computer technology but it was after 1985 when the real explosion of the advancement of GPR occurred (Annan 2002). During this period GPR technology became better known worldwide and more affordable and the scope of its applications expanded. As a consequence, the strengths and weaknesses of GPR were better understood and this opened new ways into hardware development for further improvements. Recent advancement includes the multichannel system that greatly improved the speed, the area coverage and the spatial resolution (Goodman and Piro 2013).

GPR can be used in a series of applications like the mapping of the bedrock depth (Davis and Annan 1989), the determination of the stratum thickness and the aquifer depth (Doolittle *et al.* 2006), the location of physical and artificial cavities in the subsurface (Benson 1995) and detecting fracture zones (Grasmueck 1996, Theune *et al.* 2006). It is widely used in archaeological prospection for the detection of numerous archaeological features (Conyers, 2012). Among them are the mapping of graves in cemeteries where location of both wooden and metal coffins can be identified (Conyers, 2012). GPR has been successfully used by Goodman and Piro (2013) to identify the moat's shape of a burial mount located in Saitobaru, Miyazaki, Japan. This information derived by GPR, contributed to the determination of the monument's construction date. GPR has also been successfully applied in mapping with high detail Roman buildings and structures like cisterns (Spanoudakis *et al.* 2011), a 1st DC amphitheatre, living quarters and villas (Goodman *et al.*, 2004). It also has proven to be very useful when applied in urban and industrial areas for archaeological explorations. Examples can be found in the works of Conyers (2012) and Papadopoulos *et al.* (2009).

In this article the operational principle of GPR is going to be discussed along with all the important parameters that one should take into account when it comes to archaeological investigation in order get reliable results. Additionally, the basic steps of data processing are briefly described providing examples derived from real world data. Finally, three case studies are presented and the capabilities of the method are discussed.

Theoretical background

GPR is an electromagnetic technique (EM) and its operation principle has similarities with the seismic reflection method. A typical GPR system consists of the

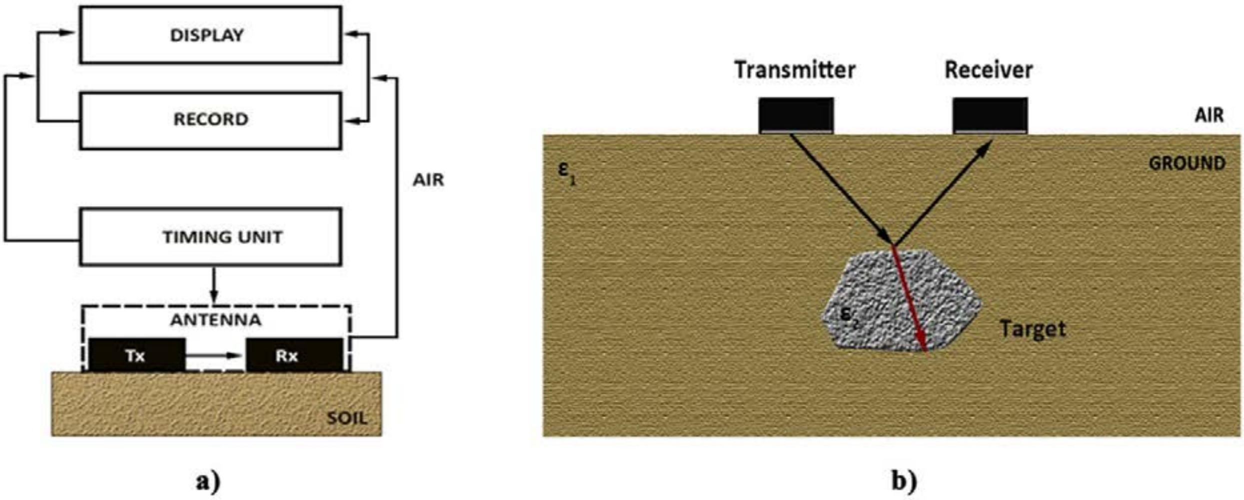

Figure 1. The operation principle of GPR where a) describes the system components and b) the behavior of the EM waves when they meet a boundary with different electrical properties from the soil (ε1>ε2). Part of the energy is reflected to the surface and another one (red arrow) is diffused at deeper levels (Daniels 2000).

antenna, the timing unit and a portable computer (Fig. 1a). The antenna is responsible for emitting and detecting EM energy (10~2000MHZ) through a transmitter (Tx) and a receiver (Rx). The timing unit is the most important part since it controls the generation of the radar signal and converts the received signals as a function of time. The portable computer is used for storing the data and displays them in real time.

The operation principle of GPR is simple. The transmitter emits high frequency pulses of short duration into the ground that 'travel' through the subsurface until they meet a boundary of different material. At this point, part of the energy is reflected back to the surface and recorded by the receiver antenna (black arrows in Fig. 1b), while the remaining energy is diffused deeper (red arrow in Fig. 1b) until it hits another boundary, where it will be reflected and diffused again. This procedure reaches an end when all of the energy is absorbed by the ground. This boundary or *reflector* is defined by differences in subsoil's materials electrical properties, such as the *conductivity* and the *permittivity*. Both of them affect the EM waves' propagation and are of significant importance. Conductivity affects the energy absorption, thus the signal penetration and the depth of the investigation, while permittivity affects the velocity of the signal. In general, GPR is most useful in low-electrical-loss materials (i.e. very low conductivity values). Clay-rich environments or areas of saline water will affect negatively the method's effectiveness (Cassidy 2009a).

Unlike magnetic or electrical methods, GPR doesn't directly measure the properties of the ground. What is recorded by the receiver is the *amplitude* of the reflected signals associated with the EM energy of the reflected pulses in respect to their *travel time*. This time series is called *trace*. The travel time, also known as *double travel time or two-way time*, is the time that a signal needs to cover the route transmitter-reflector-receiver and depends on the propagation velocity of the EM pulse. When an EM pulse leaves the transmitter, its energy is spread at different paths that are illustrated in Fig. 2. In this example, the subsoil consists of two homogeneous layers of different electrical properties. The first records are the direct airwaves and ground waves since in air the EM waves have their maximum velocity ($0.3x10^9$ m/s). Additionally they exhibit the highest amplitude values since the energy loss during this path is minimum. Critical refracted and reflected waves exhibit slower velocities that depend on the electrical properties of the medium and their recordings appeared in greater return times than the direct waves. If the velocity is known then the depth of the reflector can be determined.

To better understand the GPR records or traces, we can consider that the subsurface is a single homogeneous layer (i.e. without contrast in electrical properties). If we place the antenna at some point on the surface and trigger a pulse, what it would be recorded is the direct waves only since, due to homogeneity, the pulse is not allowed to be reflected. Now, if we add a layer of different electrical properties below the previous one mentioned above and trigger a pulse again, the resulted trace will include amplitudes that derive from the direct waves as well as amplitudes from waves that are reflected on the boundary within the two layers. The latter will be recorded at a time that corresponds to the depth of the reflector, i.e. the boundary (Fig. 2). In other words, GPR method depends on the record of the waves reflected on surfaces that divide regions with different electrical properties.

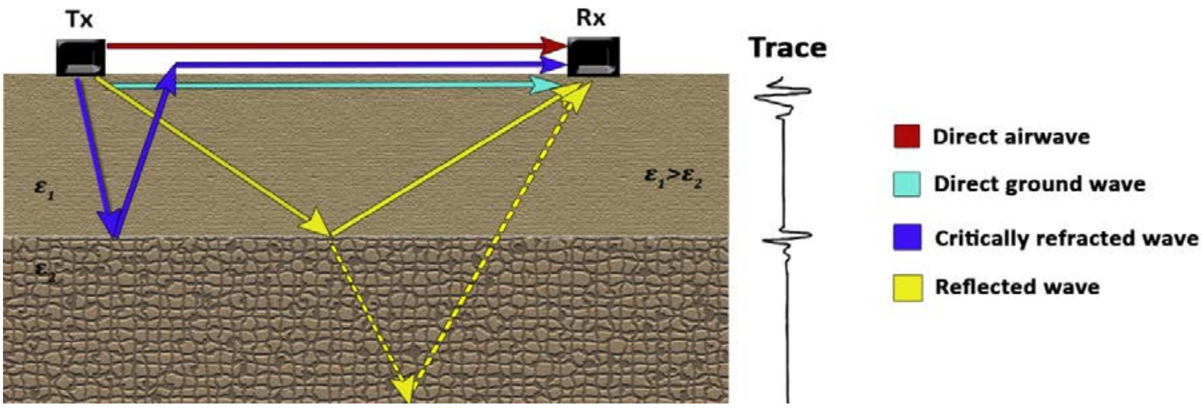

FIGURE 2. THE PATHS THAT THE EMITTED PULSE CAN FOLLOW BETWEEN THE TRANSMITTER AND THE RECEIVER ARE INDICATED (ANNAN 2009). THE DIRECT AIRWAVES AND GROUND WAVES ARE THE EARLIEST RECORDS AND ARE LOCATED AT THE TOP OF THE TRACE, WHILE THE REFRACTED AND REFLECTED WAVES ARE CAUSED BY THE REFLECTOR WHICH IN THIS CASE IS THE BOUNDARY BETWEEN THE TWO LAYERS.

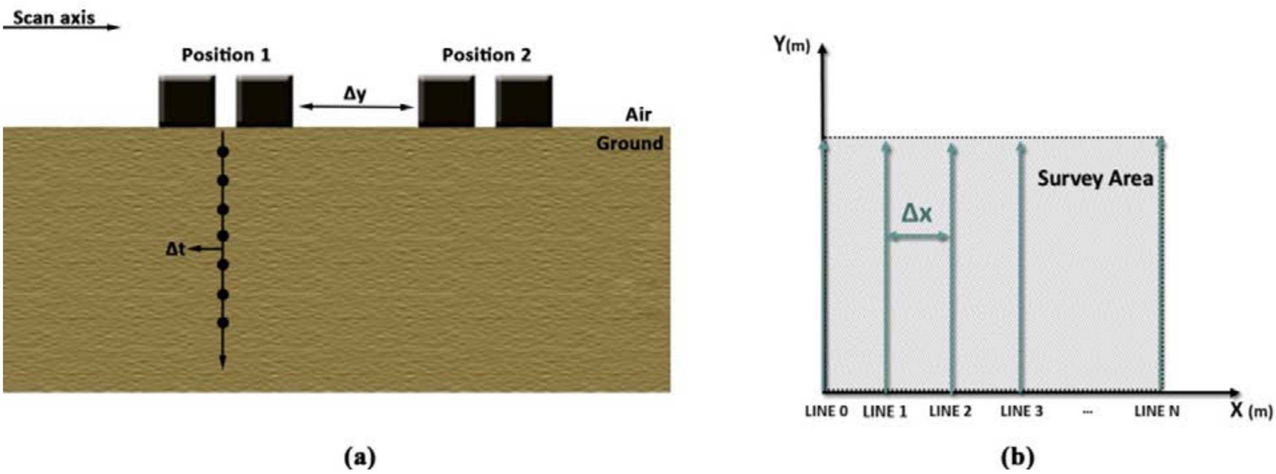

FIGURE 3. SURVEY PARAMETERS OF COMMON OFFSET REFLECTION GPR SYSTEMS. (A) AS THE ANTENNA IS MOVING ALONG THE SURFACE, TRACES ARE RECORDED WITH A STEP THAT IS DEFINED BY ΔY ALONG THE SCAN AXIS. ADDITIONALLY, EACH TRACE INCLUDES A FINITE NUMBER OF RECORDS (BLACK DOTS) THAT ARE OBTAINED WITH A STEP OF Δt. (B) THE SURVEY GRIDS CONSIST OF PARALLEL LINES THAT ARE SEPARATED BY A CONSTANT DISTANCE DEFINED BY ΔX.

Survey methodology and important parameters

The GPR method that is most often used in archaeological investigations is the *common-offset reflection*. The transmitter and the receiver have a fixed spacing and orientation at each measurement (i.e. trace) location. The data are collected by moving this fixed offs*et al*ong the surface (scan axis or Y direction) at regular station intervals (Δy) as depicted in Fig. 3a. Additionally, in the common offset reflection systems, antennas come with a fixed *central frequency*. Frequency is a very important parameter which affects both the investigation depth and the data resolution. The higher the central frequency the lower the pulse penetration depth, but the resolution on both vertical and horizontal directions is better. Thus, prior to survey with GPR, one must know the target(s) expected depth and select a frequency that will allow to reach that depth. The antenna frequency selection is based on previous experience. As an example, a range of 200-300MHz can penetrate up to 2-3 m if the ground conditions (conductivity and permittivity) are appropriate.

The data are usually collected by employing grids that cover the area of interest. An important parameter is the *line spacing*, Δx, which is the distance between the GPR parallel profiles (Fig. 3b). Line spacing should be a fixed value during the survey and is set accordingly to the targets' expected size and geometry. For detecting buried structures such as walls or foundations, a line spacing of 0.5m is suitable, since they can be fully resolved without

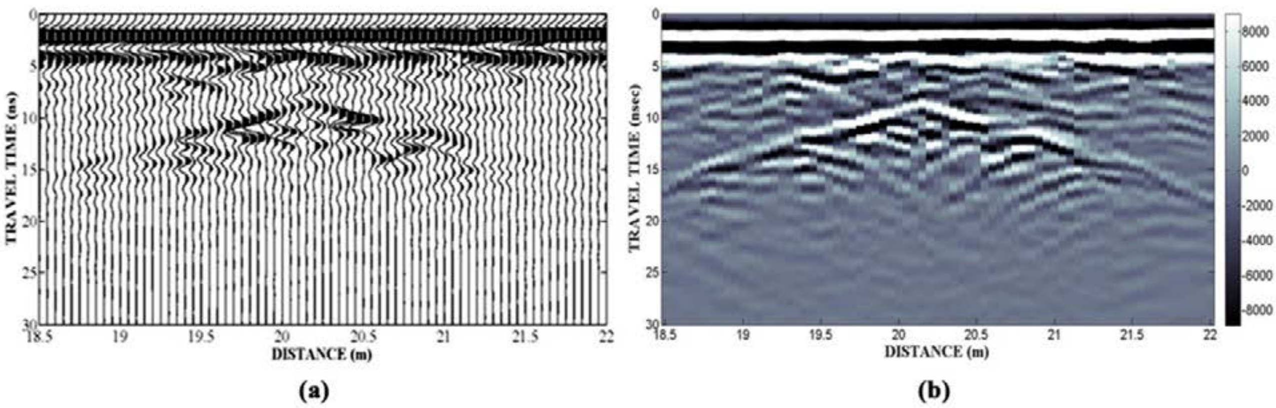

Figure 4. Radargram or section, where (a) is the outcome when a survey line is completed, while (b) is the resulting image after the application of a colormap.

losing information about their continuation in space and unnecessary overlapping is avoided.

GPR transmits continuously but only records discrete signals. This means that sampling intervals should also be set. The *spatial sampling interval*, Δy, defines how often the traces are recorded along the scan axis or the survey line (Fig. 3a). Thus it affects the total number of traces that the line will include. A small value will result in a high detail coverage but caution is needed in order to avoid oversampling that can lead in spurious results. Usually, this value is selected with respect to the central frequency. The *time sampling interval* is the time lapse between two records in the same trace (spacing among the black dots on Fig. 3a). It affects the resolution on the vertical axis. Similar with Δy, the time sampling interval value is set accordingly to Nyquist criteria and the central frequency (Annan 2009). As an example, for a 250MHz antenna the recommended values are Δx=0.025m and Δt=0.4ns.

As the antenna moves along the scan axis, traces are collected forming the image of Fig. 4a. If a colormap is applied on this image, the outcome is called *radargram* or *section*, and it is actually what the user sees on the display while surveying (Fig. 4b). Radargrams contain information about the subsurface along the survey line. The reflections from targets can appear as *hyperbolas* or *linear reflections* depending on the orientation of the antenna with respect to the target geometry. For better understanding, consider an example of a buried wall (Fig. 5). If the survey line is oriented perpendicular to the wall ('point' target), its signature on the section will be a hyperbola. If the scan axis is along the wall, then the signature will be a linear anomaly (Fig. 5b). Also, if the velocity is known, the time axis is converted to distance indicating the depth of each feature/reflector. In case the velocity is unknown, it can be estimated from the hyperbolas appearing on the sections. This operation is included on every GPR processing software packages and is usually carried out by fitting a curve on the hyperbola.

Data processing

Processing is a very important and time consuming procedure that aims to highlight reflections related to the target(s) and to remove unwanted information i.e. noise. Various types of noise are present in GPR data. The most common are *white* or *random* noise and *coherent* noise. The former appears usually at deeper levels and hides reflections from targets. Coherent noise can be caused by external sources (cell phones, TV antennas, etc.) or by the remaining energy that escapes the ground to the air and reflected by objects on the surface (trees, modern buildings, cars, rocks, electrical cables etc.) back to the transmitter. Coherent noise appears as echoes similar to the ones caused by targets, and caution should be exercised during interpretation.

As described above, radargrams are created by moving a transmitter-receiver along a profile of the surface and are 2D images (Distance (m)-Time (ns) or Depth (m)) of the subsurface. When working in grids, 3D images of the subsurface can be constructed from the radargrams out of which *depth slices* (or *time slices*) are extracted. Depth slices are also 2D (Distance (m) – Distance (m)) images that provide information about the reflections of the subsurface at a certain depth.

Data processing of GPR data can be divided into two major stages: (1) the processing of the radargrams where signal processing techniques are used and slices are extracted, and (2) the processing of slices where image processing corrections are applied. More emphasis will be given into the first stage that aims to filter the noise from the data along a profile and enhance the reflections of the raw data. Some standard processes that are usually applied regardless the field of application are (Cassidy 2009b):

- **Traces reposition** that corrects the position of GPR traces included in a survey line. This correction is useful to eliminate systematically offsets in survey

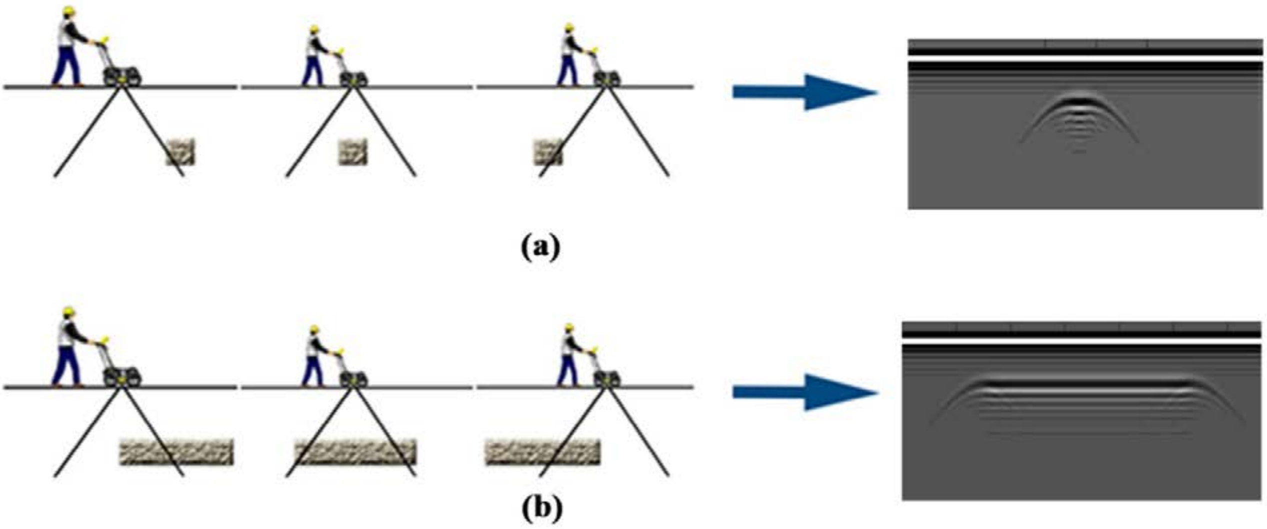

FIGURE 5. REFLECTIONS FROM TARGETS CAN BE HYPERBOLAS OR LINEAR ANOMALIES. (A) HYPERBOLAS ARE FORMED FROM SMALL TARGETS OR WALLS THAT THE ANTENNA PASSES PERPENDICULAR TO THEIR LONGEST DIMENSION. (B) LINEAR ANOMALIES CHARACTERIZE LINEAR REFLECTORS AND ARE FORMED WHEN THE ANTENNA IS MOVING ALONG THEIR LONGEST DIMENSION.

lines' starting and ending positions which usually occur in rough terrains.

- **Timezero correction** which allows to estimate the correct vertical position of the first pulse that left the antenna and entered the subsurface (Tzanis 2006). The effect of time zero correction is shown on Fig. 6b, where (a) is the raw section.
- **Dewow filter** which removes low frequency noise derived by low frequency energy near transmitter and is associated with electrostatic and inductive fields. The output of dewow filter is presented on Fig. 6c, and it is applied after time zero correction.
- **SEC (Spreading & Exponential Compensation) gain** that enhance signals located at greater depths and have much smaller amplitude compared with that of the shallower signals. This correction emphasizes the reflections but also highlights noise as it appears in the example of Fig. 6d.
- **Background subtraction filter** which reduces random noise from the data and also removes the direct waves and ringing noise. On Fig. 6e, the output of background removal filter is shown. The noise is removed while the hyperbolas are highlighted. When gain correction is applied, background subtraction filter is recommended to be applied next, in order to remove the noise that the gain emphasized.
- **Frequency domain filters** consisting of low- or high-pass are 1D filters that remove high or low frequency noise correspondingly. These filters can be combined to retain frequencies at a certain range and are called bandpass filters (Cassidy 2009b). The effect of a bandpass filter is presented on the slices of Fig. 7. Fig. 7a presents the slice where all the above corrections have been applied but noise couldn't be removed sufficiently, shadowing reflections from buried structures. By selecting an appropriate frequency range, the stripping noise caused by plowing lines is significantly removed on Fig. 7b highlighting structures that were barely visible before.
- **Migration** that removes distortion due to diffraction, by trying to reconstruct the signal to fall at its correct position. In such a case, ideally, a hyperbola signal will be reduced to an isolated point target.

The above correction, besides timezero and dewow, are consider to be basic but are not standard, meaning that they may not always enhance the original data.

By the time the processing on the radargramms is complete, *Hilbert Transform* is applied to calculate the *instantaneous amplitude* (Spanoudakis and Vafidis 2010) and to extract depth slices. The slices indicate the changes on the instantaneous amplitude at a certain depth. High values designate strong changes in the electrical properties or high reflectivity.

Case studies examples

Ancient Demetrias, Volos, Greece

The ancient city of Demetrias is located south of the modern city of Volos. The city was established by the Macedonian military leader and eventual king, Demetrius Poliorcetes (337-283 BCE) in 294 BCE (Batziou-Efstathiou, 2001). The city became the royal residence of the Antigonid dynasty of Macedonian kings and flourished as an international and political center. The city permanently fell to the Romans following the battle of Pydna in 168 BCE. The Antigonid dynasty was immediately dissolved and the

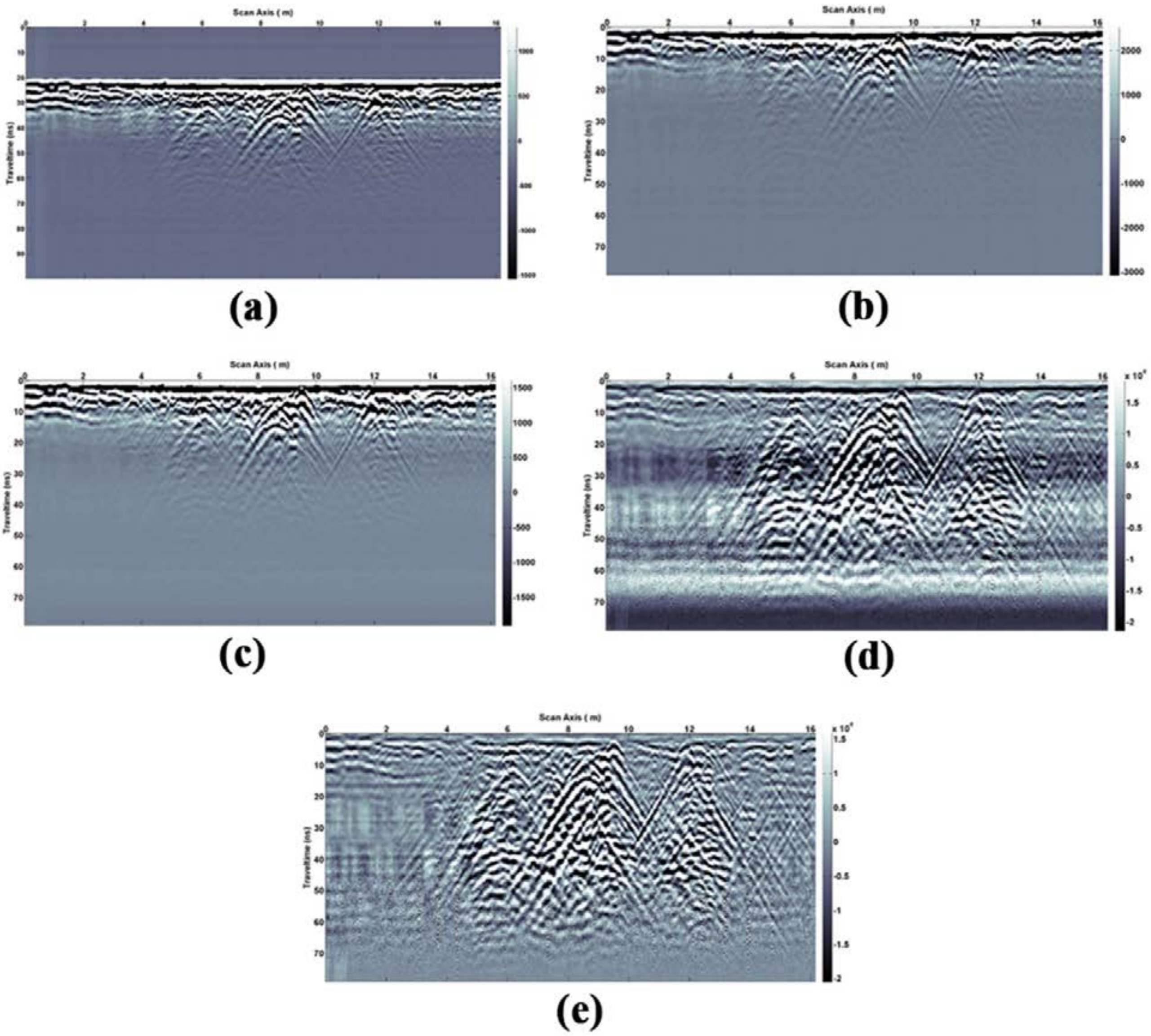

Figure 6. Processing example of GPR data where (a) is the raw section, (b) the time zero correction, (c) dewow filter, (d) gain correction and (e) background removal noise correction, applied to the raw data respectively.

Roman province of Macedonia, in which Demetrias was a part, was officially established a few decades later in 146 BCE. During the Roman Imperial period, many central areas of the city, including the area around the Hellenistic palace, were used for burials. Demetrias experienced a brief recovery beginning in the 4th century CE, when the Roman emperor Constantine the Great made the city an episcopal sit (Batziou-Efstathiou 2001). The city was finally abandoned during the 6th century CE and it was never reoccupied again.

The geophysical survey at the ancient Greek city of Demetrias was conducted by the Laboratory of Geophysical, Satellite Remote Sensing and Archaeo-environment of the Institute for Mediterranean Studies (FORTH) during March 2014. Two GPR systems were used. The first was a single channel Sensors and Software NOGGIN Plus-Smart Cart system equipped with a 250 MHz shielded antenna frequency (Fig. 8a) and the second was a multi-channel MALÅ Imaging Radar Array (MIRA) with 400 MHz antennas (Fig. 8b). Both radars were employed for surveying the area of the soccer field that is located east of the city agora and southeast of the Hellenistic palace. The area was ideal for using GPR due to the flat surface and the lack of vegetation. The total area covered is a 120x60m with a 0.5m line spacing. The results for both radar investigations are very detailed and they are presented in Fig. 9.

The overall arrangement of the architectural features beneath the soccer field recalls Hellenistic and Roman urban houses with courtyards or gardens in the back and shared partition walls between houses (Rumscheid and Koenigs 1998, Zanker 1998). Two main roads are clearly distinguished (Features **1** and **2**) with a dense collection of buildings in the rectilinear city blocks in between. Features

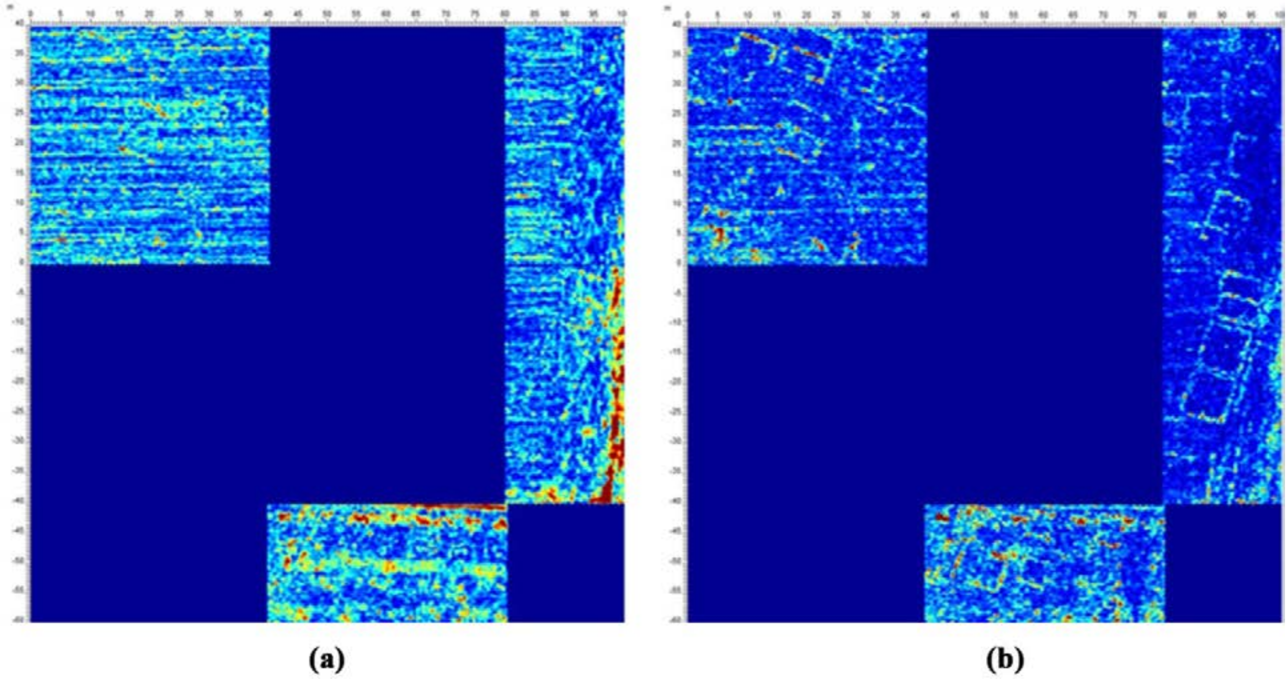

FIGURE 7. THE EFFECT OF BANDPASS FILTERING WHERE (A) IS THE SLICE AFTER THE BASIC PROCESSING AND (B) IS THE OUTPUT OF BANDPASS FILTERING. STRUCTURES THAT WERE NOT VISIBLE BEFORE ARE HIGHLIGHTED.

FIGURE 8. GPR SURVEY AT DEMETRIAS MODERN SOCCER FIELD. (A) SINGLE CHANNEL NOGGIN PLUS GPR SYSTEM EQUIPPED WITH A 250MHZ ANTENNA AND (B) THE MULTICHANNEL MALA MIRA GPR EQUIPPED WITH 400MHZ ANTENNAS.

3 and **4** seem to be a single structure with at least seven rooms located at the west and a large free zone at the east with few walls that functioned as perhaps a backyard courtyard or garden. A similar arrangement is noted with Features **5** and **6**. Feature **7** reveals another collection of rooms that take up the whole width of the city block, but there is no clear evidence for an open courtyard. The survey found another cluster of rooms described by Feature **8**, while Feature **9** appears to be a large open area that is not clear if it is connected with Feature **8**. More than a dozen rooms were mapped from Feature **10**, and at least four from Feature **11**.

Comparing the two GPRs, the multichannel Mala seems to exhibit better resolution than the single channel Noggin and the data are less noisy. Differences can be seen in Feature **9** where the former managed to map parts of walls and a semicircular structure at the southeast corner of the division wall that are not visible on the single channel GPR. This manifests the obvious advantage of using multi-antenna GPR systems, as they are collecting information with a much more dense spacing than the single antenna GPR units.

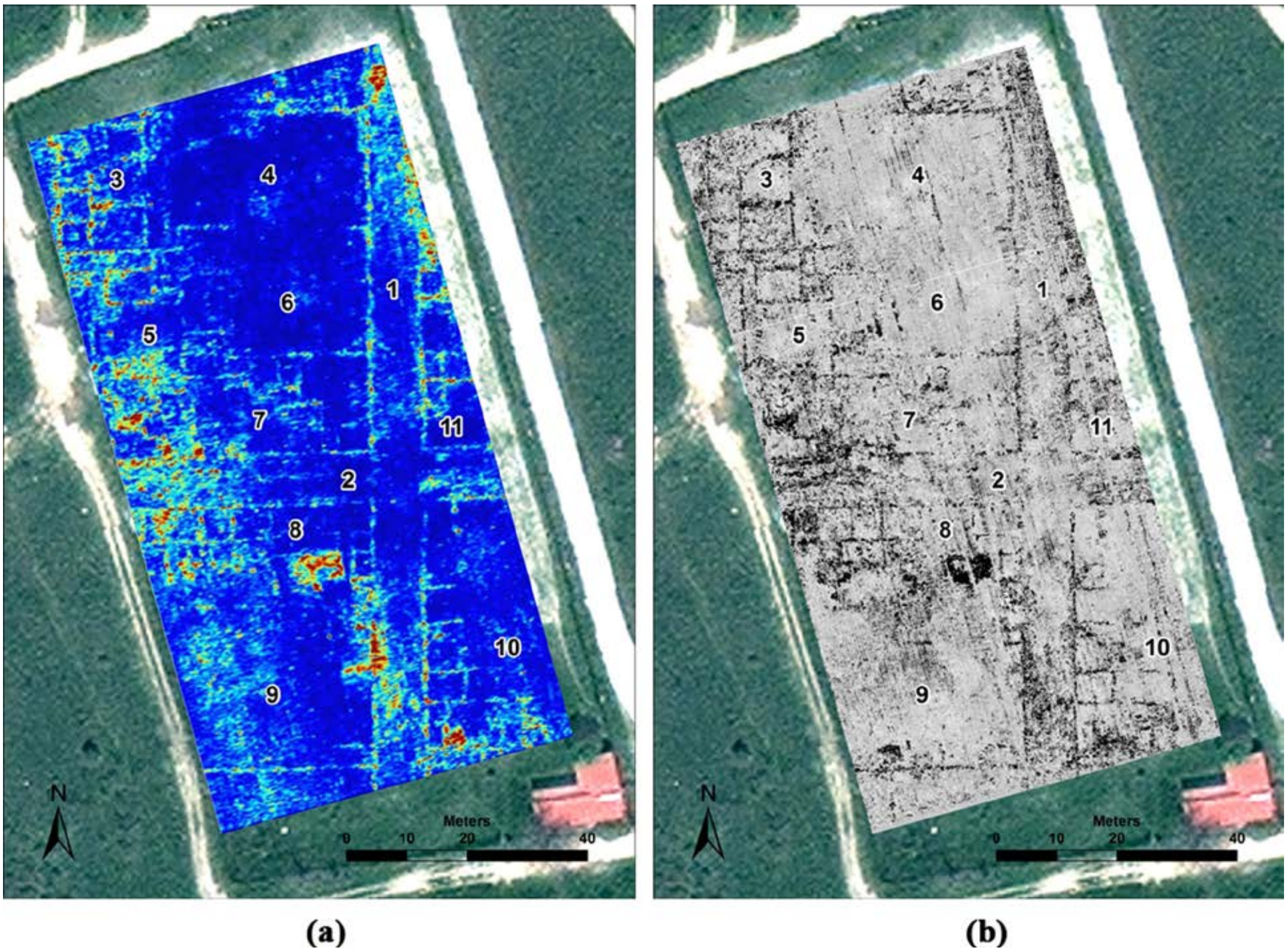

Figure 9. GPR survey in the soccer field at demetrias. (a) The slice at 0.4-0.5m depth derived from Noggin GPR and (b) the slice at 0.47m derived from MALA Mira are indicated.

Ancient Mantinea, Peloponnese, Greece

Mantinea was established within a level flood basin of northeastern Arcadia in the Peloponnese before the middle of the 5th century BCE. At 385 BCE the city was destroyed by a Spartan invasion and its citizens were forced to depopulate. For 15 years Mantinea was abandoned until it was reestablished in 370 BCE after Sparta's defeat in the Battle of Leuctra. The city played a prominent role in the activities of the newly established Arcadian League during the 4th century BCE, and along with Megalopolis and Tegea it continued to have an influential regional presence in Arcadia and the Peloponnese for several centuries.

The known archaeological features at Mantinea include the well-preserved elliptical fortification walls, approximately 4 km in circumference, and the agora and theater at the center (Hodkinson and Hodkinson 1981, Winter 1987, 1989) but very little of the remaining urban area inside the fortification walls (~120 hectares) has been explored. A geophysical survey through the use of soil resistivity and magnetic methods was conducted by the University of Patras (Greece) from 1988-91 northwest of the theater (Sarris 1992). The target area was limited to 1 hectare but the survey revealed evidence for subsurface streets arranged at right angles together with various buildings, possibly domestic in nature.

A geophysical survey was conducted to explore the structure and urban development of the classical Greek city of Mantinea in the Peloponnese through an intensive geophysical fieldwork campaign carried out by the Laboratory of Geophysical, Satellite Remote Sensing and Archaeo-environment of the Institute for Mediterranean Studies (FORTH). For this task the GPR system Noggin smart cart of Sensors & Software was also employed using a 250MHz antenna. An area of 3.41ha was covered in total with GPR using 0.5m spacing between each transect.

The data acquired with Noggin GPR were noisy but they exhibit anomalies related to buried structures. In order to enhance the anomalies related with buried antiquities, data were processed using the following corrections in order: trace reposition, time zero correction, dewow filter, SEC gain, background removal, bandpass filtering and migration. Here, the results obtained from the eastern side of the agora are presented (Fig. 10a) where public buildings including a long 'L' shape stoa with columns appear as high amplitude anomalies with high detail. Many of these features appear to be related to the public

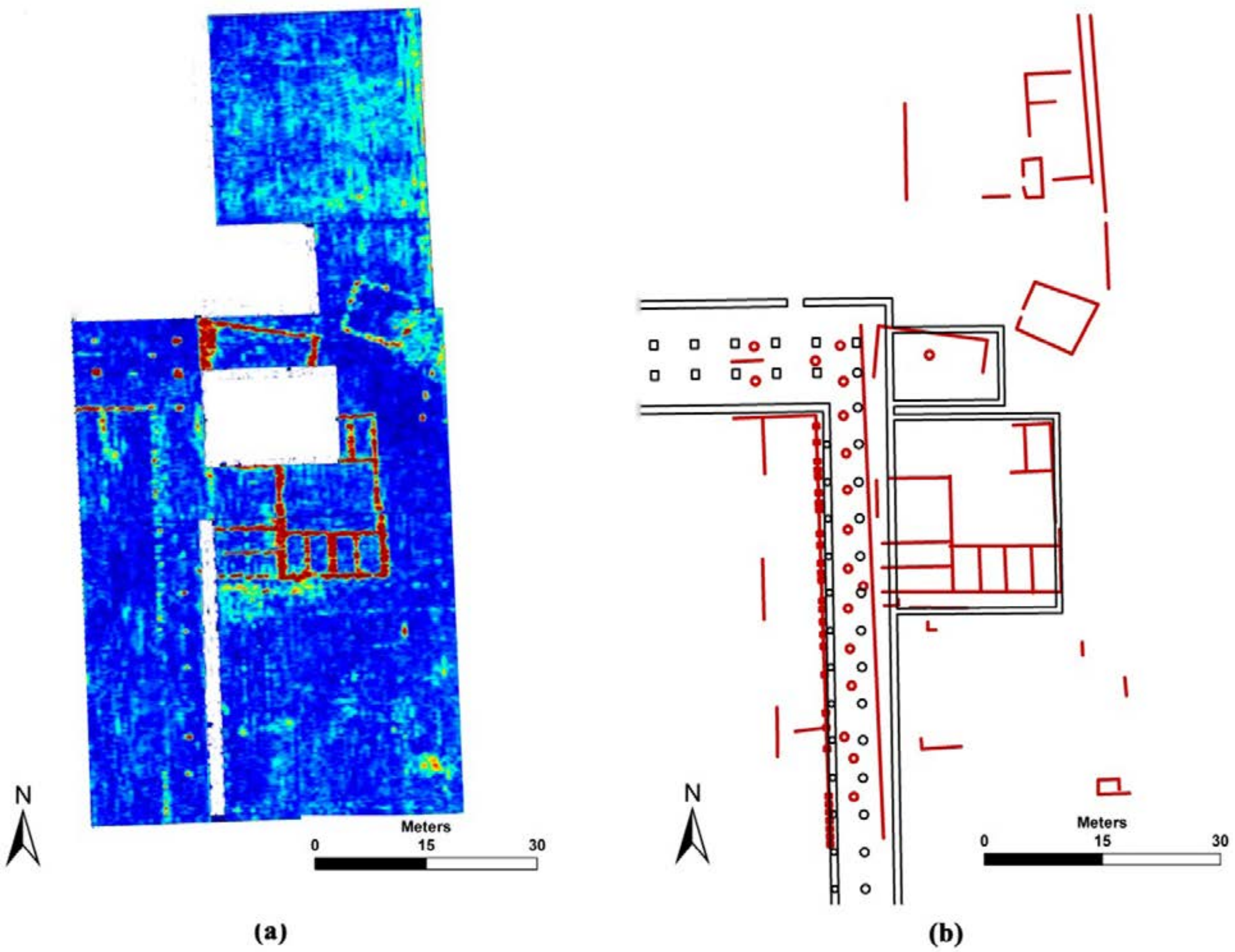

Figure 10. Results of the Noggin Plus GPR survey at the eastern side of the agora at Mantinea. (a) GPR slice illustrating the anomalies at 1.0-1.1m depth. (b) Comparison of the French plans (black color) and interpretation (red color) as occurred from all slice depths.

buildings excavated by the French in the 19th century but they were reburied (Fougères 1898). The similarities and differences with the French plan are shown in Fig. 10b, where with black lines are the findings of the excavation, while with red lines are the interpretation of the GPR data as occurred from all the depth slices. There is a slight shift in the orientation of the whole settlement. The 'L' shape stoa has a double row of internal colonnades on the north-east direction and a single row along the north-south direction. Two adjoining structures appear as strong linear anomalies behind the west section of the stoa. These structures are also present in the French plan. The southern one is almost a perfect square and is subdivided into smaller rectilinear rooms on either side of larger central rooms. The French plan of the agora did not show the internal subdivision of space. Only part of the other structure could be surveyed because of a large tree, but it is clear that this building is smaller than its neighbor and likely had no internal rooms. The building is also oriented at a diagonal angle (unlike the southern building), which is a distinct characteristic not present on the French plan. Another notable anomaly further to the northeast is a small structure and is also set at a diagonal angle.

Neolithic Thessaly, Greece

A large-scale geophysical exploration was conducted by the Laboratory of Geophysical, Satellite Remote Sensing and Archaeo-environment of the Institute for Mediterranean Studies (FORTH) during 2013-2015 at a large number of Neolithic tell sites (*magoules*) in Thessaly. The purpose of this study was the identification of intra- and inter-spatial patterns of Neolithic settlements through the comparative study of both archaeological and geophysical data. Non-destructive geophysical methods like electrical resistivity, magnetics, EM and GPR were used on selected archaeological sites that have been partially excavated or have been identified by survey expeditions. The most interesting results derived from magnetics included features like ditches, enclosures, paleochannels, burnt structures, daub and stone structures, etc.

Survey with GPR on such landscapes is not an easy task, due to the rough terrain and the modern cultivation. The geomorphology of the area and the soil condition (clay-rich environments) resulted in noisy data with very limited penetration (to a maximum depth of 1.0m). Thus, GPR

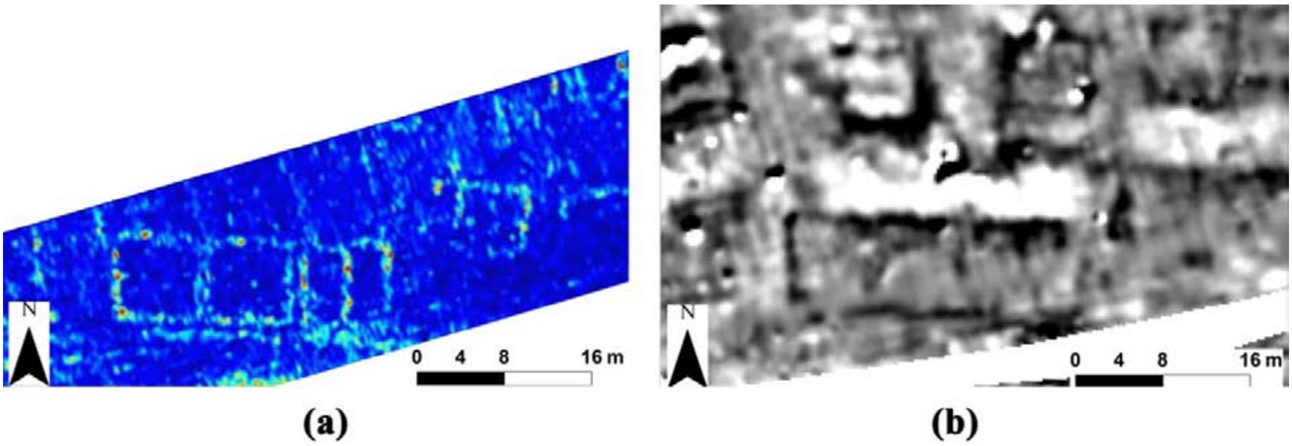

Figure 11.Comparison between GPR and magnetic results from *Magoula* Almyriotiki. (a) GPR slice at 0.7-0.8m and (b) magnetic slice. GPR exhibits better resolution revealing that the large structure indicated by the magnetic results is a cluster of individual buildings.

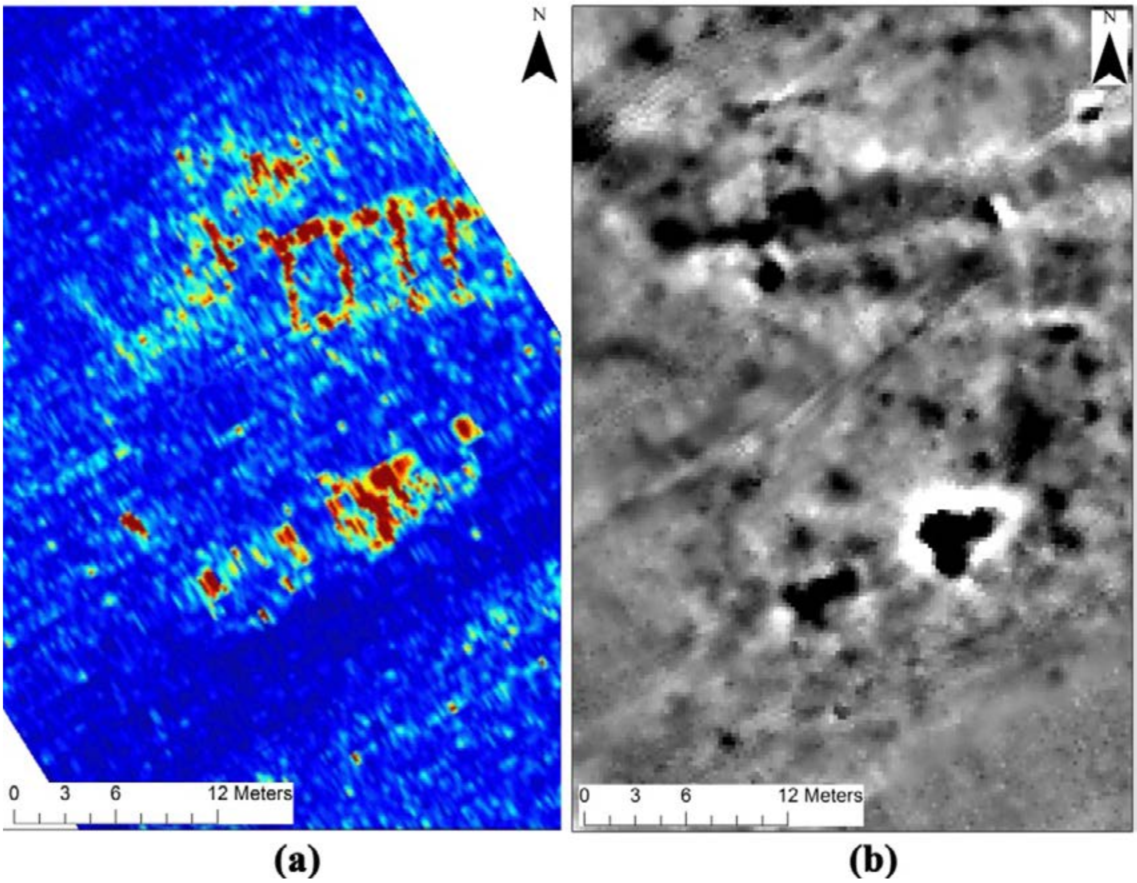

Figure 12. Comparison between GPR and magnetic results from *magoula* Perdika 2. (a) GPR slice at 0.7-0.8m and (b) magnetic results from the same area. GPR revealed a structure, probably stone-made, that is barely visible on the magnetics data.

was used mostly as a supplementary method to enrich the information obtained from other geophysical methods. Such an example is presented in Fig. 11, where the left image is the depth slice derived from GPR with 250MHz antenna at Magoula Almyriotiki, while the right image is the magnetic results from the same region. Even though GPR could not map all the structures as the magnetics did, it managed to provide better resolution, revealing that the large structure appearing in the magnetic data consists of individual dwellings.

In another survey at Perdika 2, GPR managed to map a structure with high detail that is barely visible on the magnetic data due to the geological background noise. This contrast between the two methods indicates complementary information, as it seems that the local building material of the strauctures was not able to produce significant anomalies in the magnetic measurements. In contrast to other magoules, where burned clay structures were appearing as vivid anomalies, the stone structures show a very weak magnetic signal, but are easily resolved through the GPR techniques. This is a clear indication of the fact that GPR relies mostly on the contrast of the electrical rather than magnetic properties of the targets.

Conclusions

Overall, GPR proves to be an extremely useful tool for archaeological investigations. When soil conditions and geomorphology are appropriate, it can provide very detailed results of the subsurface and map successfully buried structures, roads, city blocks and other features. Even if the survey conditions are not ideal, the data can be significantly improved with proper processing. In such cases, GPR is better to be used as a complementary method that will provide additional information with respect to both the horizontal and vertical extent of the subsurface targets. This has been manifested by the case studies presented here. GPR was able to retrieve information from various targets, at different depths and within diverse geological contexts. Compared to other methods, the GPR technique has the advantage to provide information not only about the lateral extent of the targets but also of the stratigraphy of the site and the vertical extent of the monuments, contributing in this way to the 3D reconstruction of the cultural landscapes.

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Identification of Shapes and Uses of Past Landscapes through EMI Survey

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Abstract: Over the last ten years, the use of Electro-Magnetic Induction (EMI) instruments for archaeological purposes has increased considerably. This development has come both from the availability of new instruments with multi-coils spacing allowing a multi-depth analysis and because of the wide availability of high quality GPS positing which can be easily integrated with EMI. These new possibilities promote the use of EMI instruments for the study of archaeological landscapes and sites. Indeed, the capability to simultaneously map both the electrical conductivity and the magnetic susceptibility presents a great advantage for archaeological purposes compared to other geophysical instruments. The combination of these two measurements means that it is possible to geomorphologicaly characterize past landscapes while simultaneously mapping anthropogenic activities. To maximize the potential of EMI measurements, this technique requires specialized processing and calibration to limit confusing and unclear results. In order to obtain quantitative conductivity and magnetic susceptibility data, it is necessary to correct instrumental drift and calibrate for local soil conditions. In this paper we introduce the theoretical basis of the EMI technique, discuss common instruments and explain the calibration procedure before presenting three case studies that illustrate applications of EMI to archaeological sites on a range of scales.

Keywords: EMI, multi-coil, multi-frequency, electrical conductivity, magnetic susceptibility, landscape archaeology,

Introduction

The current use of EMI techniques in archaeology is inherited from a long story of discovery and improvement. The first case studies of this method for archaeological applications was undertaken in the 1960s to map the soil conductivity at a proto-historic site in southern England (Howell 1966). On subsequent surveys, it was demonstrated that EMI can be sensitive to the magnetic properties of soil through the use of both a TDEM (Time Domain Electro-Magnetic) instrument (Colani and Aitken 1966) and a FDEM (Frequency Domain Electro-Magnetic) instrument (Tite and Mullins 1969). Furthermore, it was shown that FDEM instruments can simultaneously measure both electrical conductivity and magnetic susceptibility (Parchas and Tabbagh 1978). A range of instruments were then built and tested during the 1970s and the 1980s (McNeill 1980; Tabbagh 1986). Since it is not necessary to have direct ground contact for measurements, EMI is a well-adapted method often used to map the electrical conductivity over large areas, where electrical measurements would need more time for acquisition. The most common contemporary use of EMI is mapping the electrical conductivity of soils, which fails to full exploit the potential of this method. New approaches include the robust calculation of magnetic susceptibility (Marmet 2000) and the use of multi-coil instrument for the simultaneous measurement of multiple depths (De Smedt et al. 2013).

Theory

EM measurement is based on the transmission of a time varying magnetic field (primary field) through the transmitting coil (Fig. 1). This field spreads in the soil and creates eddy currents in conductive materials. Currents generate a new electromagnetic field called a secondary field. Both primary and secondary fields are then measured by the receiving coils. At the same time, the electromagnetic field magnetizes the soil through an induced magnetization. This magnetization also modifies the secondary field. The intensity of this magnetization of the soil is magnetic susceptibility. The primary and the secondary fields are offset in time. It is then possible by the identification of both parts of the complex electromagnetic secondary field to characterize both the electrical conductivity and the magnetic susceptibility.

The behavior of electromagnetic fields is described through Maxwell's equation. Three physical properties are involved: the electrical conductivity, the dielectric permittivity and the magnetic permeability. The use of approximations allows the simplification of Maxwell's equation and offers a mathematical solution to understand the EM signal (Scollar *et al.* 1990).

At first, the magnetic permeability of natural material is very low (close to μ_o). Moreover, in the case of the low frequency (<100 kHz) instrument, the displacement

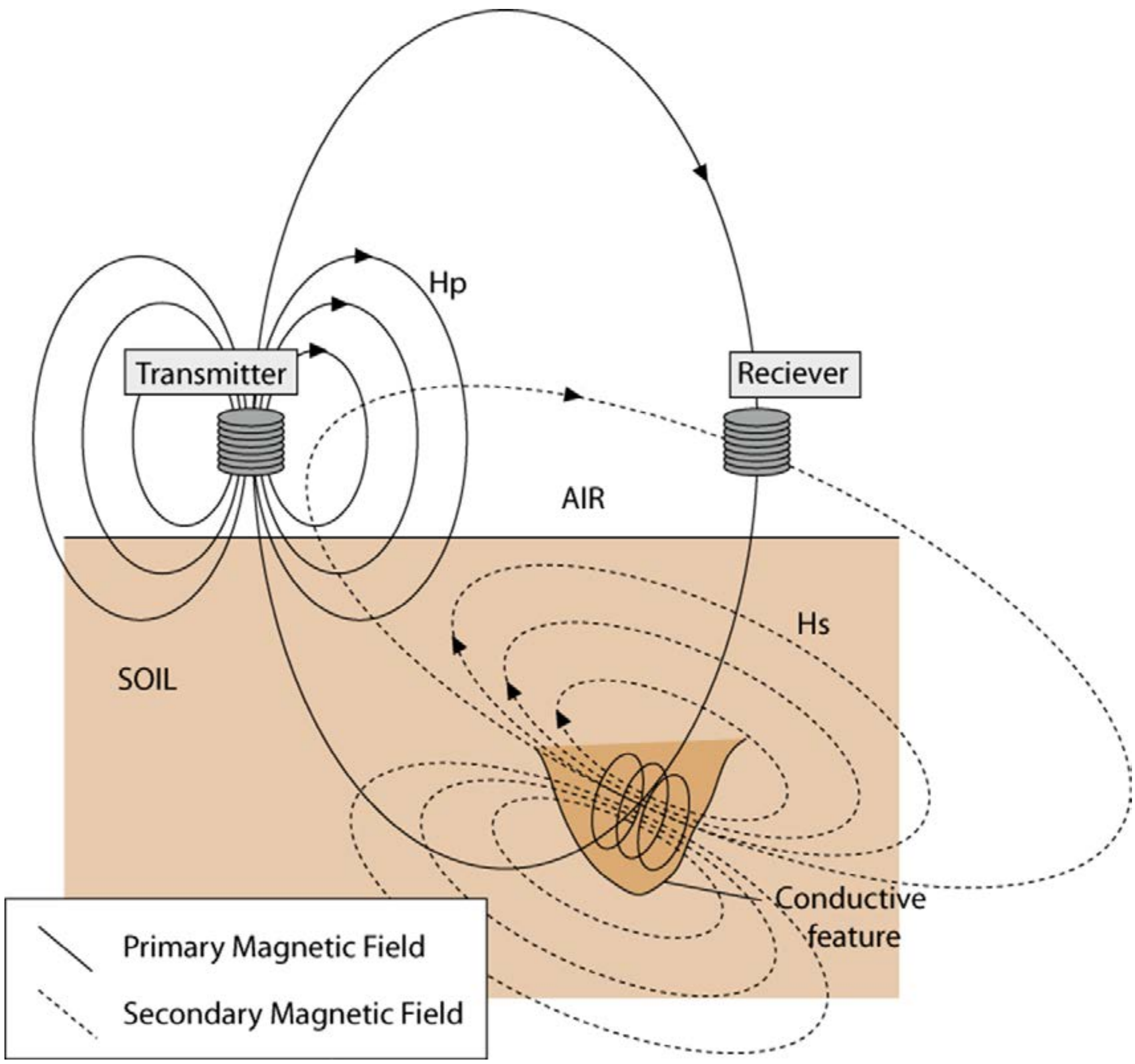

Figure 1 : Principle of electromagnetic measurement

current is negligible compared to the conduction current. In this case, only the electrical conductivity and magnetic permeability affect the EM field. This approximation is known as the induction case where the conductivity needs to be high enough to verify that:

$$\sigma > \varepsilon\omega$$

In a low frequency case, Maxwell's equations are reduced to:

$$\nabla^2 E - \sigma\mu \frac{\partial E}{\partial t} = 0$$

$$\nabla^2 H - \sigma\mu \frac{\partial H}{\partial t} = 0$$

Induction currents are then concentrated close to the surface, limiting the depth of investigation. To describe this effect, called the skin effect, the following parameter is employed:

$$p = \sqrt{\frac{2}{\sigma\mu\omega}}$$

with $\omega=2\pi f$.

The skin depth or penetration depth, p, is defined as a diminution of the amplitude field to 1/e of its initial amplitude. This value limits the effective investigation depth.

In the general FDEM case, the electrical conductivity mostly affects the response of the EM signal. Nevertheless, in the case of a Low Induction Number (LIN), the response of the conductivity is completely related to the quadrature out-of-phase part of the signal so the in-phase part is related to the magnetic susceptibility. The low induction number is defined by the following approximation:

$$L^2\sigma\mu \frac{\partial}{\partial t} \ll 1$$

where L is a characteristic size of the system (depth and size of the target, coils spacing).

If L < p, we are close to the static case and the depth of investigation is controlled by L. If p<L then the depth of investigation is controlled by the frequency through the penetration depth.

Wait/McNeil approximation

Considering the case of a Low Induction Number and a low frequency, we can apply the following relation linking the ratio of primary and secondary field with the electrical conductivity (Mc Neill 1980). This equation is available for the electrical conductivity and limited to some specific cases:

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_0\sigma s^2}{4}$$

Where, ω = 2 f= frequency, H_s secondary field, H_p primary field, σ the ground conductivity and s the inter-coils spacing. As an example for a high apparent conductivity, this relation however is not completely true.

The full solution

In the absence of approximation, the in-phase is not fully related to the magnetic susceptibility nor is the quadrature fully related to the apparent conductivity. The in-phase component can be affected by the apparent electrical conductivity (for high value of conductivity) and quadrature out-of-phase can be affected by the quadrature component of the magnetic susceptibility. The use of a full solution avoids these limitations. The calculation of the response of a homogeneous ground, or of layered one, has been established by the work of Wait (1959) and is based on Hankel's transforms. It can be rapidly calculated using convolution products (Guptasarma and Singh 1997). Complete expressions and a description of the different subsequent approximations can be found in Thiesson *et al.* (2014). They express the measurement in terms of apparent conductivity and susceptibility, based on a simplified conversion since the variations are monotonous yet not simply linear. In this case we overpass the problem of the LIN limitation. Multi-frequency measurement also enables the correction for both parts of the complex signal in the case of an extreme conductivity, where the LIN is not fully observed (Simon *et al.* 2014).

Coils geometries

As previously stated, the depth of investigation in the case of an EMI Slingram instrument is first of all defined by the inter-coils spacing and the geometry of the coil. We will consider here only the available geometries offered by the commercially available instruments which include HCP (horizontal coplanar), VCP (vertical coplanar) and PERP (perpendicular) configurations. These different geometries also provide different levels of complexity for the interpretation of the data. In the case of HCP, a deep magnetic source can create a negative anomaly where the same source in a shallow position will create a positive anomaly. In the case of 3D bodies, the interpretation of the anomalies is also complex because they may produce anomalies with shapes different from their sources. HCP has the deepest depth of investigation for the electrical conductivity measurement in 1D context but it also a shallower depth of investigation for magnetic susceptibility. In the case of VCP, the depth of investigation is deeper for the magnetic susceptibility and shallower for the electrical conductivity. Depending on their design, EM instruments deliver different data values. The EM31, after correct calibration, delivers a measurement in mS/m, because it immediately undertakes the transformation given by McNeill's approximation. This approach is less accurate when using smaller coils spacing or when focused on magnetic susceptibility, in which case a full solution calculation may be required. In the case of the GEM2, the instrument delivers a reading in ppm which requires one to undertake a conversion after acquisition with external software.

Soil physical properties

Magnetic susceptibility is generated by magnetic grains in the soil including magnetite, maghemite and hematite. These minerals are produced by fire, pedogenic process and are enhanced by human activities (Fassbinder *et al.* 1990), the introduction of organics and soil disturbance (Marmet 2000). The soil susceptibility range of values is quite large, from 1000 10^{-5} SI in volcanic areas to 10 10^{-5} SI, but values close to 1000 10^{-5} SI are rare.

Conductivity, the inverse of resistivity, is related to the clay content, degree of water saturation and the water salinity. In the frequency range where the displacement currents can be ignored (below100 kHz), the electrical resistivity, *ρ*, is well defined and extends from 1 to 2 Ω.m in the intertidal zone to 10000 Ω.m in permafrost or in crystalline dry soils (Telford *et al.* 1990). This very wide dynamic range is the greatest observed for usual geophysical properties, but values out of the 10, 1000Ω.m may occasionally be observed in soil studies.

Instrumentation

Instruments

A range of commercial instruments are available to undertake electromagnetic induction investigations. Five companies share the largest part of the market: Geophex, Geonics, GF Instruments, GSSI and DualEM (Fig. 2). Geonics has historically been the most popular manufacturer; however, the use of GF Instrument and DualEM has grown considerably since they offer a multi-coils spacing and a steady calibration. Multi-frequency instruments (manufactured by Geophex and GSSI) became commercially available in the 1990s and

Figure 2 : Instruments in use in the field: CMD mini-explorer from GF Instruments S.r.o. (Manataki, IMS FORTH), GEM2 from Geophex Ltd. (Manataki, IMS FORTH) and EM31 from Geonics Ltd. (Hulin, Inrap)

their manufacturers argued that they allow simultaneous investigation of multiple depths, which can be selected by changing the investigation frequency. Unfortunately, this claim is not supported by experimental evidence. Nevertheless, these instruments do take measurements of the magnetic viscosity and allow for a robust correction to measure electrical conductivity and magnetic susceptibility.

The Geonics EM31 (Geonics Ltd) is the most commonly used commercial instrument, but it is mainly limited to conductivity measurements. The coils spacing is 3.66 m and the frequency is 9.8 kHz. Its use is limited only to measurements of electrical conductivity (with a maximum depth of investigation of 6 m). Unfortunately, the in-phase part of the signal is difficult to link to the magnetic susceptibility because of the large coils spacing. The Geonics EM38 (coils-spacing 0.5 meter and 1 meter) is well adapted to archaeological survey due to its small coils-spacing. The disadvantage of this configuration is that the in-phase zero of this instrument is extremely sensitive and can easily vary from day to day. This issue affects other instruments with small coils spacing. GF Instruments and DualEM now offer instruments with multiple coils spacing which means that they cover three simultaneous depths of investigation.

Other families of EMI devices that collect multiple frequency measurements include the Geophex GEM2 and the GSSI Profiler. These multi-frequency instruments offer a correction on the conductivity and the susceptibility measurement when the LIN is not completely observed. We have successfully applied the GEM2 because it resists drift and the depth of investigation for the magnetic susceptibility is well adapted to archaeological targets. The Profiler should also be well-suited to archaeological purposes, particularly based on the slightly smaller coils spacing of this instrument (1.21 m compared to 1.66m for the GEM2).

The development of accurate GPS positioning allows one to survey large areas with EMI instruments. The NMEA code system is usually used to send the positioning to the instrument. The major part of the data logger used for the measurement manages this information and delivers data directly as an accurate map. Nevertheless when the interspace profile is small, some modifications must be applied. The velocity of the user generates a spatial offset between the measurement and the positioning. Also the time to process the positioning information and the EM measurement can create delay on the correlation of both data. Nevertheless, simple procedures can remove this effect by applying an offset, using the time or the direction of the acquisition (when the time is missing on the measurement).

Calibration

One of the most difficult steps for the collection of EMI data is the accurate calibration of the instrument. This measurement is undertaken with an electronic system, but temperature and the geometries of the instrument are a significant source of noise. Usually, instruments are designed to correct for temperature and geometrical drift. But these solutions are not completely efficient since drifting can be abrupt, especially for magnetic susceptibility measurements. For this reason it is essential to calibrate the instrument before each survey. There are a number of different solutions for EMI calibration (Sasaki *et al.* 2008), but the most effective is the solution applied by Thiesson *et al.* (2014), which works both for electrical conductivity and for magnetic susceptibility.

The steps for effective calibration are to find the coefficient and offset of the instrument. The coefficient is the ratio between the theoretical value and the experimental one, for both electrical conductivity and magnetic susceptibility for the same ground. Then we try to calculate the value of the offset, as the EMI instrument is not able to deliver a constant value of zero. Usually one can consider the coefficients for both parts of the complex signal, which is the procedure suggested for most commercial instruments. In reality this assumption is not valid and the coefficient could change considerably. Moreover, the calibration procedure is only available for the conductivity and not for the magnetic susceptibility measurement, which is unfortunate as this is more prone to electronic drift. For calibration of the conductivity, a vertical electrical sounding is applied using resistivity to create a model for the local soil. We do the simulation with the same characteristics for this model and then compare the theoretical and experimental value for two different heights of the EMI instrument from the ground. The comparison between the EMI and resistivity data gives us the value of the coefficient and the offset (between the theoretical value and the measured one) for the quadrature out-of-phase part of the signal. For the in-phase part of the signal we measure the response of the instrument for an aluminum ball of known volume and we calculate the ratio between the measurement and a model of the measurement. This ratio gives us the coefficient for the in-phase part of the signal. To determine the value of the offset for the quadrature-out-of-phase part of the signal we do a measurement at two different heights from the ground. As the sensitivity of the instrument is decreasing quickly with the height the value measured at two different altitudes (at least 2 m apart) is only affected by the conductivity. We then use the first modelling to remove this effect on the measurement.

Case studies

Three case studies (from the IGEAN project) (Sarris *et al.* 2014) are presented here to demonstrate how electromagnetic survey can successfully contribute to archaeological investigations. The first case study concerns the characterization of a paleo-channel which may have affected the spatial organization of a Neolithic tell site (*magoula*) in Thessaly. The second case study discusses the distribution of magnetic susceptibility at another Neolithic tell site, showing differences on the treatment of soil. The last example shows how EMI methods can be useful to map buildings through the measurements of both magnetic susceptibility and electrical conductivity.

Palaeochannel mapping

Almiriotiki magoula is a Neolithic tell site located in the eastern coastal plain of Thessaly (Central Greece). A recent geophysical survey of the site revealed an extensive settlement containing an abundance of near-surface architectural features. Most of the prehistoric settlement now lies within open agricultural fields where corn and wheat are cultivated. Geophysical prospection showed that a network of ditches or enclosures defined the spatial organization of the main settlement. The presence of fluvial channels passing next to the settlement was identified by aerial and satellite remote sensing.

For the EMI survey at Almiriotiki, a GEM2 from Geophex was employed, since it is well adapted for a deep characterization of electrical conductivity and a shallow characterization of the magnetic susceptibility. On the main settlement we used a line spacing of 1 m with differential GPS positioning and a line spacing of 5 m at certain peripheral parts of the settlement. The spacing between the measurements was chosen on the basis of the depth of investigation and the size of the targets. In this particular case the target is large (the palaeochannel) and the depth of investigation close to 2.5 meters. The primary use of the EMI instruments in this survey was to measure the conductivity to map changes in soil composition. Palaeochannel sediments often have a different conductivity from sediments from rivers and floodplain deposits due to changes in lithology, porosity and water saturation. The profile of the fluvial system during deposition controls the nature of the sediments contained in it: steep (usually braided) system are characterized by gravels and sands with high porosity values and flatter (usually meandering or anastomosing) systems are characterized by a finer grained sediments and lower porosities.

The south part of the site shows a low value of conductivity which indicates the presence of low clay content in the soil. At the northwest, the conductive sediment is crossed by a relatively resistive anomaly. If we consider the likelihood that this part of the settlement was influenced by palaeochannel activities, these resistive remains could match with a gravel or sand ridge from sediments caused by faster fluvial activities. The low conductivity in the north and northeast part of the site might also explain the absence of magnetic anomalies in this localized area which were damaged by the palaeochannel or were prevented from expanding further to the north.

Soil use: The magnetic susceptibility as a relevant proxy

Magnetic susceptibility can be an excellent proxy for the anthropogenic use of space, especially due to workshop activities and the introduction of organic material into the soil. The Neolithic tell of Belitsi in eastern Thessaly was investigated using a magnetometer; however, an overabundance of pottery sherds on the surface and the disturbed surface overwhelmed the signal and made it difficult to define the geometry of the settlement (Vouzaxakis 2008). Despite this difficulty, magnetic survey was able to locate a circular ditch delimiting the boundaries the site, but on top of the tell only a fuzzy disturbed area was indicated without any clear evidence of buildings. Magnetic susceptibility (GEM2, HCP

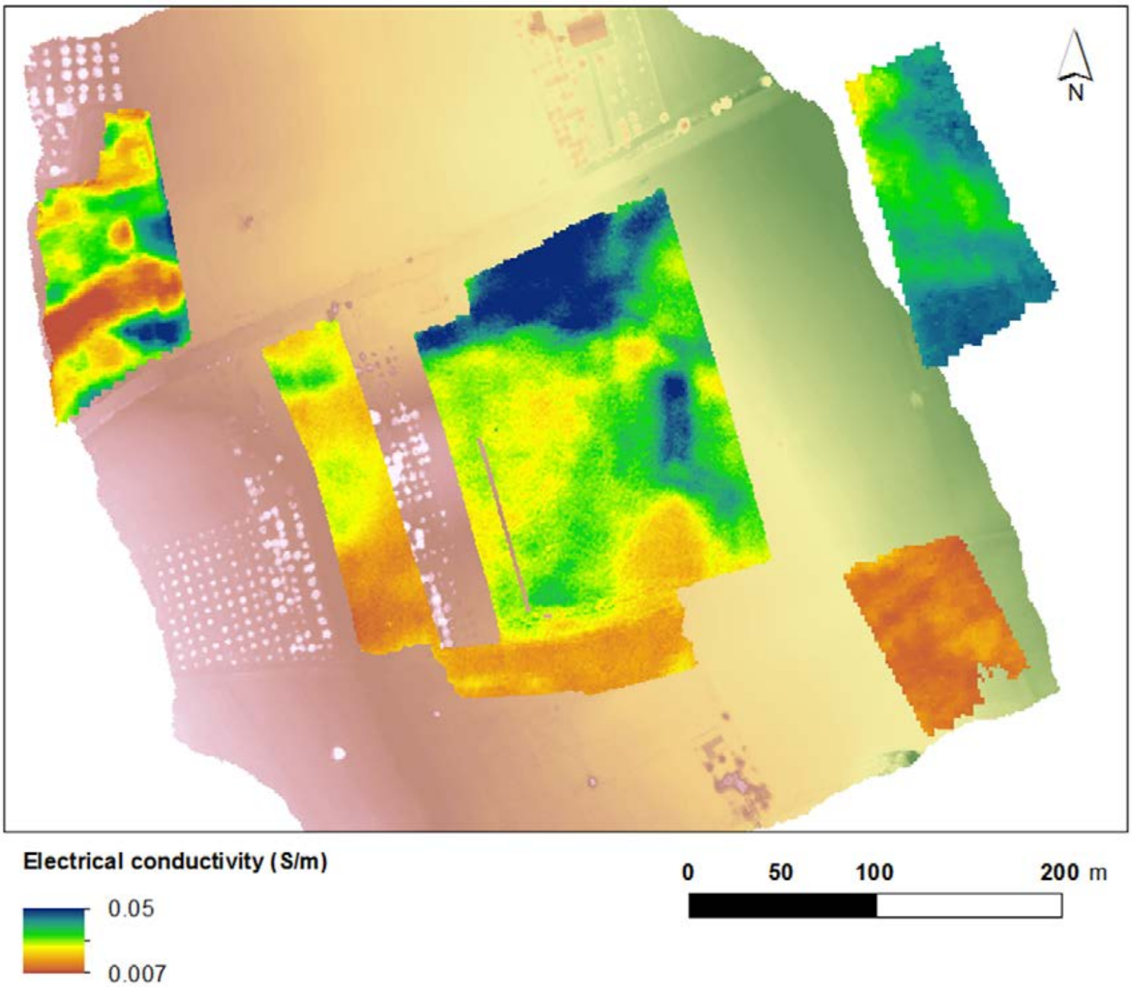

Figure 3: Map of the apparent electrical conductivity (GEM2, HCP) at Almiriotiki. Overlap of the map with a DTM created by photogrammetry. The amp shows the high conductivity (in blue) associated with the Palaeochannel on the east and north parts of the site.

measurements) was used with a 1 m line spacing, but it too was unable to extract a more accurate picture of the site (Fig. 4).

Only some anomalies can be related to buildings on the top of the *magoula* and it is difficult to distinguish between archaeological features and noise originating from surface scrap metal, sherds and the olive trees which cover half of the site today. Aside from this observation, there is an overall increase of the magnetic susceptibility all around the site and delimited by a ditch visible on the magnetic survey. The overall increase of magnetic susceptibility is an indication of the anthropogenic activities on the site as an enrichment of organic matter. Determining the exact cause of the enhancement of the magnetic susceptibility requires laboratory analysis of the soil to study the mineralogy and grain size of the magnetic minerals causing. The lack of specific anomalies in this area can be explained either by the high background magnetic susceptibility values overwhelming the rest of the features, or by a heavy disturbance of the soils due to cultivation.

Neolithic enclosures

The Neolithic site of Perdika 2 in the eastern Thessalian plain was mapped by four different geophysical methodologies (magnetics, electrical resistivity, EMI, GPR). The site is located on the level plateau of a natural hill. EM measurements were done with the GEM2 with a 1 m line spacing all around the site. The results from this survey showed a strong correlation to those from the magnetometer (Fig. 5). Both techniques suggested a complex enclosure system, which is not visible on the surface. The curvilinear anomalies which define these enclosures are clearly magnetic and probably relate to a system of enclosures and internal divisions.

There is a complicated correlation between the conductivity results and the magnetic susceptibility results from these features, with some areas being defined by high conductivity and some by low conductivity. This suggests that the enclosure was made up of walls (conductivity low) and the internal fluctuations of the conductivity may

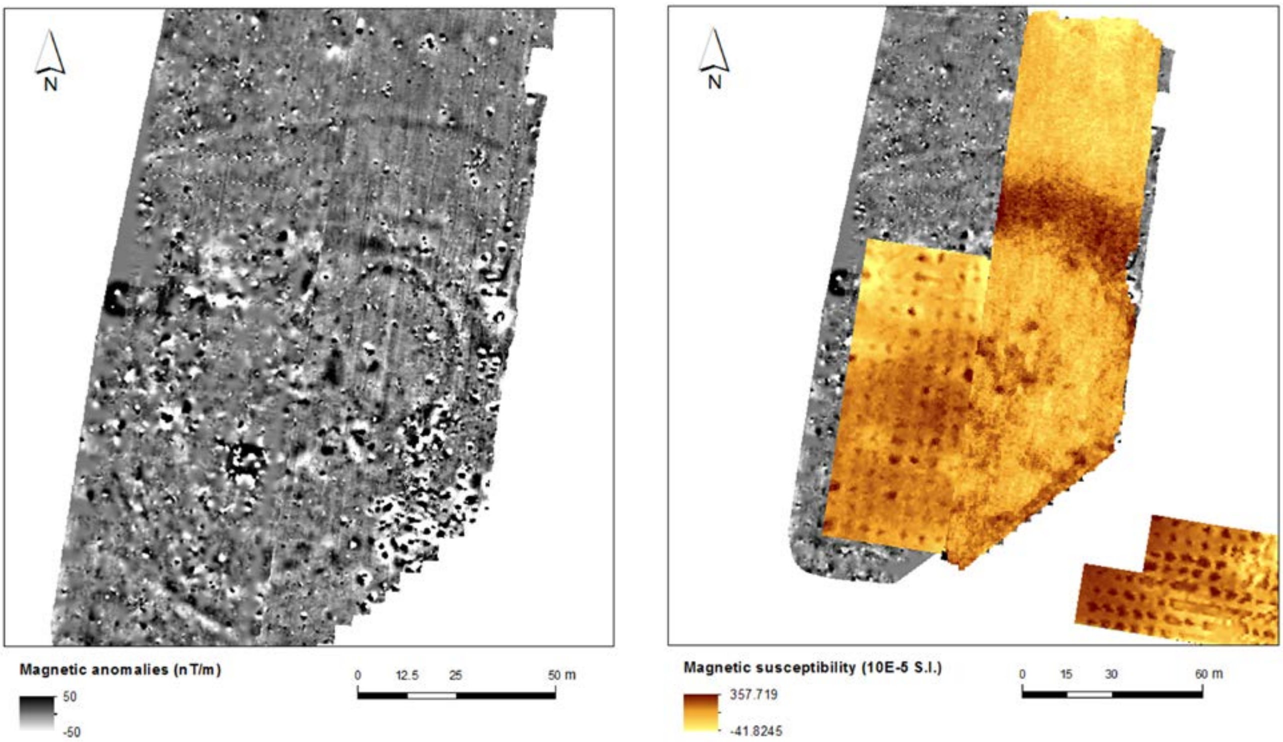

Figure 4: Neolithic site of Belitsi in Thessaly: a. Map of magnetic anomalies and b. Overlap of the magnetic susceptibility (GEM2, HCP) on the magnetic anomalies map. The high magnetic susceptibility belt is not connected to the external circular ditch, but it is falls between the outer enclosure and the nucleus of the tell.

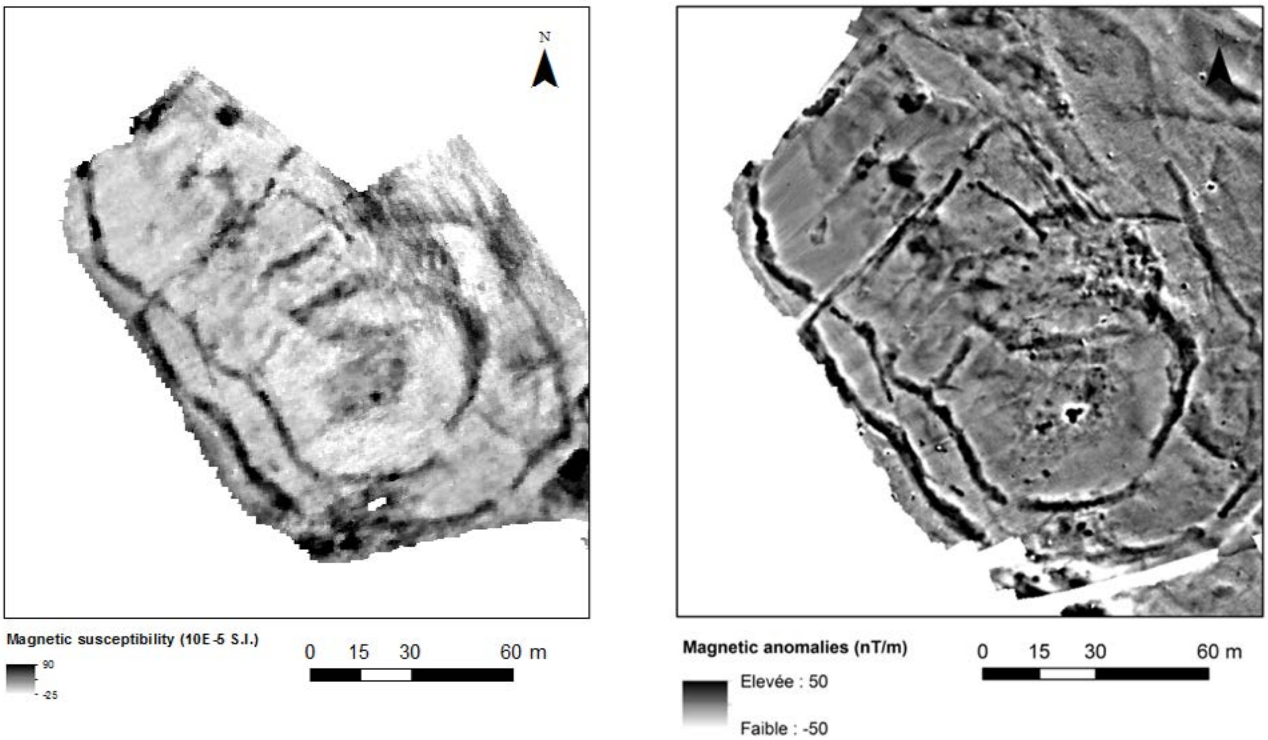

Figure 5: Neolithic site of Perdika 2. Left: Map of the magnetic susceptibility (GEM2, frequency =5010 Hz, HCP). Right: Vertical magnetic gradient data resulted from the SENSYS magnetometer survey.

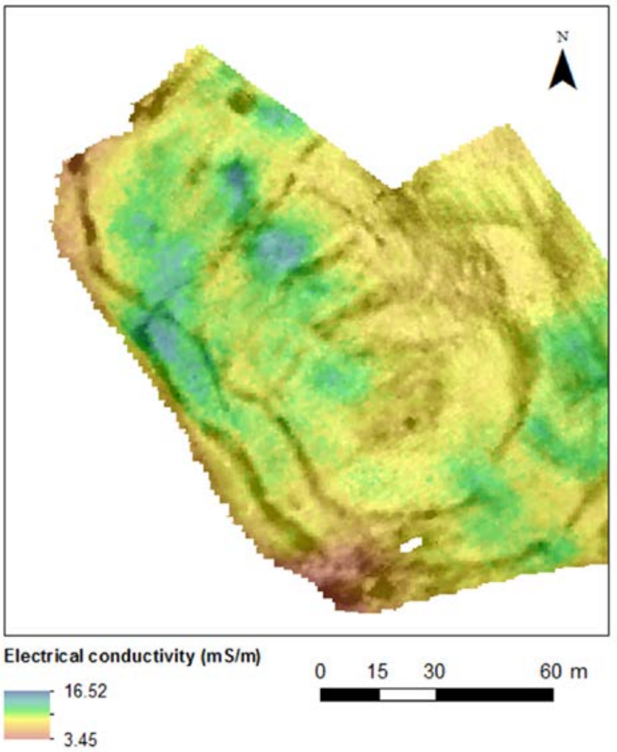

Figure 6: Electrical conductivity (color-scale) and magnetic susceptibility (black and white) at the Neolithic site of Perdika 2. Several local conductive anomalies are observed in various sections of the settlement, probably related to different activities within the site.

indicate various activities within the settlement (Fig. 6). This hypothesis awaits further investigation, but highlights the utility of measuring two physical properties for the interpretation of archaeological features.

Conclusion

EM methods have proved to be an essential tool for the characterization of archaeological sites and palaeo-landscapes. The great variety of instruments offers measurement ranges and device configurations suitable for any application. The possibility to add a global positioning system during the acquisition enlarges the coverage area from less than one hectare to more than two hectare per day. The new method proposed here regarding the use of this multi-frequency instrument corrects the measurement when the LIN limitation is not fully respected and obtains a measurement of the magnetic viscosity and dielectric permittivity. For both properties, some further work needs to be done in order to better understand the relation between the archaeological remains and the physical properties and to find the best way to carry out this kind of measurements. These new developments mean that EM methods are becoming even more useful and will become an even more important tool for archaeological prospection.

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Seismic Geophysical Methods in Archaeological Prospection

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Abstract: Geophysical methods (as a non-destructive method) have been used in archaeological prospecting since the 1940s. The geophysical techniques that are most commonly used are electrical methods, magnetic, electromagnetic soil-conductivity systems and ground penetrating radar (GPR). Less commonly used methods include microgravity and seismic techniques. Most commonly, the geophysical survey is used to create maps for the detection of subsurface archaeological features. The features are recognized as lineaments in the geophysical image or due to regular shapes, thickness and geometrical characteristics of the resulting geophysical anomalies/signals.

Geophysical instruments can detect buried features when their physical properties contrast measurably with their surroundings. Geophysical images can be used to guide archaeologists for planning excavations and to give them insights into the patterning of non-explored parts of the site under investigation. Unlike other archaeological methods, geophysical survey is neither invasive nor destructive. For this reason, it is often used where preservation (rather than excavation) is the goal, and to avoid disturbance of culturally sensitive sites.

The main purpose of this work is to present a review of the application of seismic methods to archaeology. Geophysicists have experimented with refraction seismic methods in archaeological applications with limited success, since refraction methods work best in mapping undisturbed layers that have velocities increasing with depth. The method becomes less useful and interpretation becomes very qualitative and difficult when there are velocity inversions representative of human cultural disturbance or highly three-dimensional objects such as burial sites or stone foundations. Nowadays new sensors, acquisition systems, processing/simulation techniques and configurations are adopted to overcome any complexity and to help the archaeologists map in an efficient way the subsurface.

Keywords: Seismic methods, tomography, 2D/3D modeling, microseismic method, borehole seismic, special arrays.

1. Introduction

Classical archaeological methods include the construction of trenches and/or leveling excavation by using trowels and brushes which are time consuming and relatively expensive. The application of geophysical methods to archaeology started in the mid-1940s and continued by testing different techniques and defining the limitations and advantages of each applied method to near surface targets. Several geophysical methods are now available for mapping the subsurface, covering large areas in a short amount of time.

The main reason of applying geophysical methods in archaeological prospection is the extremely rapid and accurate reconstruction of the site under investigation. Geophysics can provide information about changes in the cultural layers, since it can easily recognize any changes in subsurface due to habitation or burials. Geophysical methods can find buried foundations, roads and walls made of different building materials. Moreover, we should also consider that not all archaeological sites can be excavated. In cases of historical buildings, churches, monuments or ancient structures underneath modern constructions, geophysical methods are often the only resource that archaeologists can use. Finally, prior or during large construction works (metro, buildings, tunnels, etc.), geophysical methods can be of great value for any archaeological project as it is one of the fastest survey techniques.

The most often used geophysical methods in archaeology are the geoelectrical (Griffiths and Barker 1993; Griffiths *et al.* 1990; Hesse *et al.* 1986), magnetic (von der Osten-Woldenburg *et al.* 2002; Morariu *et al.* 1989; Gaffney *et al.* 2000) and electromagnetic (Bevan 1983; Brooke and Maillol 2007; Frohlich and Gex 1996) methods for finding various kinds of ancient relics (caves, tombs, walls, foundations, monuments, paleorelief, etc.). There are some other geophysical methods with limited or supplementary use in archaeology, such as microgravity (Panisova and Pasteka, 2009) and seismic methods (Tsokas *et al.* 1995; Xu and Stewart 2002; Brzostowski and McMechan 1992). During the last decades, archaeologists and geophysicists started applying seismic methods in places where the radar signal absorption was high, the penetration depth by applying electrical or electromagnetic methods was limited, and the environmental noise for these methods was high.

Seismic methods have been developed and implemented in a conventional way by measuring and processing the first and later arrivals, processing the spectrum of the surface waves and producing 1D and 2D subsurface models of S waves and applying special arrays for reconstructing a tomographic model (forward and inverse modeling). The data can be collected on the surface by using linear and special arrays, in a borehole or between boreholes (crosswell experiments) or into the sea. Finally, the scale of the application of seismic methods can vary from large scale surveys to meso- and micro-scale experiments.

In this paper, a review of the application of seismic methods in archaeology is presented, commenting on different aspects of the method as mentioned above and presenting the results of their application from various archaeological case studies.

2. Seismic method oriented to archaeology

Compared to other geophysical methods, seismic methods have several distinct advantages and disadvantages. Seismic techniques can detect both lateral and depth variations of seismic velocity, produce a detailed image of the structural features present in the subsurface, and delineate stratigraphic and in some instances depositional features. Response to seismic wave propagation is dependent on rock density and a variety of physical (elastic) constants (porosity, permeability, compaction, etc.). On the other hand, the amount of data collected can rapidly become overwhelming and the logistics of data acquisition are more intense and expensive than other geophysical methods. In general the equipment for the acquisition is more expensive than other instrumentation and data processing can be time consuming, requiring sophisticated hardware/software.

Beyond the aforementioned limitations, there is one more ‘inherent’ limitation related to the development of the method. The seismic method was originally developed by oil industry and it was mainly intended to image the subsurface at the depth of hundreds or thousands of meters. As a result, conventional seismic acquisition systems use very energetic sources and a large number of geophones. The use of seismic methods for imaging very shallow targets is a relatively recent development (Steeples *et al.*, 1986; Miller *et al.*, 1994), and consequently its application in near surface experiments is still in progress. Shallow seismic experiments use portable seismic acquisition systems having a limited number of channels (24, 48 or 60 is a typical number), single geophones and relatively weak (and cheap) surface sources (usually a sledgehammer). In this case, a survey of this scale can be performed very fast by two people, so that acquisition costs and time will be similar to those for a GPR survey.

To define the applicability of the seismic techniques in archaeological prospection, one should consider what physical properties of archaeological features will make them detectable. In general, any ‘velocity anomaly’ which is considered as a signal/target of interest for excavation can be defined in the uppermost few meters (2-5m) of the earth. Most cultural layers are expected to be located in the upper strata of the soil (disturbed zone) above the first competent bedrock layer (e.g., previous structures/ old uses) or else involve some disruption of the bedrock surface itself (e.g., construction of a burial chamber). An archaeological target will be seismically detectable if it presents different properties (density, porosity or velocity) from its surroundings. Moreover, the geometrical characteristics of the target (shape, size and orientation) also influence its seismic detectability, depending upon the particular kind of seismic configuration, sensors and processing method used for interpretation.

At the beginning, archaeological seismic surveys had sources and receivers located only on the earth’s surface, and by collecting the data along a line, a seismic model was expected to be estimated by applying refraction or reflection tomography. More recently, different kinds of data/information (seismic surface waves) acquisition have been developed to reconstruct the 2D/3D S-wave model of the study area. Since archaeological structures are extended or buried in deeper horizons and a borehole or a pair of boreholes can be constructed in the framework of an archaeological project, seismic methods can be applied by deploying geophones and sources on the surface or into the boreholes, increasing the resolution of the resulted seismic model. Finally, depending on the size or the purpose of an archaeological survey, the scale of the experiment can be changed, collecting and processing data in meso- and/or micro-scale.

3. Case Studies

3.1 Surface Large Scale Seismic Experiments

In the framework of the Istron Geoarchaeological Project, several methods (geophysical, coring, dating, geological, tectonic, geomorphic, etc.) were used in the wider area of Priniatikos Pyrgos of the Istron River valley located in eastern Crete (Fig. 1). These surveys focused on exploring the type and distribution of architectural monuments and the intensity and extent of habitation of the particular settlement in various chronological periods, which suggest a diachronic exploitation of the site since prehistoric times. The study area has shown evidence of settlements, port facilities and ceramics (mainly in the prehistoric periods) and metal workshops (mainly in historical periods) (Kalpaxis *et al.* 2007, Pavlopoulos *et al.* 2007). A faulting region in the area between the promontories of Priniatikos Pyrgos and Nisi Pandeleimon and the weathered limestone bedrock may also designate the location of an ancient harbor in the specific region (Hayden *et al.* 2008, Sarris *et al.* 2005, Sarris *et al.* 2007).

The main objective of this work was to reconstruct the paleo-relief and the morphological characteristics of the bedrock of the study area and indirectly identify the location where the buried old natural harbor of the archaeological site of Priniatikos Pyrgos was located. In order to accomplish the objectives of the project, the seismic refraction technique

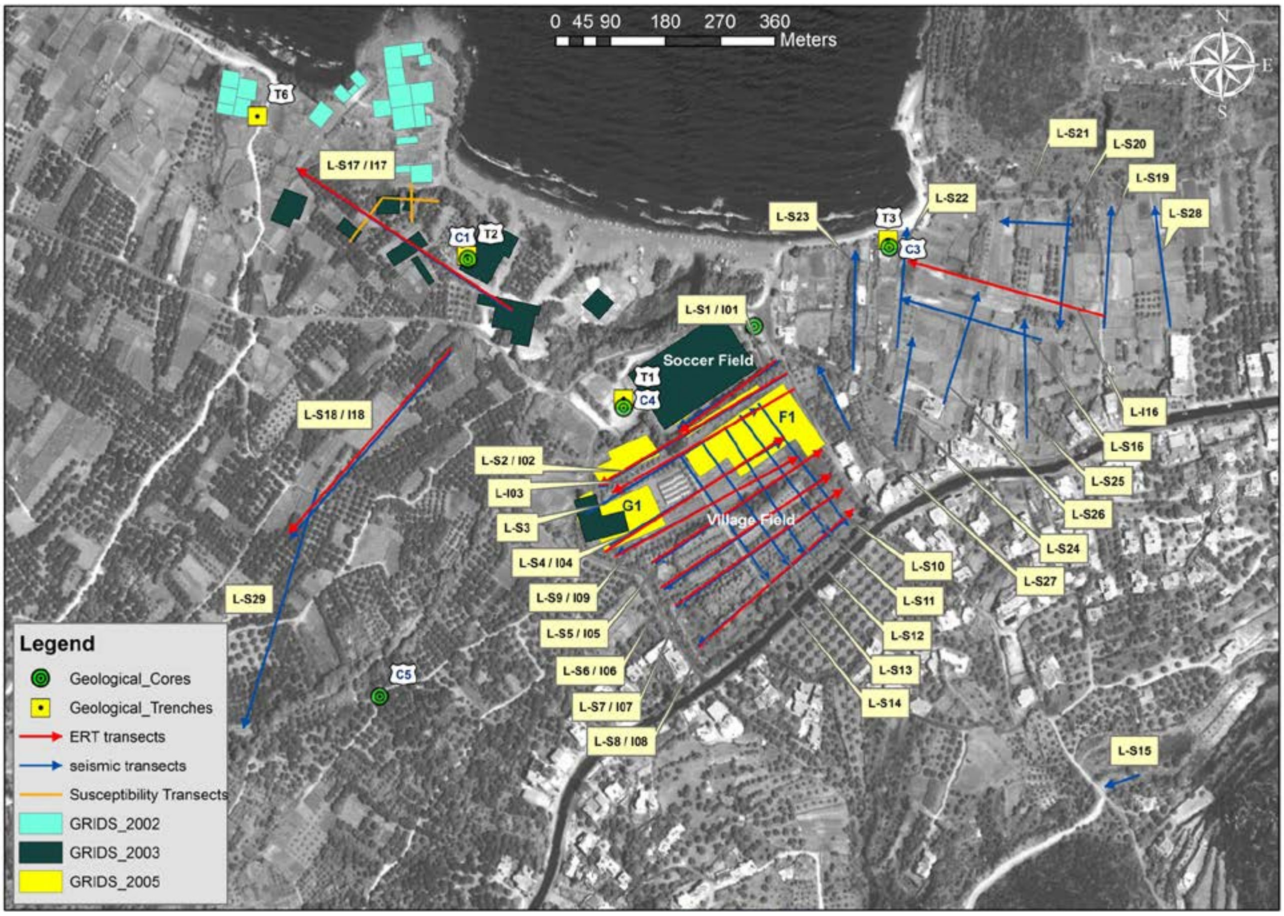

Figure 1. Locations of the geophysical profiles where electrical resistance tomography, seismic and magnetic susceptibility measurements were carried out in the area of Pryniatikos Pyrgos. Most of them are located to the south and east of Priniatikos Pyrgos promontory. The locations of the spots where geological cores (C#) and geological trenches (T#) were conducted (Zacharias *et al.* 2009) are also indicated in the specific map (Sarris *et al.* 2012; Shahrukh *et al.* 2012).

was applied in several places to determine the stratigraphy, the depth to the bedrock and the velocity distribution of different lithofacies of the subsurface.

In order to overcome the limitations (lateral and in depth) in velocity reconstruction following conventional processing methods for refraction experiments, a 3D tomographic approach is presented in this work. Specifically, a freely available 3D tomographic (ATOM-3D) inversion algorithm (Koulakov 2009, 2011) was used for resolving the expected complex characteristics of the subsurface of the area under investigation. The refraction seismic survey covered an area of about 600m (E-W) x 500m (N-S) to the east of Priniatikos Pyrgos (Fig. 1). A total number of 25 profiles were used for applying the 3D refraction tomography algorithm. Supplementary, some refraction profiles were collected over the bedrock (at the southern part of the broader study area) and over different geological units in order to calibrate and classify the resulting velocity images. The acquired velocity information was used as a priori information (initial velocity model) in seismic tomography. After removing noisy traces from all the collected seismic data, 456 receivers and 166 shots were used for producing a total number of 2,657 picked travel times which were imported as input data to ATOM-3D for reconstructing the 3D velocity model of the study area.

Horizontal tomograms of velocity (depth slices) at depths of 0, 10, 20, 30, 40 and 50 meters are presented in Figure 2. A tectonic depression (about 80-100m wide) of the bedrock at the centre of the study area is confirmed and the hypothesis about the detection of the ancient harbour is strengthened even more. It is worth mentioning that the detected feature can be reconstructed by the tomographic method based on the velocity model and the acquisition geometry (geophone locations) of the experiment.

3.2 Surface Meso-Scale Seismic Experiments

In 2008, Forte and Pipan published a meso-scale example of the application of seismic methods over a Late Bronze Age burial mound in Northern Italy trying to reconstruct the subsurface of the study area at several depths. After processing, the authors managed to present an accurate and reliable 3D model of the tumulus (with dimensions of 30m x 30x) showing the chamber and some pre-excavated sectors due to disturbance of the soil.

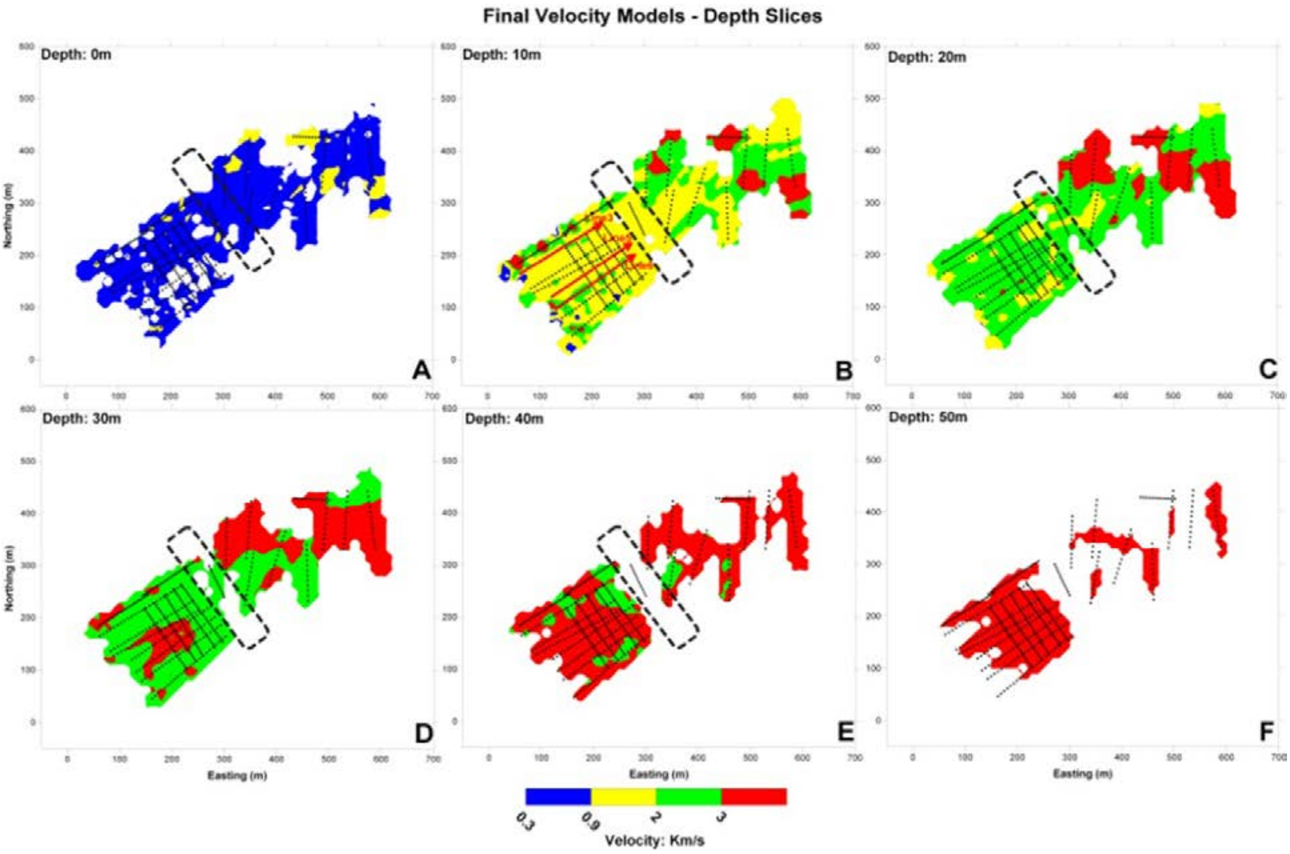

FIGURE 2. FINAL VELOCITY MODELS RESULTING FROM THE INVERSION OF REAL DATA AT DIFFERENT DEPTHS. DOTTED LINES INDICATE THE LOCATION AND ORIENTATION OF THE REFRACTION PROFILES, AS WELL AS THE COVERAGE OF THE STUDY AREA. DASHED LINES DEPICT A POSSIBLE TECTONIC GRABBEN SINCE AN INTERRUPTION OF SEVERAL GEOLOGICAL LAYERS WAS FOUND (SHAHRUKH *ET AL.* 2012).

For the seismic experiment, a 24 channels digital seismograph with 24 vertical geophones of 40Hz was used for the acquisition of raw data. Since the distances were short, a sledgehammer was used as the energy source. The geophones were installed around the study area at constant distances and elevation (Fig. 3). In order to achieve good raypath coverage, 24 source locations between pairs of adjacent geophones were deployed, as is shown in Figure 3. In total, 576 seismic traces were used for each tomographic model.

The inversion code was repeated several times before calculating the final (optimum) velocity model based on the convergence criteria. Figure 3 shows the broader study area and the digital model of the tumulus, which was used for any topographic corrections of the resulted tomographic model. In the upper right image of Figure 3, the raypath coverage is shown from which the sensitivity (bending rays) of the raypaths to lowand high velocity anomalies becomes clear. The raypath coverage ensures the reliability and accuracy of the resulted tomographic velocity model. The figure also shows that the final calculated velocity model ranges between 200m/s in the shallow layer and more than 1000m/s in the inner part of the tumulus. The same method (surrounding the tumulus with geophones as different elevations) can be applied to tumulus or similar archaeological targets of different sizes.

A similar meso-scale geophysical survey was accomplished at the archaeological site of Delphi in Greece where several geophysical methods were applied in order to test the reliability of the collected data and the resulting models. Five methods were applied at the site: magnetic gradiometry, electrical resistivity tomography (ERT), multi-frequency controlled source electromagnetic (CSEM), ground penetrating radar (GPR) and seismic refraction tomography (SRT). The locations of the geophones or shots were carried out by a total station and a differential GPS survey.

This work focused on the results of an integrated geophysical approach that was applied in a small (50 by 40 meters) section of the archaeological site. The plateau and the road that exist close to the facilities of the modern theatre and the storage area of epigraphic stones were scanned by seismic refraction and resistivity tomography methods in order to enhance the information context up to the depth of 5 meters below the ground surface. Only the result of seismic experiment is presented here.

The seismic refraction tomography survey covered the whole area of interest. In total, 24 P-wave geophones were randomly installed on the ground following arbitrary directions in order to have a 3D coverage of the study area. The seismic energy was created by vertically striking a metal ground plate with a sledgehammer. 73 shots were

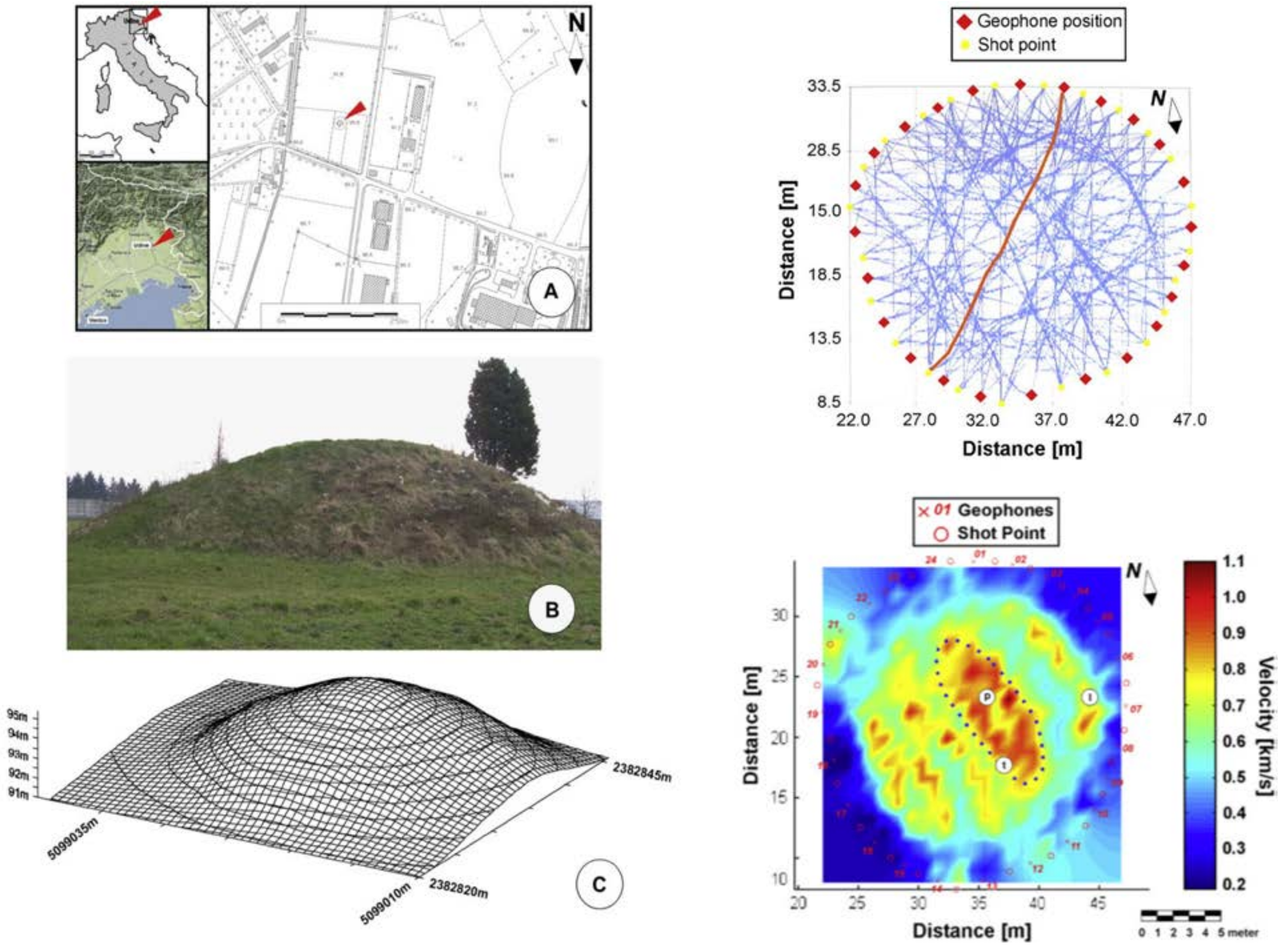

Figure 3. Left: (A) Map of the study area in Italy; (B) Photo of the study area before archaeological excavations; (C) digital terrain model (DTM) of the area under investigation. Upper right: seismic raypaths (in blue) for all the source (in yellow) and receiver (in red) combinations. The orange raypath shows an example of a seismic trace across the tumulus; (lower right) Velocity model from seismic tomography. (L) Lateral structures; (T) funeral chamber: perimeter of boulder layer; (P) skeleton deposition zone (Forte and Pipan, 2008). Permission for the reproduction of the figure was provided by E. Forte and M. Pipan.

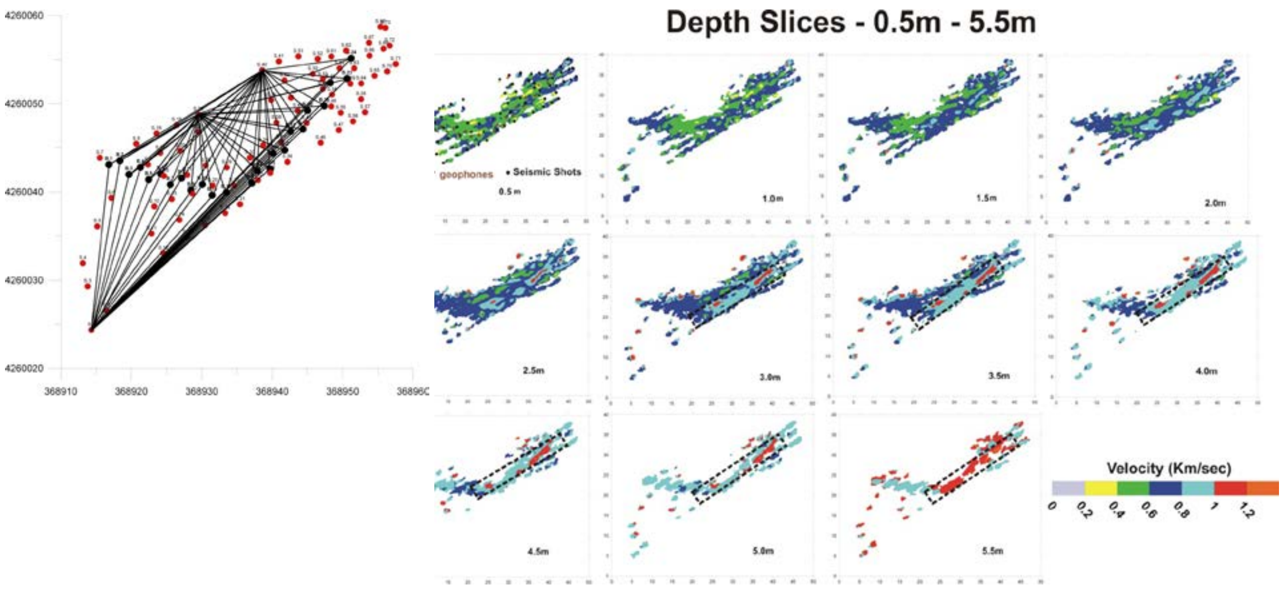

Figure 4. Left: The source and receiver location is presented. The raypath coverage ensures the applicability and the high quality of collected seismic data. Right: Depth slices of resulted velocity tomographic models from surface to the depth of 5.5m.

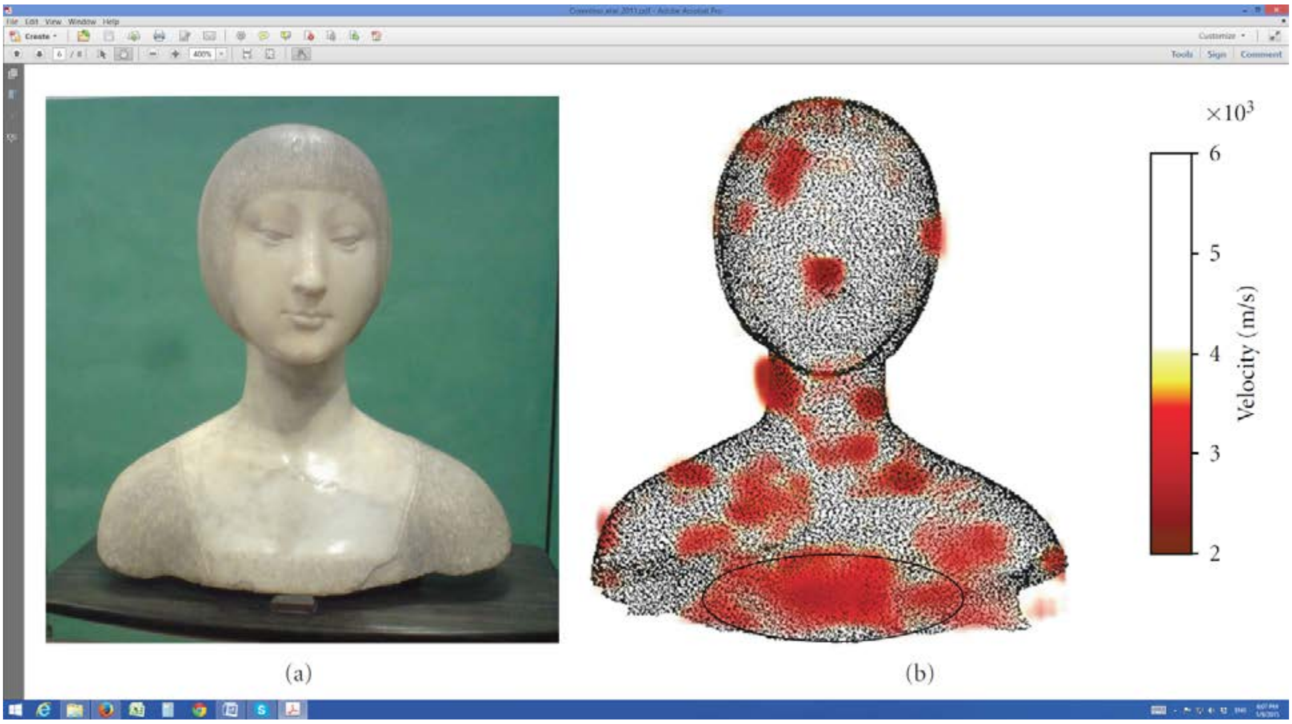

Figure 5. At left the bust of Eleonora d'Aragona (F. Laurana, 1468). At right the frontal 3D image with transparency of the investigated volume showing an area at low velocity, corresponding to the support point of the bust (Agnello *et al.* 2009). The figure was originally captured from Cosentino *et al.* (2011) and permission for the reproduction of it was provided by Prof. Pietro Cosentino.

used to collect about 1,752 traveltimes (73 shots x 24 geophones = 1,752 raypaths). Prior to the application of seismic tomography, all the collected seismic data were processed in order to pick the first arrivals. The data were afterwards pre-processed providing information about a) source and receiver exact locations including topographic corrections (Fig. 4 left), and b) the traveltimes recorded per source-receiver pair. Non-commercial software (ATOM_3D, Koulakov 2009) was used for the inversion and interpretation of the seismic refraction traveltime data. The program uses a ray tracing bending algorithm for solving the forward problem and the LSQR (Paige and Saunders 1982) routine to solve the inverse problem. The appropriate regularization parameters were used for inverting the data. Finally horizontal velocity tomograms every 0.5 meter up to the depth of 5.5 meters were extracted by the 3-D velocity model.

In all tomographic models, a linear high velocity feature is found at a depth of 3.0m until a depth of 5.5m (Fig. 4). This linear feature (possibly a retaining wall) is depicted by the dashed rectangular oriented from the northeast to the southwest. The continuity of this structure is confirmed at the depth of 5.5 meters. The experimental application of the seismic survey indicated the potential use of it in detecting large architectural sections, but it was not very successful in the detection and mapping of smaller scale architectural targets.

3.3 Surface Micro-Scale (Microgeophysics) Seismic Experiments

An excellent example of the application of Microgeophysics for cultural heritage is presented by Cosentino *et al.* 2011. The authors in the introduction mention that, 'Microgeophysics is a new and rapidly developed branches of geophysics. It includes a lot of methodologies derived from geophysics and it is applied, with more or less miniaturized instrumentations, to small volumes of soil or masonry, as well as to simple artifacts such as statues, pottery, corbels, and so forth.'

Cosentino *et al.* (2011) presented a nice example of the application of seismic technique to study the structural failure of a statue. Specifically, they applied a 3D ultrasonic tomography (UST) on the statue of Eleonora d'Aragona (sculptured by F. Laurana, 1468, see Figure 5a). The statue is an excellent piece of art carved from a massive and unified, white microcrystalline piece of marble (Cosentino *et al.* 2011). Some cracks were found due to the heterogeneity of the material (natural veins in the marble). To map the size and distribution of failure surfaces into the statue, the 3D UST method used collecting raw seismic data from 157 measurement points evenly distributed (every 2-5 cm) along the surface of the object (Agnello *et al.* 2009). In total, 1,768 data were finally used for modeling after filtering. The use of 1cm^3 voxel size was selected for inversion process (Fig. 5).

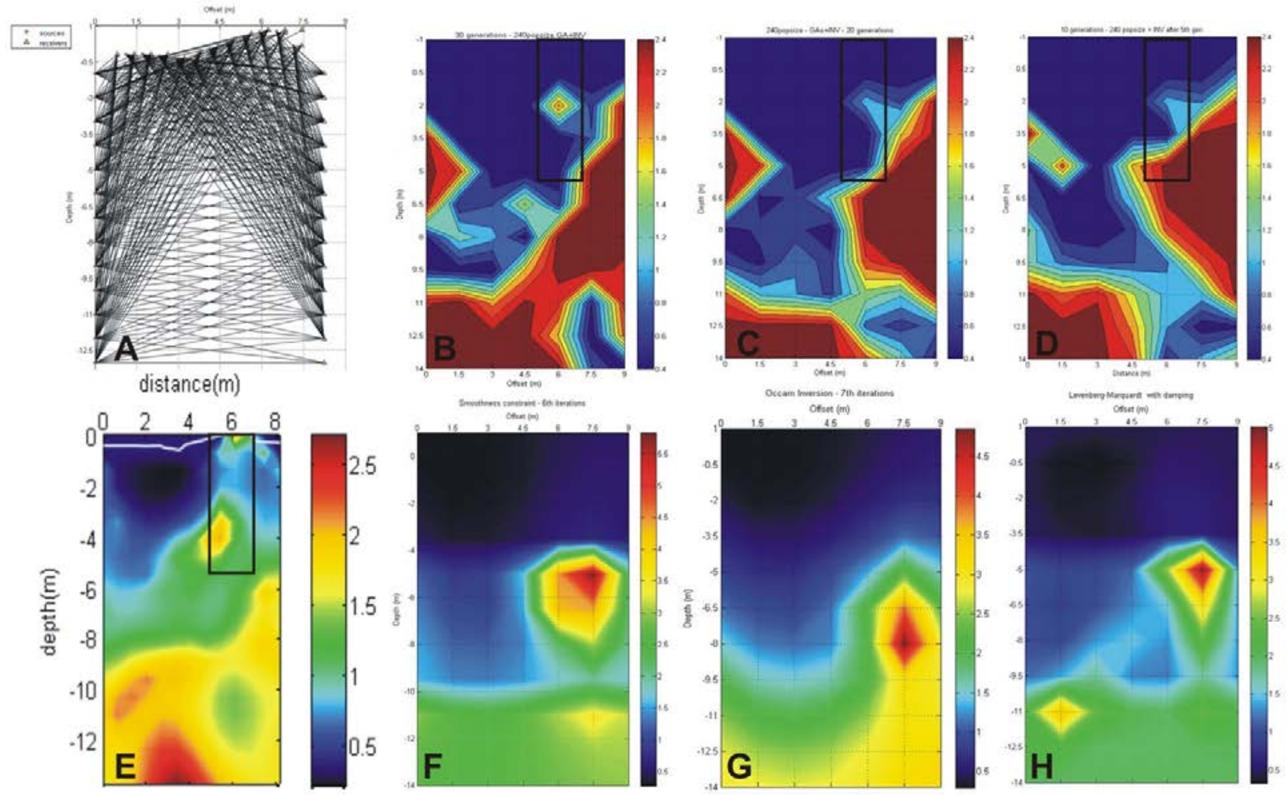

Figure 6. Final velocity models for the Byzantine wall foundation study area examined in this work. (A) The sources–receivers configuration as well as the raypath coverage for the real experiment is presented to highlight the good coverage of the study area. (B, C, D) The reconstructed velocity models by using the hGA method after 30, 20 and 5 generations, respectively, are shown. (F, G, H) The final tomographic velocity models by applying different local optimization methods (smoothness constraint, Occam inversion and Levenberg–Marquardt with damping, respectively) to the same experimental configuration are given. (E) The final tomographic velocity model (Mpogiatzis, 2010) adopting different weights to data, topography corrections, threshold to 'bad' measurements and a finer grid is shown. The solid black line depicts the relics of the ancient Byzantine wall (Soupios *et al.* 2011).

After final modeling and reconstructing, the 3D velocity model depicting the low velocity areas (red zones in Fig. 5), Cosentino *et al.* (2011) concluded that the velocity model does not show significant problems or possible micro-cracks on the face of the statue. The resulting velocities (greater than 4000 m/s) of the upper part of the model correspond to a homogeneous cohesive marble. In some places, at the lower part of the model, low velocities were calculated which can be correlated with possible failure zones. Consequently, the application of noninvasive tomographic investigation can help the restorers preserve this antiquity.

3.4 Crosswell seismic experiment

An example of a crosswell seismic (CWS) geophysical survey in an urban environment is presented here. It is known that modern structures, such as concrete foundations, piles, etc., often mask the signal from deeper archaeological targets (Tsokas *et al.* 2011). Moreover, an urban geophysical survey must be noninvasive and not all methods can be applied in such noisy environment. Thus, there are several constrains (method, data quality, etc) that make the geophysical survey a very difficult task.

The particular example refers to a seismic survey that was part of a more extensive geophysical investigation (geoelectrical measurements, Tsokas *et al.* 2011) which was carried out in the framework of the construction of the new metropolitan underground railway of the city of Thessaloniki in Greece. The metro line was designed to cross the Roman and Byzantine city walls. Additionally, a metro station was scheduled to be constructed near the study area and as a result any information about the ruins of the ancient walls, their lateral and vertical extent, was valuable for the construction engineers. The dense urban environment made the application of large/full-scale surface geophysical prospecting impossible, thus it was decided that the optimum approach was the drilling of boreholes at either side of the wall in order to perform joint cross-hole/downhole tomography measurements (Soupios *et al.* 2011).

The distance between the boreholes was about 8m. During the casing procedure of the first (left) borehole excessive cement grout usage was required (probably due to a subsurface cavity) and as a result a wide high velocity area was expected to be identified at the bottom left section of the study area. On the surface, a total of 12 P-wave geophones were installed between both boreholes, the first with offset 0.8m from the first borehole and the rest every 0.6m. Furthermore, 3 borehole triaxial geophones (GEOSTUFFBHG-2) with 1m spacing were used and by their sequential placement inside the first borehole, recordings up to depth of about 13m from the surface were performed. P-waves were generated from a borehole source at the second borehole which placed at different depths with a spacing of 1m. Moreover, a hammer surface source was also used to provide additional surface-to-borehole recordings. The previous measurement setup yielded a satisfying coverage of the investigation area by seismic raypaths (Fig. 6A). A total of 24 sources were used from which high resolution traveltimes were collected from 25 receivers (both on the surface and in the borehole). The final data set consists of 341 first breaks of P-waves after removing waveforms with poor signal quality. The tomographic model consisted of 77 velocity nodes (7 nodes in horizontal, 11 nodes in the vertical direction, with a node spacing of ~1.5m in both directions). Using the borehole logs, an initial velocity model with a positive depth-gradient was used, consisting of 3 layers (0.5, 1.2 and 2.0 km/s).

The final velocity model after the application of the hybrid GA algorithm for 30 generations is presented in Fig. 6B, exhibiting a final misfit of ~3.2 ms. Moreover, a comparison of this model with the final inverted velocity models by using different local optimization methods (Occam method minimizing the 2nd derivative – Fig. 6G, smoothness constraint minimizing the 2nd derivative – Fig. 6F, classical Levenberg–Marquardt regression with damping - Fig. 6H) with the same configuration (77 unknown parameters) is also shown. It seems that the local optimization methods failed to reconstruct the real velocity model since the solution is trapped to local minima, either due to some bad data (low signal to noise ratio-poor quality signals) or because the starting model is close to some basin of attraction that correspond to a local minimum different than the 'real' solution. The final hybrid GA velocity model (Fig. 6B) is favorably comparable to the final velocity model of Mpogiatzis (2010), which was estimated by a joint-inversion of both P- and S-wave recordings and the application of different data weighting (according to their quality), as well as a finer model grid (Fig. 6E).

4. Conclusions

Geophysical methods can help archaeology to get information about unexcavated subsurface archaeological features. All the archaeological structures are material bodies that have different physical properties than the surrounding rock/soil. Based on this characteristic, geophysical methods can successfully reconstruct the subsurface. The above cases studies demonstrate that the seismic refraction/tomography method can provide the necessary tools in the geo-archaeological investigations of a site by compiling models and extracting new information related to ancient relics. It should be mentioned that the use of one geophysical method is never enough and an integrated geophysical exploration should be always carried out in areas of interest.

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Locating Graves with Geophysics

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Abstract: The detection and mapping of unmarked graves is a significant focus of many archaeological and forensic investigations however traditional methods such as probing, forensic botany, cadaver dogs or dowsing are often ineffective, slow to cover large areas or excessively invasive. Geophysics offers an appealing alternative suitable for the rapid non-invasive investigation of large areas. Unfortunately graves are a challenging target with no diagnostic geophysical response and so the use of a rigorous application-specific methodology is essential for a successful outcome. The most important inclusions in a successful survey methodology include ultra-high density data, the use of multiple geophysical techniques to validate results based on several physical properties, excellent quality positioning and intensive site recording. Regardless of the methodology applied, geophysics should not be considered a panacea for locating all graves on all sites but should be used as an integral part of a comprehensive survey strategy.

Keywords: graves, geophysics, clandestine, forensic, burial

Introduction

> 'Thou know'st 'tis common; all that lives must die,
> Passing through nature to eternity.'
>
> (Hamlet, Act 1, scene 2, line 72)

The universality of death provides a tangible connection with the past making graves an important, sizeable and evocative component of the archaeological record (Gowland and Knusel 2009, Pearson 1999, Tarlow and Stutz 2013). Graves contain material culture, skeletal evidence of diet and disease and even the act of interring a body has significant implications for the development of behavioral modernity (Pettitt 2010). Murder is, fortunately, a much less universal human experience however losing a loved one in this fashion leads to prolonged and intense trauma for the directly bereaved (Rynearson 1994) and distress in the immediate community and society in general (Morrall 2006). In many cases, successfully locating a clandestine grave may provide closure to the victim's loved ones and facilitate the prosecution of the murderer.

Despite the importance of locating these features, current methodologies for the detection of unmarked graves (summarized by Killam 1990) remain limited and ineffective due to their small size, subterranean position, lack of surface expression and the often ephemeral nature of their markings. Current methodologies can be effective in some situations, but commonly struggle to cover large areas and deal with burials where the flesh has completely decomposed, as is the case in most archaeological investigations. This difficulty has led to extensive research into the geophysical detection of burials for forensic and archaeological investigations which has accumulated a voluminous literature (i.e. Bevan 1991, Buck 2003, Davis *et al.* 2000, France *et al.* 1992, Miller 1996, Nobes 1999, 2000, Powell 2004, Ruffell *et al.* 2009), well summarised by Conyers (2006) and Ruffell and McKinley (2005). The appeal of using geophysical methods for this purpose is that they are non-invasive, culturally appropriate, survey large areas relatively rapidly and can provide information about depth, orientation and other burial characteristics. Unfortunately there is no 'bone detecting instrument' (Powell 2004) as skeletal material does not, in most field situations, provide a detectable geophysical response. Geophysical techniques instead rely on locating the stratigraphic disturbance caused by the grave shaft (including the disruption of bedding, conflation of different soil layers and changes in the porosity leading to variations in water or air content), the interment vessel or the presence of metallic graves accoutrements. More intact cadavers may present additional targets relating to the presence of chest cavity voids, the contrast of the fluid rich cadaver compared to the surrounding soil or local alteration to the physio-chemical conditions from escaping fluids during decay (Bevan 1991; Davenport *et al.* 1990; Koppenjan *et al.* 2003). Unfortunately the nature of the geophysical response from any of these features is not unique and so mapping the spatial distribution of the anomalies and understanding the context of the possible burial within the broader site is essential to their successful location regardless of technique. Obviously the nature of the study area is also important and geophysics may be inappropriate for many sites, such as where the subsurface is extensively disturbed.

All of these difficulties mean that geophysics has often been used inappropriately and on occasion been derided for 'missing' burials on archaeological sites. This criticism is somewhat justified in that, regardless of the specific geophysical technique or survey methodology, these methods should not be considered a definitive means of locating graves under all circumstances and instead should form part of a suite of methods including historical research and direct investigation. However, even if these methods do not definitively locate all graves, they play a useful broader role in guiding direct investigations by allowing the extrapolation of excavation results across a site, defining the subsurface geology/geomorphology and delineating the extent of a site and any disturbance (Bladon *et al.* 2011).

Types of unmarked graves and investigations

Unmarked graves can have a wide range of orientations, depths, anatomical positions and degrees of decomposition depending on the burial tradition, interment circumstances, location and age. Prior knowledge of these characteristics at a particular site is extremely useful for geophysical survey design, as it will facilitate informed decision making about data density and orientation. Importantly, it is advantageous for survey lines to cross graves perpendicular to their long axis to ensure the maximum number of opportunities to image each burial.

Christian burials are usually contained within a burial vessel (often wooden) and are buried at a regular depth and orientated east-west. Multiple burials may exist in the same grave shaft, often with significant time gaps between each interment. A plethora of alternative burial configurations exist within other cultural and religious traditions and they often change over time (Pearson 1999:6). For example, Middle Palaeolithic graves are usually sufficient devoid of regular interment patterns or grave goods that the ability of Neanderthals to intentionally bury their dead has been significantly contested (ie. Gargett 1989, 1999) although new evidence for this behavior continues to emerge (Rendu *et al.* 2014). In contrast, the Neolithic has a plethora of different burial practices with collective burials and mortuary structures being relatively common (Fowler 2011). Roman graves have a wide variety of possible configurations including an unlined graves, tile lined graves, stone lined graves and many others (Cooke 1998: 212-221).

More elaborate burials such as crypts are usually larger, constructed of less ephemeral materials and are often designed to facilitate access for future interments. Clandestine graves have a random orientation, usually a restricted depth and rarely feature a coffin. Limited grave accoutrements such as belt buckles or clothing may be present and the body may be articulated or dismembered.

Cremated individuals may be buried in vessels or scattered. The direct detection of the burial vessel containing cremated remains is possible however it is unlikely to be distinguishable from other buried material culture unless it is contained within a very specific context (i.e. a cemetery). The fire used for the cremation may be identified geophysicaly (see below and Moffat *et al.* 2010 for further discussion) however there must exist suitable criteria for identifying the fire as being related to a mortuary event.

Equally pertinent for effective geophysical survey design is a clear understanding of the impetus for locating the unmarked graves. This issue, discussed at length in Moffat *et al.* (forthcoming), critically affects the ability of geophysical methods to contribute meaningfully to a particular project. The key question is whether a survey seeks to locate graves or find areas without graves; with the first application being far more demanding. Commonly, investigations for cultural heritage management purposes are focused on locating areas without burials within a site or establishing if a site may contain burials rather than definitively locating each burial individually. Geophysics is most often employed in this type of investigation when there is a strong possibility that burials are known to exist on site, such as historic cemeteries. In this situation it is likely that a large number of possible burials will be located and few (if any) will be directly investigated. In this case the most appropriate approach to data interpretation from a risk management perspective is to consider any appropriate sized anomaly as a potential grave. Often areas identified in this way are excluded from future invasive earthworks on the site, which prevents the disturbance of graves but almost always, due to the nature of the technique, this exclusion will include areas which do not contain graves.

Definitive location of each individual grave, such as in a forensic investigation, requires a more intensive and demanding survey methodology. Invariably these investigations will require extensive direct investigation to validate the results and will benefit substantially from an iterative approach where the results of each direct investigation lead to reinterpretation of the geophysical response. While the need to validate many anomalies may appear to negate the utility of geophysics the benefit of being able to exclude large portions of the site is significant as this be very time consuming, expensive and destructive to accomplish with other techniques.

Methodological approaches

A variety of geophysical techniques, positioning methods and site recording techniques are available to detect unmarked graves. Ground Penetrating Radar (GPR) is the most widely applied technique whilst resistivity, electromagnetic induction, magnetometry and gravity are useful in specific situations. Positioning can be provided by measuring tapes and a variety of more sophisticated surveying equipment while site recording can be done using field notes, surveying equipment, photography and photogrammetry mounted on a variety of platforms.

Ground penetrating radar

Ground Penetrating Radar, summarised in respect to archaeology by Conyers (2012, 2013), works by transmitting radar energy into the ground which reflects off subsurface discontinuities in dielectric permittivity. By measuring the time taken for this energy to return to the instrument a consideration of the depth of imaged features is possible and the measurements can be combined to present the data in one, two or three dimensions. GPR surveys are most often conducted as a series of parallel transects along which the GPR antenna is dragged or pushed. These parallel data sets can be combined to

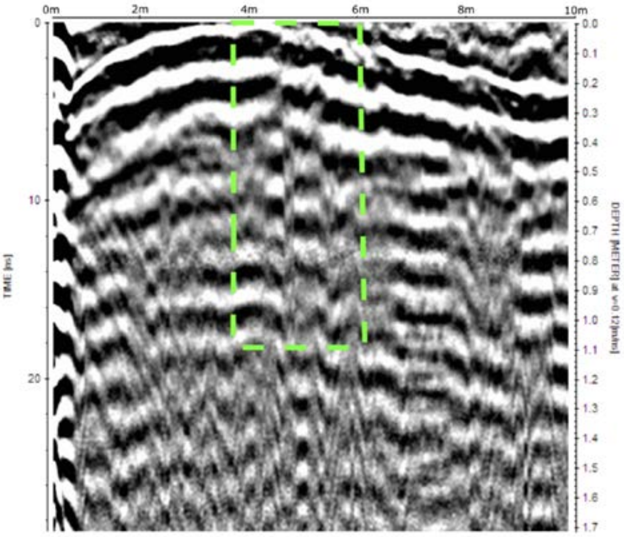

Figure 1 a (left) and b (right): GPR data from a confidential location in South Australia. The stratigraphic break from recent burials is highlighted on the GPR section in green on the left and the location of these interpreted graves is shown in the photograph of the survey area highlighted in white.

create plan view maps of amplitude at a variety of depths, often referred to as slices (Goodman *et al.* 1995). More recently true 3D data acquisition systems utilising multiple transmitter and receivers have become available allowing much smaller interline spacing (Hunter 2012). GPR is the most commonly applied method for locating unmarked graves due to its ability to rapidly cover large areas of high density data and because, when a shielded antenna is used, it is not significantly affected by surface metal.

GPR is most likely to detect graves based on the variations in soil stratigraphy caused by grave digging (Schultz & Martin, 2011). As summarised by Damiata *et al.* (2013: 269) the grave shaft may be detectable based on differences in moisture content, homogeneity, compaction, structure or velocity between the disturbed and undisturbed sediment (shown in Fig. 1a). Most commonly, the most obvious sign of disturbance is the absence of the natural horizontal anisotropy characteristics of undisturbed soil (Jenny 1994, Joffe 1936). These features are most often visible in GPR data as disturbance to the A horizon. Care must be taken when interpreting these features to not falsely include anomalies created by decoupling the GPR antenna from the ground surface due to rugged topography. This can be avoided through making comprehensive field notes and by plotting the disturbance features in plan view to observe their geographic extent. Similarly, it is important to be aware of the potential impact of post-interment disturbance from animal, plant or human intrusion, especially to the stratigraphy surrounding the grave, which can make the distinction of the shaft difficult (e.g. Moffat *et al.* 2010).

The direct detection of graves based on hyperbola signals (high frequency reflections in a characteristic parabolic shape) is a suitable approach where there is a high contrast in dielectic properties between the burial and the sounding material such as an intact (particularly metal) coffin (Owsley and Compton 1997), metallic grave goods (Novo *et al.* 2010) and the presence of a vault or (very occasionally) from the skeletal material itself (Damiata *et al.* 2013 Pringle, *et al.*, 2012, Schultz, *et al.*, 2006, Schultz, 2008). The void inside a coffin can also be detected with GPR (Bevan 1991:1311; Doolittle and Bellantoni 2010:943), however untreated wooden coffins often decompose and collapse within a decade. The accurate interpretation of burials with GPR under field conditions requires dense line spacing (≤0.5m) and high quality positioning information. This degree of spatial integrity is essential so that stratigraphic breaks can be correlated accurately between multiple lines and mapped in plan view over the site (shown in Fig. 2a). This allows the geometry and extent of the soil feature to be determined allowing differentiation between graves and other soil disturbances. On sites with extensive soil disturbance (shown in Fig. 2b) it may be impossible to interpret the position of individual graves and therefore more appropriate to map larger areas as possibly containing burials.

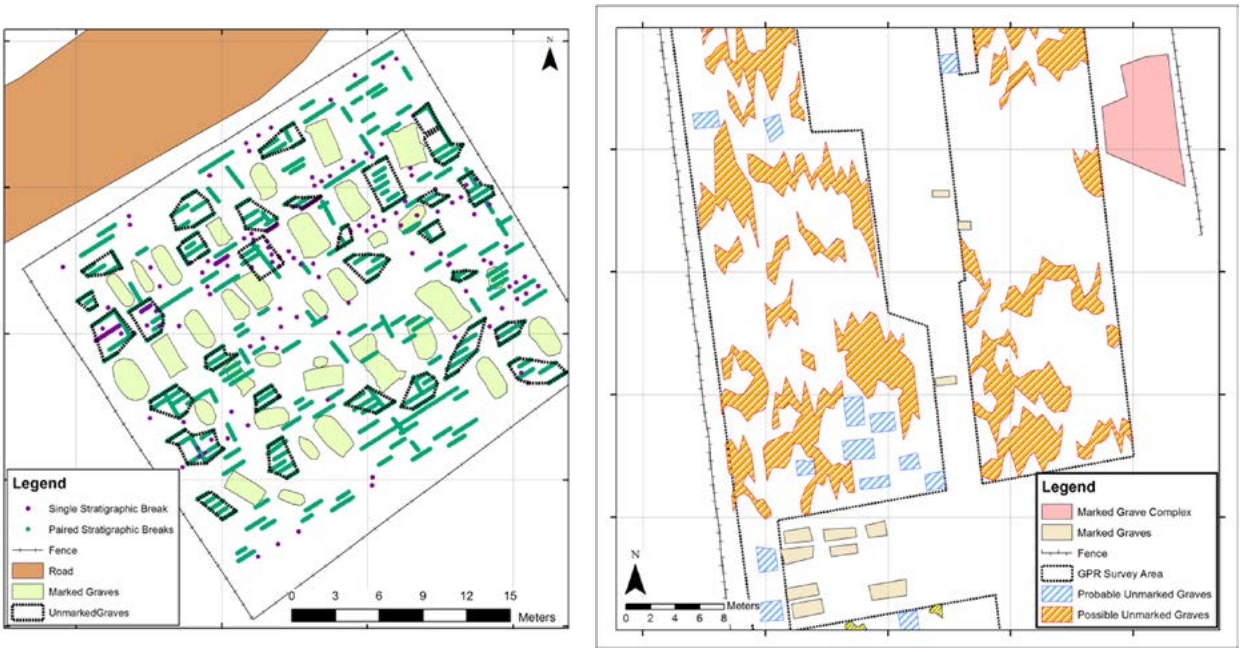

Figure 2. a (left) and b (right): Interpretation of GPR Data from the Innamincka (left) and Lake Condah (right) cemeteries. In the Innamincka data set it is easy to define discrete area with paired stratigraphic breaks that can be confidently considered graves. In the Lake Condah data set there are large areas of the site's subsurface which are stratigraphically disturbed by tree roots in this heavily forested area, necessitating the identification of larger areas. Data collected with a Mala X3M GPR with a 500 Mhz (Innamincka) and 250 Mhz (Lake Condah) antenna.

The approach of interpreting features, particularly when focusing on stratigraphic breaks, from two dimensional profiles is much more robust than exclusively using slice mapping graves in plan view with pseudo 3D data (Goodman *et al.* 1995) despite the success of this approach in some surveys (i.e. Dionne *et al.* 2010 Schultz and Martin 2011). Slice mapping is a more suitable approach for defining features with high dielectric contrast, such as crypts (Panisova *et al.* 2013), intact coffins or clusters of metal features associated with a grave.

Processing of GPR data is designed to accentuate features of interest and counteract the very rapid scatter of signal (and corresponding decrease in signal to noise ratio) with distance from the antenna. The specific processing steps are site specific however a common first pass approach is to apply a dewow, bandpass filter, background remove, running average and energy decay filter. Migration may be useful to remove the common hyperbolic distortion of subsurface reflection along the acquisition path, particularly to facilitate the imaging of stratigraphic disturbance or prior to interpolation into 3D. Migration may be inappropriate for surveys aimed at locating metallic features as it will make these features less visible.

Resistivity

Resistivity, summarized for archaeological applications by Schmidt (2013), measures the resistance of earth materials to passage of electrical current. These values are measured in one, two or three dimensions by electrodes that are directly connected to the ground, usually by metal stakes. A variety of arrays are used to measure the resistivity values which affect the nature of the response. Subsurface resistivity values are strongly influenced by the inherent properties of the earth materials, their porosity, degree of water saturation and groundwater chemistry (Schmidt 2013:123-127).

Resistivity imaging in a variety of configurations has been applied to the location of burials, including in plan view with a fixed electrode interval (Pringle *et al.* 2012: 1473-1474), along a profile (Powell 2004) and in 3D configuration (Matias *et al.* 2006). The most common target for locating graves with resistivity is soil disturbance in the grave shaft which may manifest as a relative resistivity high or low (Fig. 3) compared to the surrounding soil. The relative resistivity of the anomaly compared to background will likely vary over time based on the fluid saturation of the soil pore space, which is controlled by environmental conditions. Containment of the cadaver appears to have a significant effect on resistivity values during the decay stages with an unwrapped pig cadaver appearing as a diffuse conductive anomaly whilst a wrapped pig cadaver in the same location appears as a small resistivity feature (Pringle *et al.* 2012: 1477). A coffin may also act as a locus for clay deposition, leading to a conductive anomaly (Powell 2004: 92). Resistivity can be used to investigate larger burial structures, without necessarily prospecting for individual burials (Papadopoulos *et al.* 2009, 2010, Tsourlos *et al.* 2014).

Electrode spacing in resistivity directly impacts the resolution and depth of investigation, with most

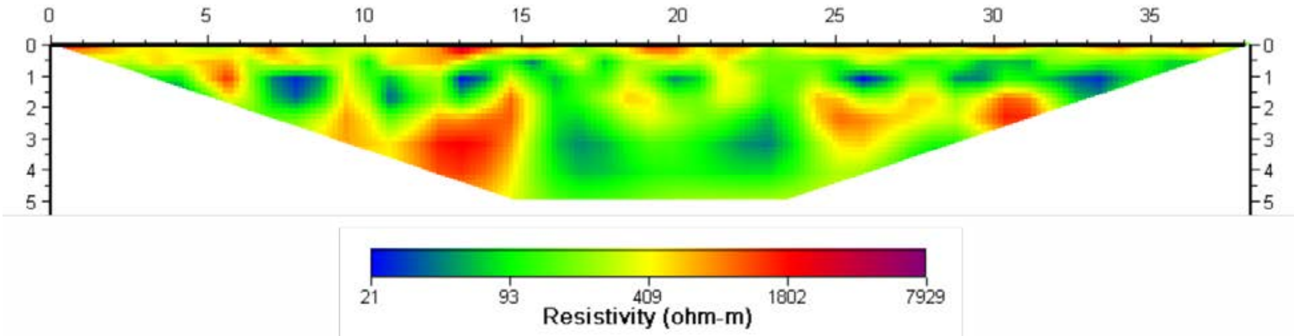

Figure 3: Inverted Resistivity Image from the Meadows' Wesleyan Cemetery, South Australia. The unmarked burials have lower resistivity values than the surrounding soils and appear in blue. Data collected using a ZZ Resistivity FlashRES-64 with a 0.75m electrode spacing.

investigations for burials requiring a maximum electrode spacing of 0.5m. A key challenge for resistivity, which has recently been somewhat ameliorated by multi-channel instruments, is that measurement is much slower than for comparable techniques such as GPR due to the need to couple the electrodes directly to the ground. This can mean that the definition of the shape and size of an anomaly can be neglected, which significantly compromises robust data interpretation. In contrast, an advantage of the use of electrodes is that the discontinuous ground coupling means that resistivity can more easily survey through crowded cemeteries where fences and grave markers may obstruct GPR investigations.

Magnetometry

Magnetometry, summarized for archaeological applications by Aspinall *et al.* (2011), measures local variations in the earth's magnetic field caused by the presence of iron. The most direct application of magnetometry in the detection of graves is to locate iron associated with a burial such as grave markers, belt buckles or coffin parts (Stanger and Roe 2007). Another robust method is to detect the presence of magnetic enhancement formed in the soil surrounding the graves by burning associated with burial practices (shown in Fig. 4a) (Wallis *et al.* 2008, Moffat *et al.* 2010). There is also evidence to suggest that the fluid emitted from decaying burials increases the iron in the surrounding soil (thus increasing the magnetic intensity contrast) which may cause magnetic anomalies (Juerges *et al.* 2010). Similarly the presence of organic material and nutrients may facilitate magnetic enhancement through microbial colonization (Linford 2004).

Magnetometers may include single sensor, gradiometer or multi-sensor configurations with the gradiometer or multi-gradiometer configurations most suitable for archaeological applications. An advantage of magnetometry is that it is not significantly affected by soil disturbance and so is useful where GPR is unlikely to be appropriate (Moffat *et al.* 2010). A key methodological challenge in applying magnetometer to the detection of unmarked graves is recognizing that a magnetic anomaly is spatially related to a burial and not related to the abundant metal often found on the surface of cemeteries.

Electromagnetic induction

Electromagnetic induction, summarized for archaeological applications by Witten (2006), works by inducing a series of related electrical currents and magnetic fields in the

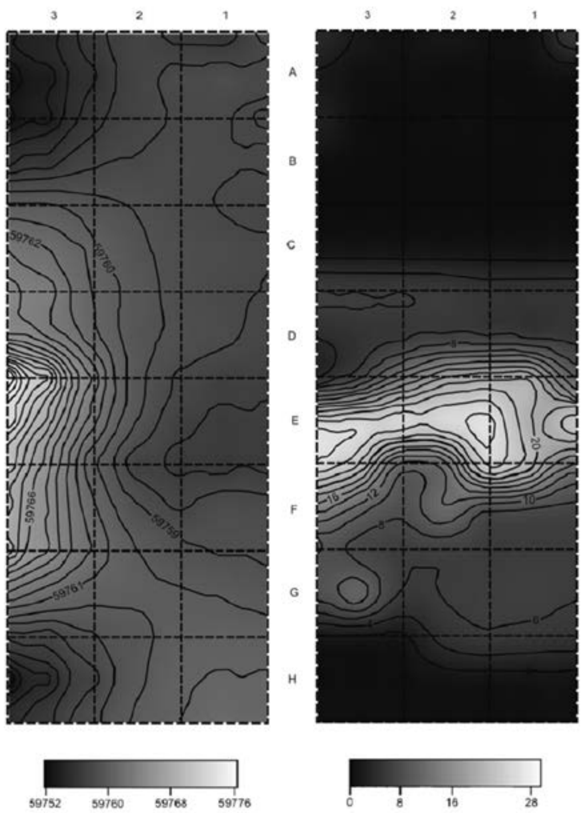

Figure 4. a (left) and b (right): Magnetic Intensity in nT (left) and Magnetic Susceptibility in SI Units (right) Results over Two Holocene Burials at Hack's Point, South Australia (Moffat *et al.* 2010). Data collected with a Geometrics

subsurface between a transmitter and receiver coils. The magnitude and timing of the response allow the approximation of the apparent conductivity and magnetic susceptibility. Depth of investigation is controlled by instrument frequency or coil spacing. Electromagnetic induction has been widely applied to archaeological research (see Bigman 2012: 32 for a summary), but has only been used for the detection of unmarked graves on relatively few occasions.

Electromagnetic induction can detect graves by measuring the differences in conductivity or magnetic susceptibility (Dalan *et al.* 2010) in the soil caused by disturbance to the stratigraphy, by detecting metallic features in the subsurface relating to the burial such as belt buckles and coffin attachments and by locating burning signatures related to the burial activity (shown in Fig. 4b) (Moffat *et al.* 2008). The soil disturbance shown by the change in the conductivity may represent mixing of topsoil with subsoil, differences in compaction or the presence of air cavities (Bevan 1991). This disturbance may appear as either resistive (Bigman 2014) or conductive (Bigman 2012, Nobes 2000) compared to surrounding soil and depending on environmental conditions, particularly soil moisture. Downhole and laboratory magnetic susceptibility methods have proved effective at locating graves (Dalan *et al.* 2010) however the slow and invasive nature of the coring precludes this method for most surveys.

As with all geophysical methods used for the detection of unmarked graves high resolution survey is essential to ensure the detection and resolution of targets. A maximum of 0.5m line and station spacing is necessary to ensure that all features will be located. Shorter coil spacing or higher frequencies are most appropriate for the detection of graves due to the shallow depth of the targets. As discussed in the magnetometry section above, cemeteries are often replete with surface metal making it difficult to distinguish the subtle conductivity or magnetic responses exhibited by graves. It may be possible to overcome this by removing high amplitude anomalies from the data (i.e. Marshallsay *et al.* 2012) however, data quality will rarely be improved to the point of being able to locate individual burials. When faced with a site with extensive surface metal other methods which are more effectively shielded from these effects such as GPR or resistivity should be strongly considered.

Gravity

Gravity surveying, reviewed for archaeological applications by Eppelbaum (2011), works by measuring local variations in the acceleration of the earth's gravitational field caused by differences in the density of the subsurface. This method is not suitable for the location of conventional coffin burials or clandestine graves due to their insufficient density contrast from background but is exceptionally useful in cases where a significant subsurface void may exist such as when prospecting for crypts or rock cut tombs (Panisova *et al.*, 2013, Sarris *et al.* 2007). The key methodological consideration for microgravity investigations is the availability of high quality elevation and positioning data to facilitate a terrain (Fournier *et al.* 2004) and, in specific cases, an accurate model for building correction (Panisova *et al.* 2012).

Survey positioning and site recording

High quality survey positioning is essential to the successful location of unmarked burials with geophysical methods. The application is particularly demanding in this respect because of the subtle nature of the geophysical response of these targets, their small size and the need to validate them on multiple lines to effectively locate them. As well as positioning the data accurately, it is essential to locate site features that may hinder the effective interpretation of the geophysical data, such as evidence of soil disturbance, tree roots or surface metal. The most effective survey methodology is to use a combination of real time kinematic GPS and/or robotic total station for positioning the geophysical data in combination with very high resolution aerial photography from a kite or unmanned aerial vehicle to record the site. The choice between real time kinematic GPS and robotic total station will often be made by equipment availability however the degree of tree cover on the site should more correctly suggest what method is more appropriate. Very high resolution aerial photography, particularly when the photos are merged into a composite image and a Digital Elevation Model (DEM) using photogrammetry software such as Photoscan (discussed in detail in this volume by Cantoro), diminishes the burden of recording all of the surface features on the site by facilitating their mapping (see Fig. 5b). It is possible to undertake survey for unmarked graves over small areas without elaborate survey positioning (see Fig. 5a) however it relies on excellent site recording (site photos, plans and notes) and the application of the highest degree of care in starting and finishing lines correctly on the baseline so as to facilitate mapping anomalies between adjacent lines.

Data display and intepretation

In every geophysical survey for unmarked graves it is necessary to interpret and display the data in a way that is useful to the non-specialist user. Most organizations seeking these surveys have little experience in geophysics and so it is incumbent on the geophysicist to provide results which are unambiguous and easy to understand. Most often this will be a map of graves, preferably with some quantification of certainty. It is usually inappropriate to provide raw or processed geophysical data as a survey product, except for archival purposes or to facilitate later re-interpretation by a qualified specialist. In the interpretation of any geophysical data set there will be varying degrees of uncertainty concerning each anomaly (discussed in detail by Hargrave 2006) and it is important to be able to capture this in the resulting data products. This is particularly important in cultural heritage management investigations when consumers of the geophysical data must weigh the risk of disturbing unmarked burials

Figure 5. a (left) and b (right): High quality survey positioning and site recording: Using survey tapes to conduct a 0.25 m station and line spaced geophysical where DPGS was ineffective due to a ring of tall trees surrounding the site (left) and high resolution site recording and photogrammetry using a pole mounted camera (right).

against the cost (both financial and emotional) of direct investigation or abandoning the site entirely.

Despite these issues, the development of a methodology for quantifying uncertainty in the investigations of unmarked graves has been unfortunately largely ignored. A possible approach is to classify the nature of the anomalies and their relationship to each other loosely based on the conventions developed by the petroleum industry which reports reserves as 'proved', 'probable' and 'possible' (90%, 50% and 10% certainty of commercial extraction respectively) based on explicit diagnostic criteria (Society of Petroleum Engineers 2001). One example of such a classification scheme for GPR data for the detection of unmarked graves is a scale ranging from two adjacent stratigraphic breaks with a hyperbola between them ('most likely'), two adjacent stratigraphic breaks without a hyperbola between them, a single stratigraphic break and a single hyperbola ('least likely'). The flaw in this scheme is that it focuses undue consideration on the accurate interpretation of the results from an individual line and doesn't consider the spatial relationships of the anomalies. An alternative approach is to combine considerations of the spatial distribution and nature of the anomalies. An example is described in Moffat *et al.* (forthcoming) in which probable anomalies are classified as 'probable' graves where a stratigraphic disturbance is observed on at least 4 adjacent survey lines (with a 0.5m line spacing) which has an overall size and shape consistent with an adult burial. 'Possible' graves are identified by 3 or more stratigraphic breaks on adjacent survey lines which have an orientation, shape or size considered that differs from an adult burials. 'Unlikely' anomalies share the properties of 'possible' anomalies but are located in areas of the site that are outside of the area identified as a cemetery in historic records. Such an approach can be further strengthened through the use of multiple geophysical methods which all of their results merged to create a composite anomaly map (i.e. Nobes 1999).

A best practice methodology for finding graves with geophysics

Best practice geophysical survey for unmarked graves should utilize a rigorous and specialized methodology. This should include a detailed understanding of the impetus behind the survey to allow a suitable methodology to be developed. Prior knowledge of burial traditions is important to orientate the survey perpendicular to burial direction and to consider the likelihood of detecting unusual features such as crypts. GPR is the most effective method for locating graves in most cases but the exclusive use of slice maps should be avoided. GPR line spacing should be no greater than 0.5m and ideally 0.25m or less to ensure that all GPR should be supported by another survey method, most likely electromagnetic induction or magnetometry with a station spacing no greater than 0.5m required to effectively locate graves in the subsurface. Stratigraphic anomalies rather than the direct detection of skeletons should be the focus of the investigations, aided by the location of associated metal or burning features. Anomalies should be correlated across multiple lines and mapped in plan view to ensure they are of a size and shape appropriate to a grave. A rigorous scheme should be used to interpret the data which makes it accessible to the consumer and attempts to quantify uncertainty. High quality site survey positioning is essential and should be supported by intensive site recording.

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Exploring the Interior of Tumuli: Examples from Investigations in Macedonia and Thrace

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Abstract: The paper summarizes the up-to-date geophysical practices for exploring the interior of the burial mounds often known as tumuli or barrows which are found extensively within the archaeological record in many countries. The aim of such investigations is to locate and image as accurately as possible the concealed manmade ancient funeral constructions within these mounds and guide invasive investigations to minimize site disturbance. Geophysical methods are capable of obtaining information from the interior and from below these constructions. This paper summarizes the merits and drawbacks of the geophysical methods employed so far for assessing the internal structure of tumuli including seismic refraction and electrical resistivity tomography (ERT). Successful early attempts employing a refraction fan shooting technique are described in which 'dromoi', the entrances to the burial mounds, were located. The use of 2 and 3 dimensional ERT surveys is described and presented in detail.

Keywords: Tumulus, seismic refraction survey, ERT, burial chambers

Introduction

A tumulus comprises an anthropogenically constructed mound which might contains graves. Such an example is given in Fig. 1. These features are found in the archaeological record throughout the world and may provide important insights into the development of burial traditions and material culture more generally. Similar features are found which are used for other purposes such as for transferring light messages.

Since Exploration Geophysics comprises the science that deals with the investigation of the subsurface, it is reasonable that it was called to provide solutions for locating and if possible imaging the structures that are concealed in the tumuli. However, the particular problem is not an easy one but a rather challenging case. This is because the survey must be performed on uneven ground and it is much likely that topographic reductions are needed whatever the geophysical method might be. Also, the targets have usually small dimensions relative to the thickness of the embankment. This factor may be decisive as to prohibit any meaningful geophysical survey. Continuing to account the difficulties of the operation, we may add the possible inhomogeneity of the material of the embankment which may create spurious anomalies and thus mislead the data interpretation. Additionally, the embankment may be consisted of distinct strata which may have serve specific purposes as to ensure the waterproof of the buried tomb. Layering is by itself an extra difficulty in interpreting the geophysical images. Difficulties may be posed if a pit had been opened to host the tomb and also if some sort of enclosure was built. Both these factors may complicate the interpretation.

Any combination of the technical difficulties counted above may be present in each particular case. However, the geophysical methods comprise the only available non invasive solution for gaining some information about the interior of the tumuli which may result to selective partial excavation. In other words, Geophysics comprises sometimes the only procedure which may help in preserving the greatest portion of the tumuli. This is why we believe that they must be used before any excavation of such monuments besides that it comprises a rather cost and time saving operation.

Early attempts

The detection of tombs on flat ground is routine and has yielded many successful results (e.g. Tsokas *et al.* 1994; Piro *et al.* 2001). In contrast, the use of geophysical methods as part of the investigation of tumulus is much more limited and has varying results. The first surveys were attempted in the 80s (e.g. Utecht 1988; Utecht *et al.* 1993; Campbell *et al.* 1993). A variety of geophysical techniques were employed in these early surveys (Tsokas 2012).

Electrical methods have been successfully employed as part of a number of investigations of tumuli. Katevski (1986) and Petkov and Georgiev (1988) employed resistivity profiling to look at the interior of Thracian tumuli in Bulgaria. They used radial and circumferential profiles that followed the topographic contours of the tumuli. The apparent resistivities were plotted to form contour maps for various current line lengths which were interpreted to correspond to different depth levels. The high resistivity anomalies shown up were attributed to possible stone structures concealed under the embankment. Thanks to the rather homogeneous infill of the explored tumuli, most of the recorded high resistivity anomalies proved to be caused by stone made monumental tombs hosting important findings. This pure and rather simple resistivity profiling methodology yielded many successful detections of Thracian monumental tombs in Bulgaria

Figure 1. Tumuli were built to be seen from large distances. From another view, they comprise landmarks. The tumulus shown here is in the Region of Thrace (N. Greece).

(Katevski, 1995; Tonkov and Katevski, 1996; Tonkov 1996; Tonkov 2001; Tonkov and Loke, 2006; Gergova and Katevski, 2008). The success of this methodology was due to the homogeneous infill of the Thracian tumuli and the relatively large dimensions of the tombs with respect to the size of the tumuli. Therefore, the resistivity mapping resulted in recording rather clear and long wavelength anomalies which had a very high probability of being caused by ancient structures.

Instead of a mapping technique, Tsokas and Rocca (1987) used vertical electrical soundings (VES) to investigate a tumulus in the Region of Macedonia in Northern Greece. They arranged a large number of soundings on a rectangular grid but their current lines followed the topographic contours as in the case of the Bulgarians. Coherency criteria were employed to match the soundings which proved very useful since the embankment of the tumulus was inhomogeneous. No tomb location was succeeded but the rims of the ancient pit were clearly seen.

Pinar and Akcig (1997) reported a resistivity mapping employing the pole – pole array and a VES survey on a tumulus in northwestern Turkey. The special feature of this survey was that the current line expansion of the VES lines was set in parallel to the general trend of the resistivity anomalies. Obviously, topographic corrections were needed but both the burial chamber and the ‘dromos’ were located. The findings of the ground proofing verified the geophysical observations.

Magnetic survey allows very rapid acquisition of data and so is very popular for archaeological investigations (Gaffney, 2008). Despite this promise, its use on tumulus has proved rather problematic because of the magnetic anomaly which the tumulus itself creates (Tsokas 2012). This is a strong anomaly which usually masks any other anomaly originated from magnetic contrast in the interior of the tumulus (Tonkov 1995, Tsokas 2012). Correction of this effect proved to be a difficult task because modeling of the tumulus is needed followed by computation of its magnetic effect. Unfortunately the tumulus infill is often highly inhomogeneous rendering modeling difficult in many cases.

Tonkov (1995), proposed well known simple and practical procedures to eliminate the magnetic effect of the tumulus itself, instead of using rather complicated numerical techniques for modeling. In fact, he proposed the employment of gradient survey instead of total field. Then he used regional/residual separation by polynomial fitting, and finally he employed filtering. He used this approach for the investigation of a particular tumulus in Bulgaria where the conduct of the magnetic survey was considered preliminary to the following resistivity survey. Although he succeeded to locate a tomb concealed in the tumulus embankment, no other similar example has been reported so far. This is an indication that the particular approach can not be generalized.

Other studies have shown that magnetics works well if the tumulus has been lowered by ploughing or other erosion particularly if large amounts of ferrous objects are present. Smekalova *et al.* (2005) reported magnetic surveys at tumuli in Denmark and Crimea in environments that are completely different in the archeological context and in the geological setting. Megalithic Stone-Age tombs made of granitic slabs comprised the targets in Denmark. These are magnetic features buried in the relatively less magnetic embankment and thus they were located and mapped very well. Scythian tumuli were explored in central Crimea where limestone structures of negligible magnetic susceptibility had been buried in relatively magnetic embankment and so showed up as less magnetic than the surrounding area. Also, Sarris *et al.* (2000) reported a survey on a tumulus in Thrace in N. Greece employing the magnetic method among others (GPR and soil resistance).

Locating tombs of Macedonian type in tumuli in n. Greece by refraction seismics

Because of the relatively great plains that comprise the landscape in the Region of Macedonia (N. Greece), most of the tumuli were erected according to a fixed simple mode (Tsokas *et al.* 1995; Vafidis *et al.* 1995; Tsokas 2012): Initially, a pit and a ramp (the so called 'dromos') were opened. Then, the tomb was built in a monumental scale and finally everything was covered by the embankment. The material yielded by the initial pit comprised part of the tumulus infill supplemented by additional material taken from nearby quarries. Clearly, the infill has different mechanical and geophysical properties than the undisturbed surrounding of the tumuli. On the basis of this contrast, geophysics can likely detect the edges of the ancient pit and the 'dromos' allowing the tomb (or tombs) included in the tumulus to be located indirectly. This is more straightforward than the direct detection of the tomb itself which is complicated by the burial depth being much larger than its dimensions.

Based of the above considerations and taking into account the rather circular shape of the tumuli Tsokas *et al.* (1995) employed seismic refraction fan shooting to record the delayed arrivals due to 'dromos'. This study placed the geophones in a circular array along the periphery of the tumulus and shoot from the top of the tumulus. The geophysical survey was preceded by modeling and production of synthetic data to verify that the 'dromos' would be detectable. Further, they conducted an experiment on a tumulus where the tomb had been revealed and the tumulus on top of that was almost intact. Both the above mentioned procedures showed that delayed arrivals are expected at the radial direction where the 'dromos' is located.

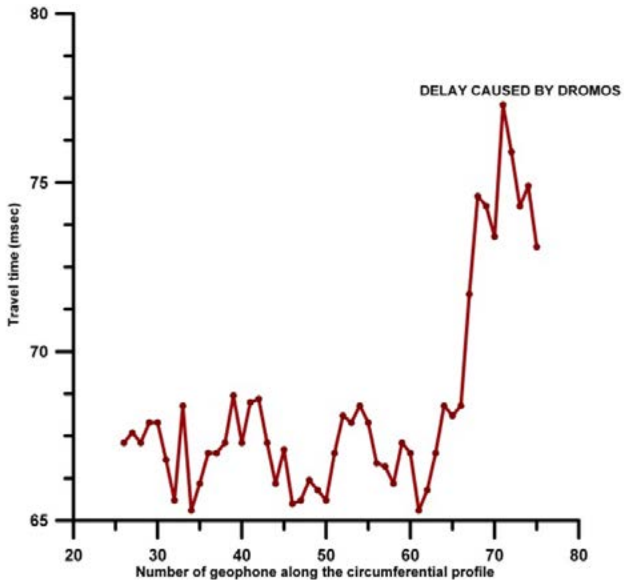

FIGURE 2. DELAYS OBSERVED AT THE FIRST ARRIVALS OF SEISMIC WAVES WHICH ARE TRAVELING FROM THE TOP (CENTER) OF THE TUMULUS TO GEOPHONES SPREAD ALONG THE PERIPHERY. THE EXAMPLE IS TAKEN FROM THE PAPER OF (TSOKAS *ET AL.* 1995). IT REFERS TO THE EXPLORATION OF A TUMULUS AT THE VILLAGE MESSIANO IN N. GREECE, WHICH IS LOCATED CLOSE TO THE RUINS OF THE ANCIENT MACEDONIAN CAPITAL, PELLA. THE DELAYS ARE CAUSED BY THE ANCIENT 'DROMOS'. THUS, THE LOCATION OF THE 'DROMOS' IS DETECTED AND CONSEQUENTLY THE LOCATION OF THE CONCEALED TOMB WHICH IS SHOWN IN NEXT FIG. 3.

After the successful experiment described and the encouraging simulations, field surveys were undertaken at a number of such monuments in the Region of Macedonia. A successful example from the modern village of Messiano (near ruins of Pella, the capital of the Macedonians) was reported by Tsokas *et al.* (1995). The obvious delays of first arrivals due to 'dromos' are clearly seen in Fig. 2 (Tsokas 2012). The geophones were spaced 1 m apart from each other along the periphery of the tumulus. An excavation followed the geophysical survey and guided directly to the location where the delays were observed (Chrysostomou, 1997) and unearthed the impressive but looted tomb shown in Fig. 3.

Tsokas (2012) discussed further that in the case of this study the homogeneity of the embankment of the tumulus is the crucial factor for the success. This is because heterogeneity in the embankment stratigraphy will create spurious delays and depending on their size, may mislead the interpretation of the data.

In a similar study, Polymenakos *et al.* (2004) employed seismic tomography to investigate the internal structure of a Macedonian tumulus near ancient Amfipolis. Though their results are disputable they showed that some information about the tumuli interior can be gained by this technology. Forte and Pipan (2008) used seismic tomography and radar in order to perform high resolution imaging of the interior of Bronze Age burial mound in northern Italy. They succeeded in assessing the stratigraphy which was

Figure 3. Photograph of the unearthed Macedonian tomb after the suggestions of the geophysical survey (courtesy of P. Chrysostomou). Refraction fan shooting was used. The tomb is at the village Messiano (Province of Giannitsa, Region of Macedonia, N. Greece) (Chrysostomou, 1997).

verified by subsequent excavations. 'The authors claimed also that a funeral chamber was detected at about the center of the tumulus. However this has not been verified by excavation.

Locating tombs in tumuli by electrical resistivity tomography (ert)

The use of electrical resistivity tomography (ERT) provides another higher resolution tool to image the interior of the embankments that comprise tumuli. Tonkov and Loke (2006) and Astin *et al.* (2007) reported relevant operations employing ERTs in a 2 Dimensional (2D) context. A Thracian tomb was successfully located in the first case and several features were detected at the site of Bartlow barrows in England in the second. Further, Akca and Gundogdu (2010) performed a 2D ERT at two tumuli in a city at the coast of the Black Sea and Cheetham and Gale (2010) used also 2D approach to investigate Clandon barrow in Dorset in U.K. The last study revealed the structure of the tumulus which demonstrated that it has been constructed in two phases.

3 Dimensional (3D) ERT survey provides superior data density compared to 2D survey and so may be more suited to defining the internal structures of tumuli. Papadopoulos *et al.* (2010) described the advantages and drawbacks of 3D ERT survey in investigating tumuli and commented on the responses of various electrode arrays. They also discussed a case study from the necropolis of the Iron Age in Ancient Aegae (Verghina, Region of Macedonia, North Greece). The last study proved that the results of the 3D inversion are effectively independent of the direction of the 2D tomographies that constitute the 3D data set. This research also demonstrated that new technology has facilitated surveying tumuli with any degree of topographic complexity.

Tsourlos *et al.* (2014) reported examples and comparisons of carrying out surveys at tumuli using ERT with two different survey methodologies. From one side, they used a regular rectangular grid established on the ground surface to collect data as parallel 2D lines which were subsequently inverted as a 3D data set. They compared these results to those from 2D lines laid out in a radial pattern which were also subsequently inverted in 3D mode. Both synthetic and field data was compared from these surveys to demonstrate that the radial configuration is superior in delineating targets positioned at the central part of the tumulus. On the contrary, the rectangular grid proved superior in imaging the parts of the tumulus that are on the periphery. Clearly, if the available means and time allow the use of both measuring modes the result would combine the merits of both measuring modes.

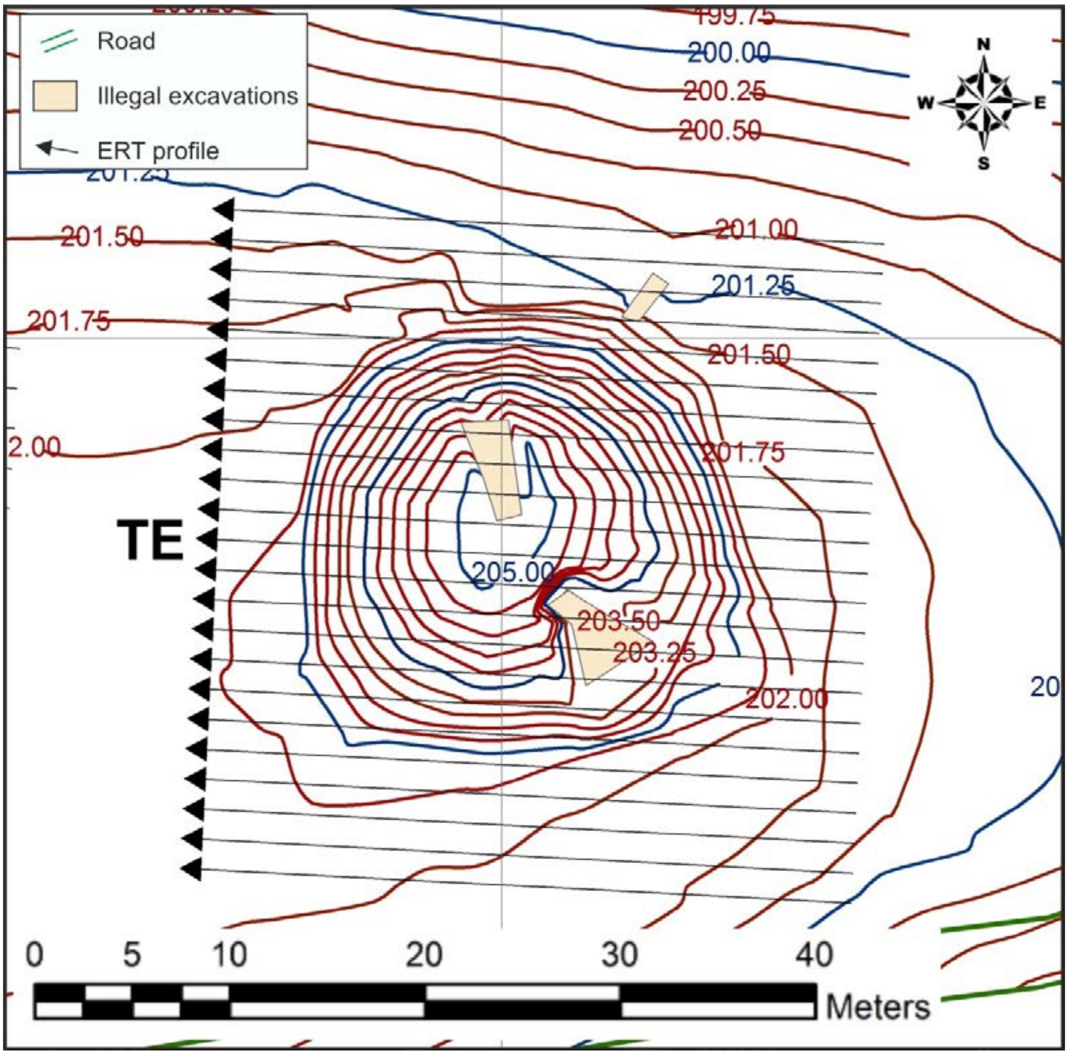

FIGURE 4. THE TOPOGRAPHIC CONTOURS DELINEATE CLEARLY THE SHAPE OF THE TUMULUS EXPLORED NEAR THE VILLAGE SPILAION IN THRACE (N. GREECE). THE LAY OUT OF THE 23 ERT TRANSECTS IS ALSO SHOWN.

In a similar study, a rectangular grid was established on the ground surface in a tumulus near the village Spilaion in the prefecture of Evros of the Region of Thrace (N. Greece). A number of parallel ERTs carried out on the surface of the tumulus following the approach of Papadopoulos *et al.* (2010) and Tsourlos *et al.* (2014). The particular layout of the tomographic transects is shown in figure 4. The 23 tomographies that were carried out form a rectangular grid. The direction of each one of the parallel transects is almost East-West. Figure 5 is a photograph of the tumulus and of the field crew during the survey. In this figure, the measuring tape marks the position of one of the tomographies of the grid.

The guidelines of Papadopoulos *et al.* (2006; 2007) for 3D processing were used in the particular measuring approach and and the inversion algorithm of Tsourlos and Ogilvy (1999) was used. The procedure yielded the 3D distribution of resistivities beneath the explored surface and subsequently slices of the either the vertical or the horizontal distribution of resistivity were produced. Figure 6 shows the resistivity distribution on a horizontal slice at the absolute altitude of 200.5 m.

At the particular slice of Fig. 6, among others, a high resistivity anomaly is present at the North-Western side of the tumulus which can be considered as a promising target which may represent an ancient structure. Unfortunately, no ground proofing has yet occurred.

Conclusions

Nowadays, geophysical prospecting methods offer a non-invasive, inexpensive and expedient means for the investigation of tumuli. They aim at detecting ancient tombs that are concealed in the interior of these structures. By providing images of the interior they offer a valuable guide to the subsequent excavation and thus they assist the effort to destroy as little of the tumulus as possible. Definitely, geophysics helps to preserve the tumuli as they stand since they comprise archaeological monuments by themselves.

In the past, simple resistivity mapping treated the problem of locating the tomb under the embankment with great success in South East Europe. However, they were used in cases where the tomb had large dimensions relative

Figure 5. Photograph of the investigated tumulus near the village Spilaion in Thrace (N. Greece) during the field work. The measuring tape shows the position of one tomography on the ground surface.

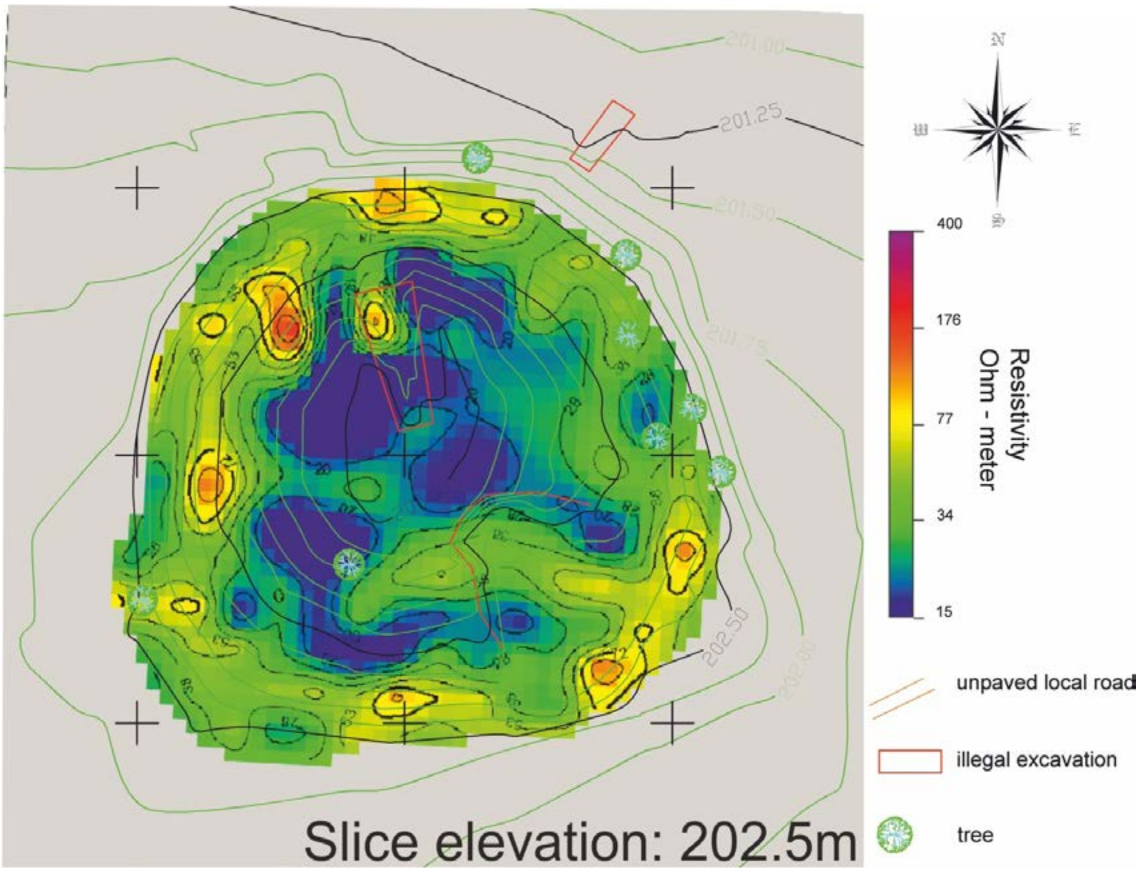

Figure 6. The distribution of resistivity at a depth slice at the level of 202.5 m above mean sea level. Many positive anomalies are present but the predominant one is at the North-West of the tumulus.

to tumulus itself. The magnetic prospecting method succeeded also to image the interior but only of tumuli of restricted height, often due to ploughing or erosion. Seismic refraction fan shooting was tried in Northern Greece and succeeded to locate the 'dromos' in Macedonian tumuli. ERT has provided the most information about the interior of tumuli and is especially effective when employed in 3D mode.

Acknowledgement

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Off-Shore Archaeological Prospection Using Electrical Resistivity Tomography

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Abstract: This work addresses the applicability and efficiency of Electrical Resistivity Tomography (ERT) in mapping archaeological remains in near off-shore environments. The approach consists of a guideline based on theoretical simulation models followed by a validation of the methodology with real data. The numerical modeling undertaken includes the testing of different electrode arrays suitable for multichannel resistivity instruments (dipole-dipole, pole-dipole) and survey modes (floating or submerged electrode positioning). Additional tests are made concerning the resolving capabilities of ERT with various seawater column thickness and target characteristics (dimensions and burial depth of the targets), in order to suggest the most suitable methodology. Finally, an application of the method at a real site is accomplished not only for verification of the theoretical results but at the same time for proposing techniques to overcome problems that can occur due to challenges imposed by the shallow marine environment.

Keywords: marine, archaeological, electrical resistivity tomography

1. Introduction

Electrical Resistivity Tomography (ERT) is one of the most developed geophysical methods that is used for near surface surveys and applications. Crucially, this method can be easily applied in a marine environment, since no special equipment is needed for the specific type of survey. Recent studies employing ERT in marine environments include the imaging of the geological stratigraphy beneath water covered areas for tunnel and bridge construction (Kwon *et al.* 2005, Kim *et al.* 2002) and the geotechnical characterization of the submerged subsurface prior to a port construction (Apostolopoulos 2007).

Despite its increasing usage in dry-land archaeological applications, the ERT method is less common for off-shore archaeological investigations in shallow marine environments and only limited studies have been reported (Passaro 2010). This work aims to fill the theoretical and practical gap in the employment of ERT for the mapping of cultural structures in near off-shore environments. Before applying the method to a real site, a number of simulations using numerical modeling were performed testing different scenarios. Different survey modes using floating on water surface or submerged cables were examined in an effort to propose the most efficient one. Different electrode arrays were tested and some additional tests were made to evaluate the horizontal and vertical resolution capabilities of the technique. A shallow marine archaeological site in Crete was selected to test and validate the theoretical results.

2. Methodology

The numerical modeling was performed with ‘DC2DPro’, a two dimensional (2D) forward and inversion algorithm (Kim and Yi 2010). The program is based on a 2.5D finite element routine to solve the forward resistivity problem and an iterative least squares algorithm with Active Constrain Balancing (ACB) constraints for reconstructing the subsurface resistivity models. An indicative synthetic model used in this work is shown in Figure 1. Basic synthetic model with electrodes (sensors) placed on surface of the water (black dots) or on bottom of the sea (white dots). The thickness of the seawater is D=1m and the chosen resistivity value ρ_{water}=0.2 ohm-m. The targets’ resistivity is ρ_{target}=500 ohm-m. The electrode spacing is set to a=1m and tests are made with the electrodes placed either on the surface of the water (floating, indicated with black dots) or on the sea bottom (submerged, indicated with white dots). The resistivity value of the water, the target and the homogeneous medium is set to ρ_{water}=0.2 ohm-m, ρ_{target}=500 oh-m and ρ_{homog}=10 ohm-m, respectively.

Electrode Arrays

The data were obtained using specific arrays that are primarily used in field studies employing a multichannel instrument. These arrays are: dipole-dipole (‘dd’) and pole-dipole (‘pd’), as shown in Fig. 2. Current electrodes are indicated with the letters ‘A’, ‘B’ and potential electrodes with letters ‘M’, ‘N’. When the pole-dipole array is used, the current electrode ‘B’ is positioned

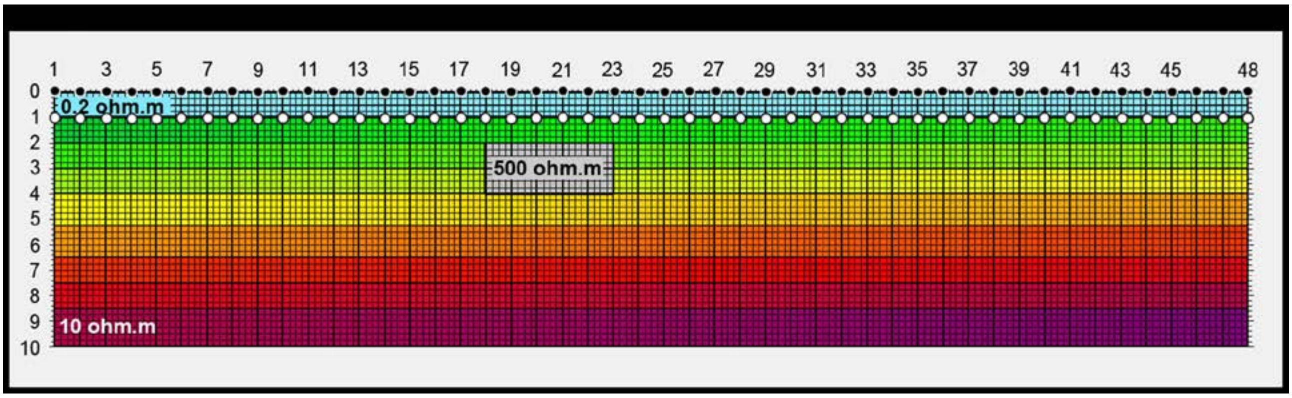

Figure 1. Basic synthetic model with electrodes (sensors) placed on surface of the water (black dots) or on bottom of the sea (white dots). The thickness of the seawater is D=1m and the chosen resistivity value ρwater=0.2 ohm-m. The targets' resistivity is ρtarget=500 ohm-m.

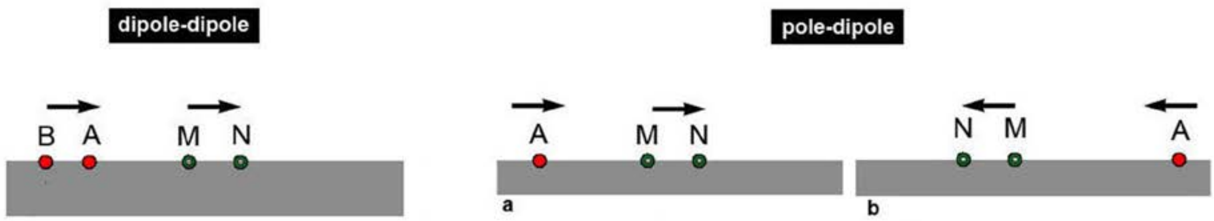

Figure 2. Dipole-Dipole (left) and Pole-Dipole in forward and reverse mode (right) electrode arrays used for marine ERT measurements.

away from the other electrodes ('infinite' distance, which is approximately five to ten times the largest electrode separation). All simulation data are corrupted with noise of ±0.05mV/V into the potential values in order to simulate better a real world scenario. The inversion images can be used for validation of the results using the % rms error and the position of the target that is indicated using a black line (the line shows the exact theoretically expected position of the target). The resistivity scale is common in all inversion figures (for comparison purposes) and it ranges from 0 to 100 ohm-m.

A comparison between the arrays ('dd', 'pd') and the electrode position (floating, submerged) is shown in Fig. 3. The water thickness is D=1m and the target (with dimensions 5x2m) is buried at a depth of d=2m below the sea surface.

On the left side of the Fig. 3, where the electrodes are situated on the water surface (floating), it is evident that the 'dd' array is not able to reconstruct the target with great accuracy as the inversion image shows some shape distortions of the target that seem to continue towards deeper levels. On the other hand, improved results are seen when array 'pd' is used, which has smaller % rms errors ('pd':0.56%) in comparison with the 'dd' array ('dd': 1.51%). The target and the background resistivity, after the inversion reconstruction is close to ρ_{target}=100 ohm-m and ρ_{back}=5 ohm-m, respectively.

On the right side of the image, where the electrodes are placed on the sea bottom (submerged), it is noticed in all arrays that the final targets' position is shifted slightly downwards. The 'dd' array is unable to reconstruct the target and once more it has the largest % rms error ('dd':1.49%), versus the protocols 'pd' where the target is better reconstructed with lower % rms error values ('pd':0.73%).

Furthermore, all of the inversion resistivity images show some inversion artifacts on both sides of the target and close to the edges of the model. This can be interpreted as being due to the limitations of the inversion procedure, since the resistivity contrast between the resistive background and the conductive seawater layer is large and it is difficult for the algorithm to account for these large resistivity contrasts.

Based on the above synthetic experiment it is advisable to use pole-dipole protocol in order to map archaeological remains in shallow marine environments.

Seawater column thickness

The water thickness of the sea is a crucial parameter since there is a depth limit above which the resolving capability of the method decreases due to the absorption of the current energy from the conductive sea layer. For this reason, different water thicknesses (D=1 and 2m) were

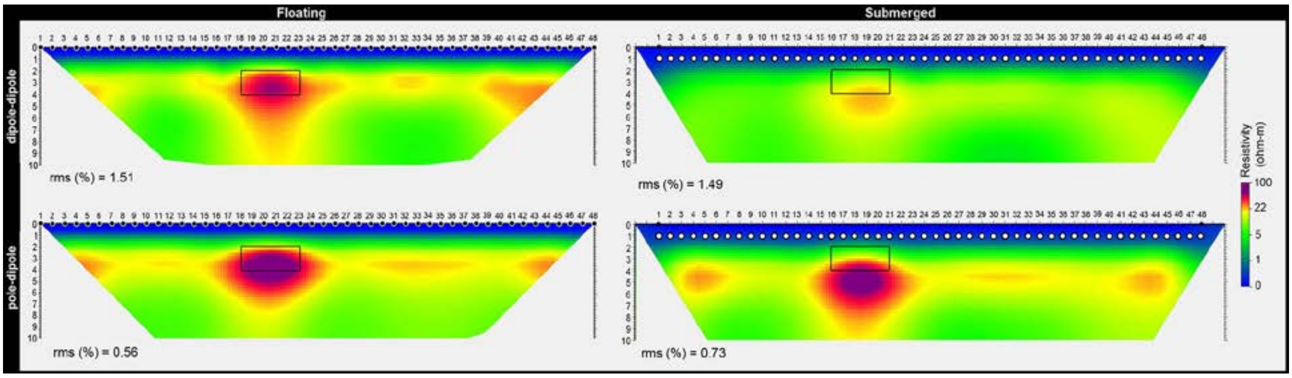

Figure 3. Inversion results with different protocols (dipole-dipole and pole-dipole) using 48 floating (black dots, left column) or submerged (white dots, right column) electrodes with spacing a=1m. Water column thickness is set to D=1m.

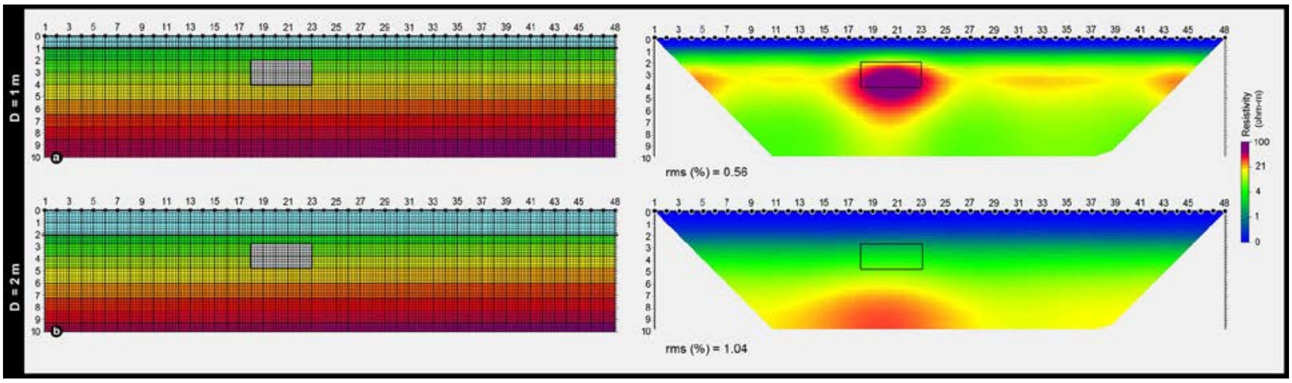

Figure 4. (left column) Synthetic model for comparing different water column thickness using protocol pole-dipole with floating (black dots) electrodes. Water depths: (a) D1=1m and (b) D2=2m, pwater= 0.2 ohm-m, ptarget= 500 ohm-m, pback= 10 ohm-m. Electrode spacing a=1m, (right column) 2-D Inversion results.

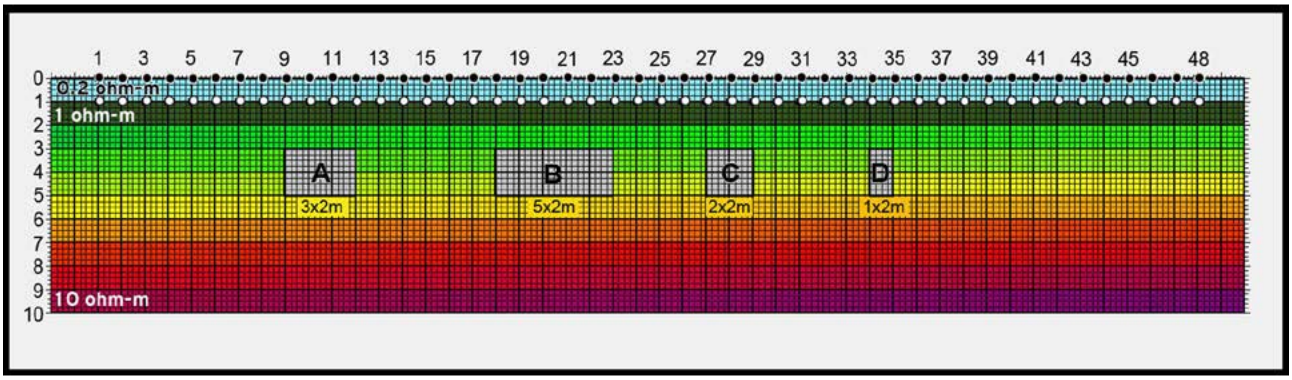

Figure 5. Model for studying different target sizes (A, B, C and D) using protocol pole-dipole with submerged (white dots) electrodes. Water depth D=1m, p_{water}= 0.2 ohm-m, p_{target}= 500 ohm-m, p_{back}= 10 ohm-m. Overburden layer 1m thick with p_{overb}=1 ohm-m. Electrode spacing a=1m.

tested, as shown in Fig. 4 (left column), where only floating electrodes are used with a ‘pd’ array protocol. On the right side of Fig. 4, the inversion results show that the water column thickness of D=1m is the actual limit at which the resistive target can be located. In case of water thicknesses of more than D=1m it becomes rather impossible to outline the target. Thus in such cases a submerged ERT survey is suggested since the sensors are closer to the target.

Target Characteristics

Some additional tests were made concerning the characteristics of the submerged target such as its dimensions (Fig. 5) and its burial depth (Fig. 6). An extra overburden layer with 1m thickness and resistivity value of ρ_{overb}=1ohm-m was used. The target resistivity was common for all targets and set to ρ_{target}=500 ohm-m.

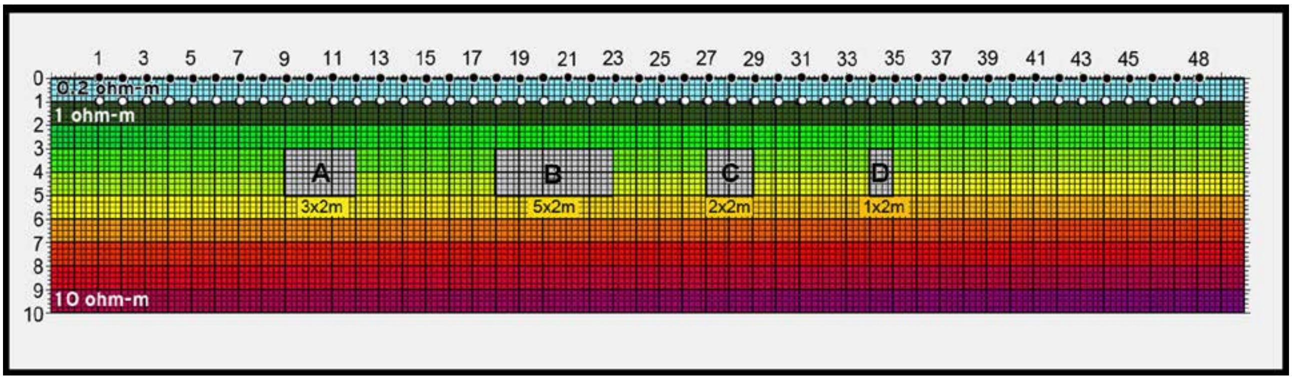

Figure 6. Model for studying different target burial depths (d=1m, 2m and 3m) using PD protocols with submerged (white dots) electrodes. Water depth D=1m, ρwater= 0.2 ohm-m, ρtarget= 500 ohm-m, ρback= 10 ohm-m. Overburden layer 1m thick with ρoverb=1 ohm-m. Electrode spacing a=1m.

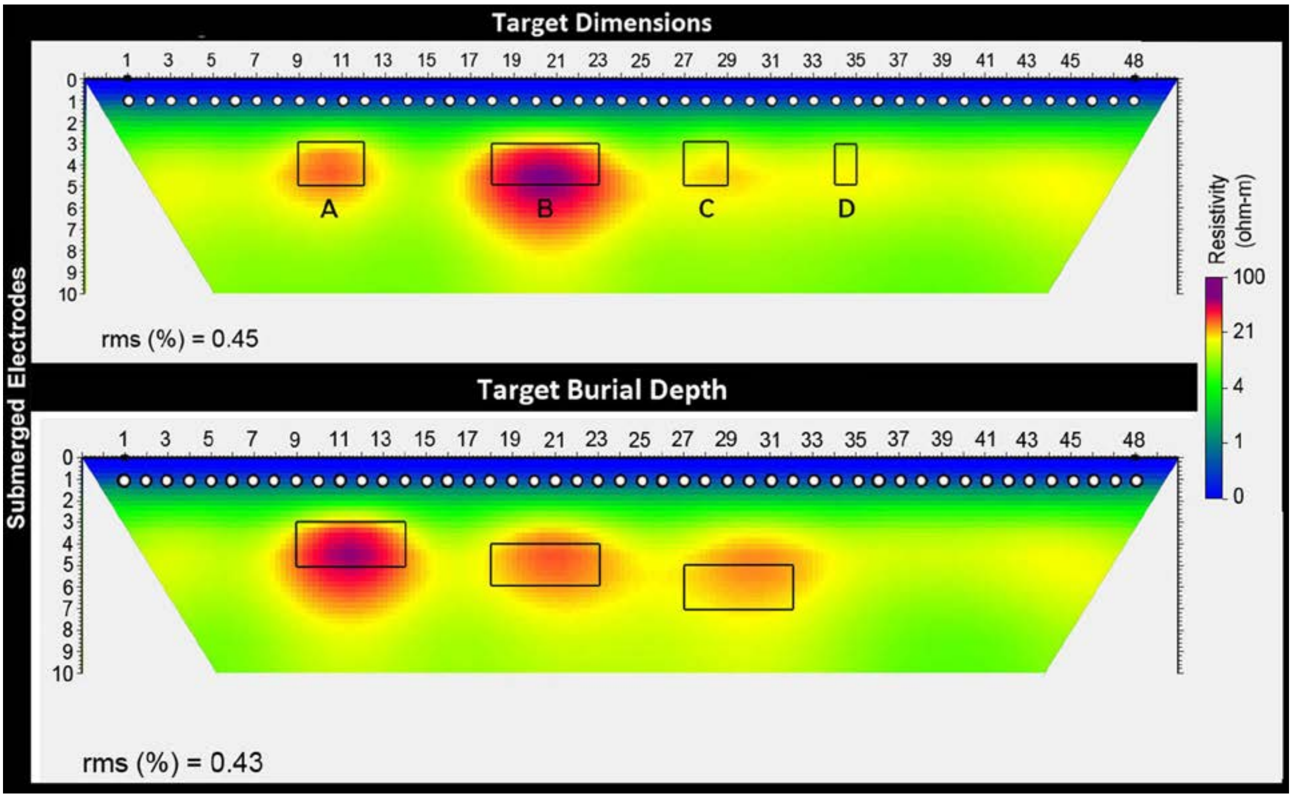

Figure 7. Inversion results with protocol pole-dipole using submerged (bottom row) electrodes with spacing a=1m, where the target dimensions and the target burial depth are examined.

Submerged electrodes with the pole-dipole array were used in both cases. Targets with different dimensions (A: 3x2m, B: 5x2m, C: 2x2 and D: 1x2m) buried in the same depth (d=2m) below sea bottom were simulated. As far as the target burial depth is concerned, a target with the same dimensions was placed at different depths (d=1, 2, 3m).

The corresponding inversion results are shown in Fig. 7 where on top of the figure, the smallest targets C and D can hardly be reconstructed. As a rule of thumb, it can be said that the minimum target dimension that can be detected, should be at least twice as large as the inner probe spacing. On the bottom of the figure, where the target burial depth is examined, the target can be located up to a depth of 3-4m and as expected, submerged electrodes were able to reconstruct the deeper buried targets with clarity.

3. TEST CASE: Agioi Theodoroi, Crete

Site Location and History

The shallow marine archaeological site of ‘Agioi Theodoroi’, located on the island of Crete about 10 km away from Heraklion city was chosen to test the ERT

FIGURE 8. SITE OF AGIOI THEODOROI FOR MARINE INVESTIGATION AND DETECTING ARCHAEOLOGICAL TARGETS (HERAKLION, CRETE).

FIGURE 9. AERIAL PHOTO OF THE SURVEY AREA IN AGIOI THEODOROI. THE YELLOW LINE SHOWS THE FLOAT POSITIONS THAT WERE USED TO KEEP THE CABLE FLOATING. THE RED LINES OUTLINE THE SUBMERGED ARCHAEOLOGICAL RELICS THAT WERE MAPPED IN THE SEA. THE DIRECTION OF THE LINE IS FROM THE COAST TO THE SEA.

simulation results (Figure 8). The site was subjected to excavations during the early 20th century (Marinatos, 1926). These early surveys revealed the existence of seaside buildings and wall constructions that continue towards the sea, dating from the Minoan period. Recent archaeological surveys included the mapping and photography of the submerged structural remains with an underwater camera.

Setup

In an effort to validate the efficiency of marine resistivity archaeological investigations in real situations, an ERT line crossing known structures was laid out in the sea, as shown in Fig. 9. The line was composed of 25 electrodes equally spaced every 1 meter. Protocol pole-dipole was used and the survey line's position was chosen in such way to cross three walls whose position had already been identified by diving. Specifically, electrodes '3', '4', '13', '14', '15' and '21', '22' were exactly above the wall remains.

For the floating survey mode, long wooden sticks were driven into the seabed at the beginning and at the end of the survey line to keep the cable fixed and steady during the measurements. Plastic floats were tied along the cable to allow the floatation of the electrodes (Fig. 10). During the submerged mode survey, no extra weight was needed as an

Figure 10. Photo with floating electrodes set up, equipment used (embedded right), water column thickness calculation with a plastic calibrated stick (embedded left).

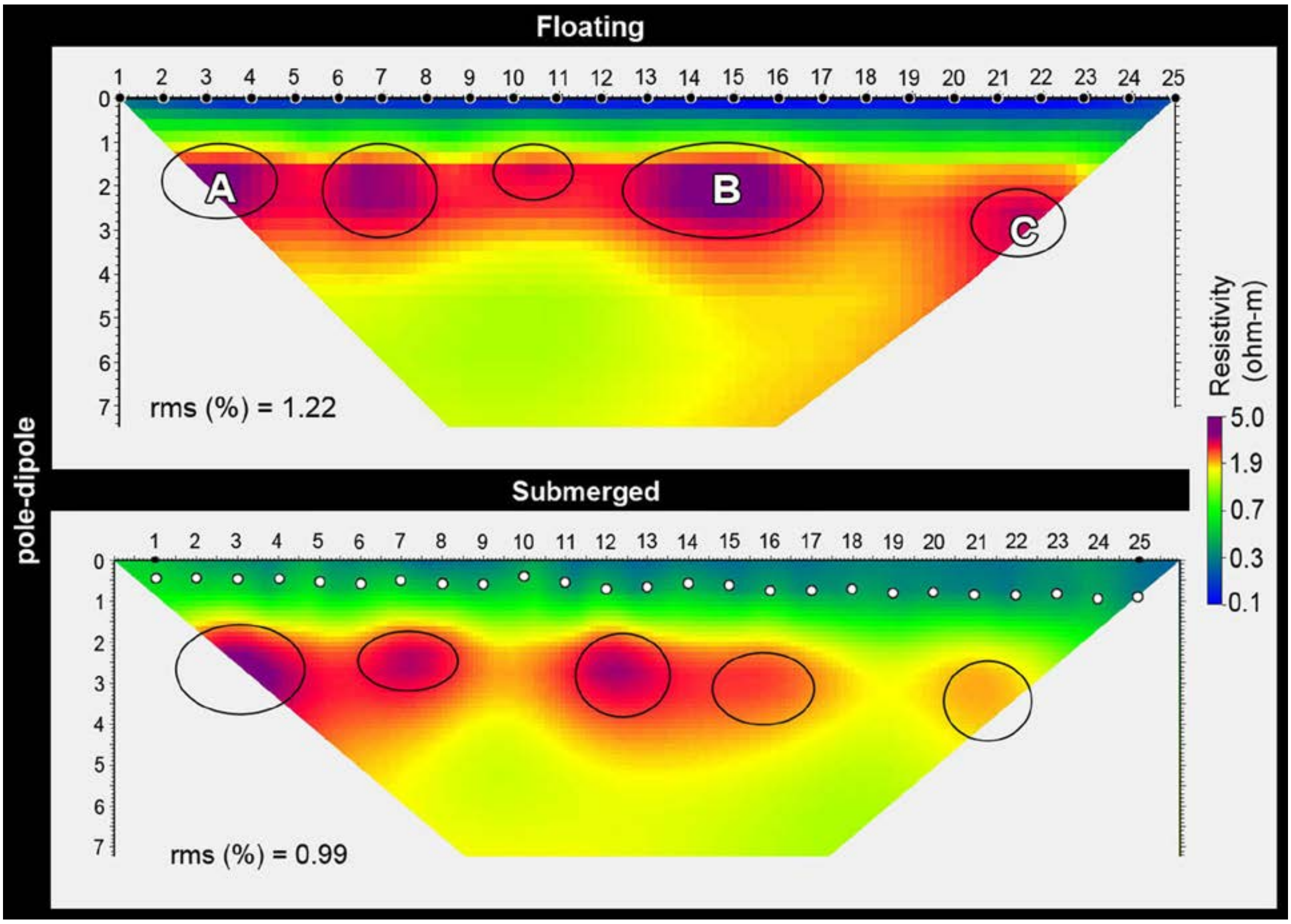

Figure 11. Inversion results with both floating (top) and submerged (bottom) electrodes using the pole-dipole array. The archaeological targets are highlighted with black circles. Letters A, B and C indicate relics that are exposed from the sea bottom and can be easily seen.

anchor as the cable's weight itself was enough to keep it on the seabed during the measurements. The seawater depth was measured with plastic calibrated stick and varied from D=0.5m to 0.9m across the survey line.

Results

Inversion results for the floating electrodes (Fig. 11, top) show that the protocol pole-dipole after 7 iterations with rms error 1.22%, has reconstructed the targets (shown with letters 'A', 'B' and 'C') that have already been identified with diving. The remains seem to be located at a depth of d=2m below sea level with maximum resistivity value calculated to ρ_{target}=5 ohm-m. Some smaller targets are also shown in the results that cannot be seen by diving. As previously seen in the synthetic data, some artifacts are created during the inversion at the edges of the survey line and should be taken into account for the real data also. For that reason, the survey line is recommended to be longer than the target area in order not to have artifacts at the edges that may be confused as potential targets. When submerged electrodes are used (Fig. 11, bottom), the targets are well reconstructed (after 7 iterations with rms error 1%) although slightly shifted downwards, as expected from the corresponding simulation.

4. Conclusions - guidelines

- This work examined the efficiency of ERT in mapping isolated archaeological targets in marine environments using both numerical simulations and validation with real data, in an attempt to offer a guideline for field surveys. The synthetic inversion results show that the targets simulating walls can be detected and among the tested arrays used, pole-dipole seems to have superior results in relation to dipole-dipole arrays.
- When the seawater thickness is less than D=1m, both floating and submerged electrodes give equally comparable results. In deeper marine environments the submerged mode survey is recommended for outlining isolated targets.
- The target burial depth is a crucial parameter and if it is buried in depth more than d=2 meters below sea bottom, locating it becomes problematic. In general, as a rule of thumb it can be said that the minimum target dimension should exceed at least twice the inner probe spacing.
- The methodology was applied in a real situation of a submerged archaeological site on Crete. The real field data verified the numerical modeling results and was also successful in mapping already known archaeological remains.

In general this work shows the applicability, the potential, as well as the constraints of ERT in mapping isolated archaeological structures (e.g. walls or buildings) in shallow marine environments.

Acknowledgements

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Data Integration in Archaeological Prospection

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Abstract: Modern archaeological prospection often involves the use of multiple techniques in order to explore different physical characteristics of buried phenomena. This strategy drastically increases the probability of the detection of archaeological features. Current research, however, usually investigates results of prospection in isolation and only provides simplistic comparisons, using overlays. In fact, 'true' data integration in archaeological prospection may offer more information than individual sensors can individually provide in sum. In search of this improvement, this chapter begins by discussing the need for employing multiple techniques in archaeological prospection and reveals a set of definitions in the literature. Next, a large set of suggested methodologies guide the reader to various opportunities of integration. Considering the limited number of geophysical data integration case-studies in archaeology, the objective of this chapter is not so much to provide an authoritative best-practice guide, but rather to attempt to draw a framework.

Keywords: data integration, data fusion, sensor fusion, fusion levels, geophysics

1. Introduction

The success of a geophysical survey depends on two main factors: signal and noise. Signal is the information about the attribute of a physical feature under investigation. All geophysical instruments —active or passive— measure signals and provide particular information on the physical characteristics of buried features. Noise (e.g. instrumental noise, background noise), on the other hand, can be defined as any other signal which is not originating from the features themselves, but masking/disturbing their signals. A high signal-to-noise ratio ensures best conditions for the interpretation of geophysical information and leads to high contrast between features and the geological matrix in which they are situated. The most important parameter to ensure a high signal to noise ratio is the choice of the most appropriate geophysical technique. Other determinants include improving data acquisition methods, applying appropriate data processing algorithms and integrating different geophysical data types (Brizzolari *et al.* 1992:47; Cammarano *et al.* 1998:359). All these determinants –except for data integration- have long history in the discipline.

2. Which method to use when?

As discussed above, detection probabilities of features depends on the level of contrast between the features and the physical background. Therefore, researchers should have considerable knowledge on the archaeology of the area as well as pedological and geological conditions of the matrix. Since almost all geophysical prospection surveys are conducted under unique conditions, there is no recipe for selecting the best method. Nevertheless, some brief general guidelines can be still provided. Hereby, we compare these methodologies in order to further discuss the sources of data noise inherent to geophysical prospection and to open up a discussion of data integration techniques.

Different geophysical methods investigate different physical properties of the environment. Moreoever, considering the variety of geophysical prospection techniques and their associated problems, it becomes clear that no single methodology can be considered superior to others. In other words, geophysical prospection requires not competing, but complementing data collection, analysis, and interpretation strategies.

Electromagnetic prospection methods (discussed in Simon and Moffat, this volume) provide information on conductivity as well as magnetic susceptibility levels. Electromagnetic prospection instruments can be effectively used over rugged or frozen terrains as this method does not require direct coupling with the ground. However, electromagnetic measurements may fail to produce reliable results if the conductivity of the soil is lower than one milliSiemens/meter. High conductivity (> 500 mS/m) reduces the reliability of the measurements of the Q-phase. Resistivity measures the earth resistance between probes. Because this method requires insertion of into the soil it can be more affected from ground conditions, resulting in lower signal-to-noise ratios under unfavorable conditions and reducing survey speed.

Geomagnetic propsection (discussed in Armstrong and Kalayci, this volume), like electromagnetic prospection, do not require ground contact and so can survey considerable areas within a sufficiently short period. On the other hand, the methodology is susceptible to external conditions such as buried or visible metal objects, power lines, etc. all of which are considered as sources background noise. Furthermore, drift, even if it can be corrected through processing, is also an issue in geomagnetic prospection resulting in instrumental noise, and thus, lowering the signal-to-noise ratio. Finally, this methodology (especially single-sensor systems) requires proper handling of the instruments to prevent erroneous results (e.g. destaggering)

Ground Penetrating Radar transmits electromagnetic signals which travel underground and interact with subsurface material, providing spatial and material information (discussed in Manataki *et al.*, this volume). High clay content of soil matrix, however, forces radar signals to attenuate and in effect it lowers signal-to-noise ratios. In some cases, other electrical/electronic equipment may interfere with radar frequencies and creates an undesirable background noise.

3. Integrated approaches: a plethora of definitions and workflows

There is a significant number of terminologies which are used to refer to integration processes including information fusion, data fusion, sensor fusion, data integration, sensor integration. This variety is due to the ways in which researchers approach to the problem. Luo *et al.* (2002) suggest there is a difference between 'integration' and 'fusion' and integration refers more to the system architecture whereas fusion is related to sensor information. A literature survey in archaeological prospection, on the other hand, immediately reveals that the term 'integration' is more commonly used than 'fusion'. In return, we can claim that this is mostly because researchers are still at a comparative stage and they interpret geophysical data in isolation (Brizzolari *et al.* 1992) and a true quantified 'fusion' is lacking other than a handful of examples (Neubauer & Eder-Hinterleitner 1997; Kvamme 2006; Ernenwein 2009). Therefore, one has to rely on other disciplines for definitions, mainly the satellite remote sensing. On the other hand, it should be noted that similar discussions on terminology also exist in other disciplines (e.g. Pohl & Van Genderen 1998). Here we provide a plethora of definitions and eventually provide yet another definition specific to archaeological prospection.

- Llinas (1988) states '[f]usion can be defined as a process of integrating information from multiple sources to produce the most specific and comprehensive unified data about an entity, activity or event.
- According to Luo and Kay (1992) multi-sensor fusion 'refers to any stage in an integration process where there is an actual combination (or fusion) of different sources of sensory information into one representational format.'
- Starr and Desforges (1998) suggests '[d]ata fusion is a process that combines data and knowledge from different sources with the aim of maximising the useful information content, for improved reliability or discriminant capability, while minimising the quantity of data ultimately retained.'
- Wald (1998) defines data fusion as 'a formal framework in which are expressed means and tools for the alliance of data of the same scene originating from different sources. It aims at obtaining information of greater quality; the exact definition of greater quality will depend upon the application.'
- According to McGirr (2001) data fusion is 'the process of bringing large amounts of dissimilar information together into a more comprehensive and easily manageable form'

Specific to archaeological prospection and while keeping the tendency towards 'integration' at sight in the scholarship, we can suggest the term 'geophysical data integration' as the process of collecting geophysical data with multiple sensors in order to fully exploit different physical characteristics of buried features and to increase the signal-to-noise ratio for obtaining a clearer picture for final interpretation of those features.

1.1. Fusion levels

Fusion takes place at three different levels (Hall & Llinas 1997); data level, feature level, and decision level (Fig. 1). At the data (or signal) level, sensor outputs (images) are combined pixel-by-pixel in order to create a data vector. In return, these feature vectors are explored for identity declaration, using a suite of statistical/mathematical methods. At the feature level, first, image descriptives are constructed using basic primitives, such as points, lines, and polygons alongside with their attributes. Second, these descriptives are concatenated in a single feature. At the decision level, features are extracted and identified along each sensor data; it is not the features, but their identifications are fused. This requires not only spatial, but semantic consistencies so that an accurate object model can be provided at the end.

If one follows a strict definition of the concept, true geophysical data integration in archaeological applications are rare and only practiced at the data level (e.g. Neubauer & Eder-Hinterleitner 1997; Kvamme 2006). The bulk of the studies which 'integrate' geophysical data (Cammarano *et al.* 1998; Piro *et al.* 2003; Scardozzi 2010) appears as feature level data fusion studies. However, they remain at the qualitative interpretation level and they approach the integration problem only '[b]y *comparing* [emphasis added] all the results shown by each single method' (Cammarano *et al.* 1998:367). Considering the advances in information sciences, there is now a potentia to provide a guideline for 'true' data integration in archaeological prospection, ranging from data level to decision level.

4. Getting ready!

Different geophysical datasets should go through various preparation steps, prior to integration for the improvement of the process. These steps may greatly vary according to

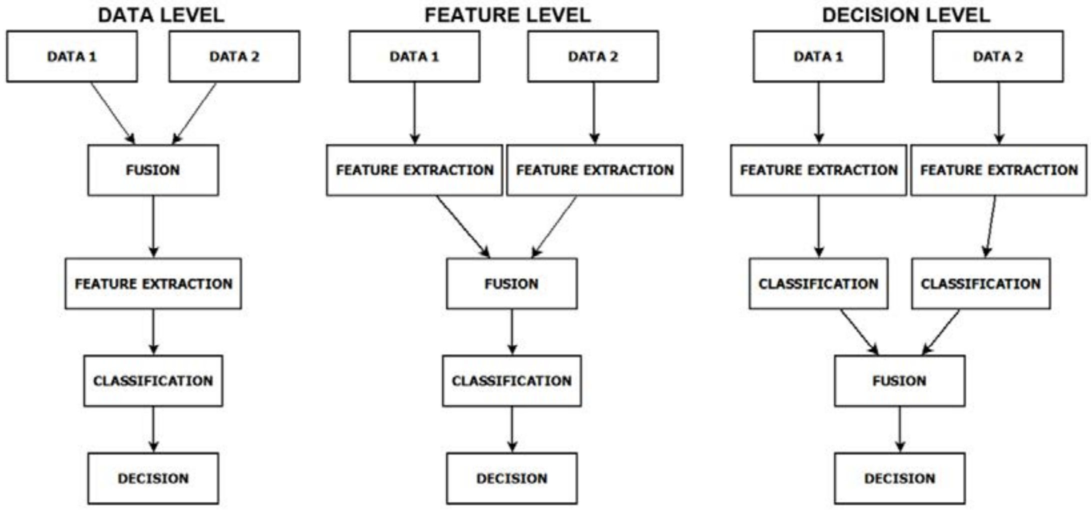

Figure 1. Fusion levels are determined by the hierarchy in the integration process (adapted from Hall & Llinas 1997).

the datasets selected for integration, but there are some minimal conditions to be satisfied.

4.1. To process or not to process

There is not much research on the effects of data processing on geophysical data integration. However, it seems plausible to suggest that unless physical modelling is the aim, it is better to fully process the data so that they reveal maximum visual information when investigated in isolation. Only then it can be assumed that different sensors will complement each other and integration will enhance 'hidden' signals from an image processing perspective. For instance, it is necessary to remove mismatching readings which do not represent a buried feature, such as instrumental noise due to sensor electronics. However, in some cases it might be preferable to keep various noises, such as the background noise (e.g. underlying geology) as it might help researchers in the final interpretation after the integration is completed. For example it may be vital to keep that background noise for the interpretation of the results of another sensor, or as in the case of the total magnetic field intensity data, it could be helpful to analyze the power spectrum to separate signals originating from geological (small wavenumbers) and cultural layers (large wavenumbers). Thus, it can be concluded that the level of processing required depends on what researchers expect as an outcome from the integration process.

Overall, we may suggest that if the noise is due to the instrument/surveyor, then it is better to minimize the noise so that signal-to-noise ratio increases. The immediate step in increasing this ratio should be taken in the field. For instance, while conducting a magnetic prospection it is a good practice to re-align the sensor at the same base location after completing the survey over each grid. This will minimize the impact of instrumental drift during the integration process. Likewise, attention should be paid to not staggering the data as they will misplace the location of the signals. Unfortunately, no approach can fully overcome problems of these sorts because their occurrence is an inherent property of the technique. To continue with the same example, a 'reduction to pole' might be necessary since magnetic data is distorted by the magnetizing vector which in return causes erroneous spatial shifts (Cooper & Cowan 2005). For geophysical surveys with high sampling density this may create problems for the data integration and should be corrected. Similar intrinsic problems exist for other geophysical sensors (See other chapters in this volume).

4.2. Geo-registration

There are two distinct ways to perform a geophysical prospection: gridded and ungridded. Historically most surveys are undertaken within regular survey grids. Results of a survey are then geo-registered using grid corners, often using an affine transformation. Newer sensors, on the other hand, are sometimes coupled with GPS, and thus collected signals are immediately registered with geographic coordinates. In both cases, the accuracy of spatial measurements determines the success of integration since inaccuracies in the locations of anomalies will feed the integration process with erroneous signals. For gridded surveys, high Root Mean Square Error (RMSE) values after geo-registration is not favorable. Likewise, the accuracy of GPS measurements when collecting data with an ungridded approach can have substantial impact on the results of integration. Therefore, extreme caution should be given for the geo-registration process, especially for data level integration (see below).

4.3. Normalization

Different sensors measure different physical characteristics of buried features and thus have different measurement units (e.g. nT/m, ohm/m). Unless data are theoretically related and a mathematical conversion is possible, data should be normalized in order to make them free of measurement units. There are numerous normalization methods, the two most useful of which are described in detail below.

4.3.1. Standard Normalization

Standard normalization is the most widely used normalization technique which is employed by all statistical/mathematical packages as well as numerical computing environments as a standard function. This ubiquity means that including this step as part of the integration workflow is an easy task. On the other hand, standard normalization projects data on the [-1, 1] range where negative values might be a concern for some of the integration methods, such as continuous data operations.

4.3.2. Normalizing the Uniform Half Space

Normalization of the difference between any measurement and the anomaly-free value of the area is a superior approach to standard normalization. In this method, f_m represents the 'undisturbed' value and $f_m(x,y)$ is the measurement (Piro *et al.* 2000:204). Then the normalization can be written as:

$$F_{m_i}(x,y) = \frac{| f_{m_i}(x,y) - \widetilde{f}_{m_i} |}{\max | f_{m_i}(x,y) - \widetilde{f}_{m_i} |}$$

where f_m is the 'undisturbed' value and i represents the geophysical survey. Normalized values have the range of [0, 1], and thus, are suitable for any type of integration. Despite the fact that it is a better approach for geophysical data normalization and an appropriate fit for integration algorithms, the utility of the method is reduced by the difficulties in choosing an appropriate 'undisturbed' value. The 'disturbance' can only be fully verified via ground-truthing, following the archaeological prospection and this effort goes against the non-destructive nature of the survey.

4.4. Resampling

Different survey strategies as well as the sampling frequencies of instruments lead to differences in spatial resolution. Almost all geophysical instruments intensively collect data along transect, but perpendicular to the transect direction the sampling interval is determined by the sensor separation. As a result, one data axis contains more data than the other one. Likewise, due to their lower efficiency, resistance meters are employed for half-meter separation on both axes. These resolution discrepancies between different sensor types may create problems at a theoretical level and thus an agreement needs to be achieved. The easiest solution would be to resample all data to the coarsest spatial resolution in the data space. This brings however a loss of information for high density surveys, but guarantees statistical soundness.

4.5. Histogram Matching

In image processing, the main purpose of histogram matching is color adjustment. It is the process in which the distribution of data is transformed in order to match to a reference distribution. To perform histogram matching, both candidate and reference histograms are converted to cumulative distribution functions (CDF). Next, values in the candidate image are mapped over the reference CDF pixel by pixel. In archaeological prospection, histogram matching on normalized data not only facilitates better visual comparisons, but also adjusts data so that data integration becomes more feasible.

4.6. Cross-correlation

Quantitative data integration is a form of reduction in the data dimension so that the totality of geophysical data can be fused into a small number sets. The reduction will lose its power if and when geophysical data are correlated (e.g. the potential relation between resistivity vs. conductivity). Therefore, it is a good practice to explore data for their correlation and withheld any dataset which is highly correlated with others.

4.7. Data import

There is no commercially or publically available software for geophysical data integration. Therefore, there is a need to build customized routines in a computational environment. This requires transforming data from their native format into a common one, such as a text file. Once, the integration is completed, data are imported into a format in which results can be visually investigated.

5. Methods of integration

Luo *et al.* (2002) classifies integration algorithms as estimation methods, classification methods, inference methods, and artificial intelligence methods in an engineering context. However, considering the lack of 'true' integration studies in archaeological prospection, a similar classification effort would remain premature. Nevertheless, a framework can be still provided for guidance.

Throughout this guide, we use an example extracted from a geophysical survey, conducted at Alymros 2. The Neolithic site is located at Thessaly, Greece and was occupied during Early and Middle Neolithic Periods. Geophysical data (magnetic susceptibility, magnetic gradiometry, and electrical resistivity) are processed for integration, using the guidelines above and some methodologies are selectively provided for a better understanding of the subject. In the guide, we don't present interpretations for visible anomalies, but rather only present integration results.

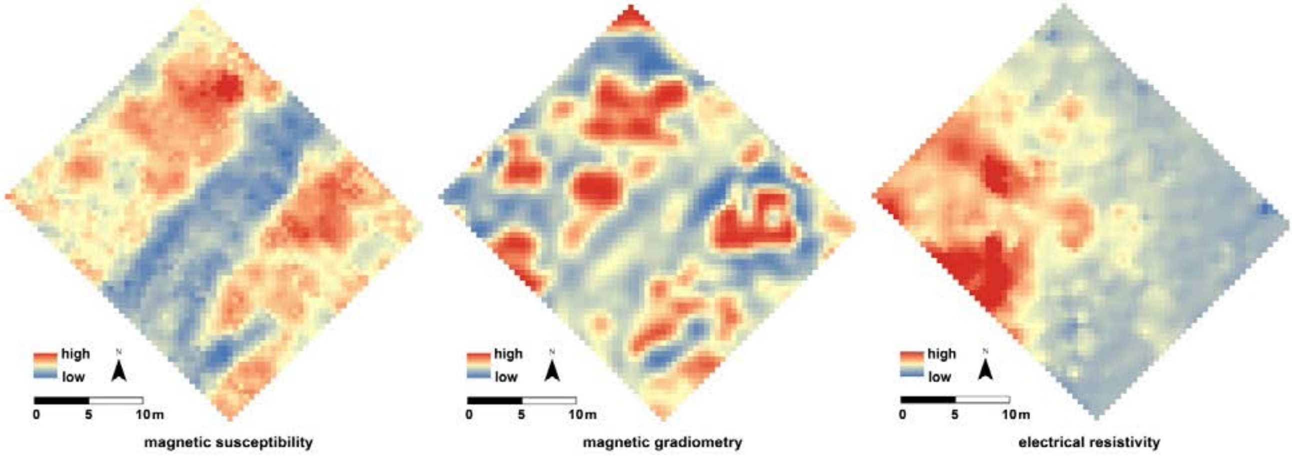

Figure 2. Processed geophysical data (from left to right: magnetic susceptibility, magnetic gradiometry, and electrical resistivity) from Alymros 2. Data are georeferenced to their exact locations, ensuring pixel-by-pixel matching and are resampled to 0.5m by 0.5m.

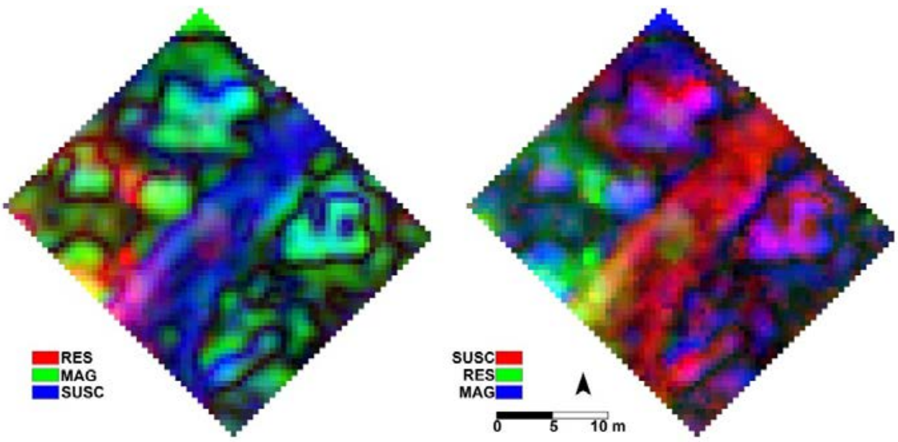

Figure 3.Two examples of RGB composites of geophysical data. Different ordering of 'bands' provides different emphasis to data, even though they represent the same area of interest.

Magnetic susceptibility data suggests that the study area is divided into two highly susceptible areas with a 'channel- like' anomaly with low susceptibility, running in the northeast-southwest direction. Areas with the highest susceptibility are concentrated to the north of the sample grid. Magnetic gradiometry data also reveal high magnetic readings at eastern and western wings. Unlike the magnetic susceptibility map, however, clusters of high magnetic readings are better delineated - as the main difference from the susceptibility data. Electrical resistance map clearly diverges from other two results. We observe high readings to the west, forming a transitional cluster in the grid. Nevertheless, the core of this highly resistive area has slightly lower readings than the periphery of the cluster (Fig. 2).

5.1. Graphical Integration

5.1.1. RGB Composites

Red-Green-Blue (RGB) color model is an additive approach for display on computer screens, televisions, etc. With the help of additive display of three main colors, other colors are perceived. This method gives the possibility to assign three different geophysical datasets to main colors and simultaneous (integrated) display of three techniques can be achieved (Fig. 3). Furthermore, knowing what color combinations result in what color (e.g. red + green = yellow) helps to visually investigate the results of different geophysical techniques in tandem (e.g. red ➔ magnetic + green ➔ resistivity = yellow ➔ highly magnetic and resistive areas).

Different combination of geophysical methods and RGB band assignments provide a differential look to the results in tandem (Fig. 3). In the first example, resistance data is

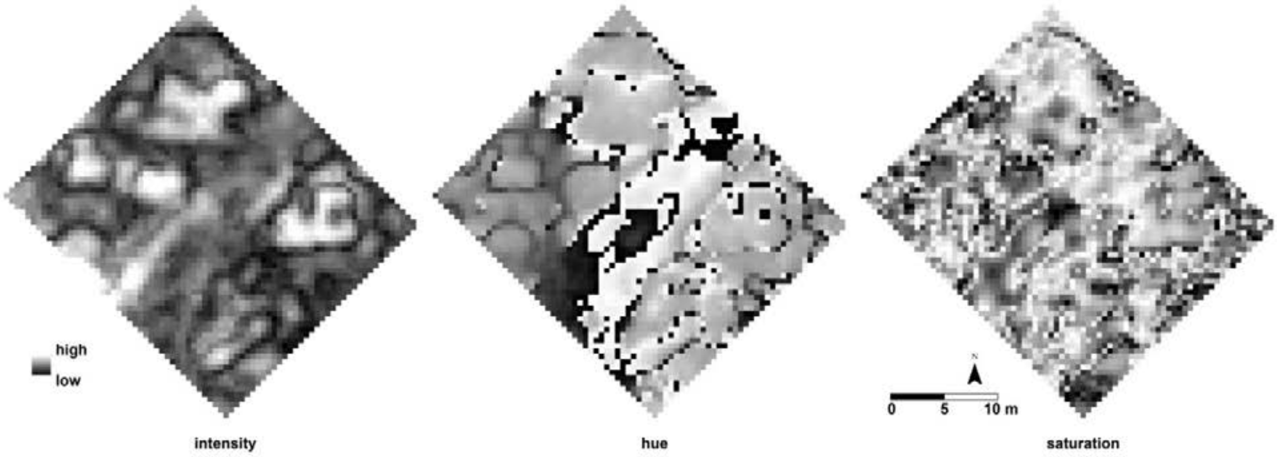

Figure 4. Intensity, hue, and saturation transformation from RGB composite in which red is assigned to magnetic susceptibility, green is assigned to electrical resistance, and blue is assigned to magnetic gradiometry.

assigned to red, gradiometry data to green, and susceptibility data to blue bands. Only very resistive areas are visible as red. The combination of gradiometry and susceptibility is in cyan color and dominates the results alongside the primary green and blue colors. In this combination not only the edges of magnetic anomalies are preserved, but also higher susceptibility measures surrounded them. Magenta color represents high resistance areas within the 'channel-like' feature. In the second example, susceptibility data is assigned to red, resistivity data to green, and gradiometry data to blue bands. With this combination anomalies are harder to decipher, suggesting a good combination is crucial for a better integration of different methodologies. Nevertheless, high resistivity areas are better preserved and high susceptibility-gradiometry data transitions are easier to read due to better contrast between cyan, red, and blue colors.

5.1.2. Alpha Compositing

Alpha compositing is a blending technique in which a background image (a geophysics data layer in this case) with a degree of transparency is applied to the rest of the layers. This makes it possible to add another layer to the RGB display so that further visual integration of four geophysics datasets is achieved.

5.1.3. HIS Transformation

Hue (H)-Intensity (I)-Saturation (S) is another coordinate system for the display of colors on electronic devices. Intensity represents the total brightness of a color. Hue is the color itself as we perceive it and saturation is the purity of that color (Carper *et al.* 1990). There are various algorithms which transform RGB space to HIS space and yet another form of visual integration can be achieved.

For Alymros 2 geophysical sample grid, the original RGB composite is formed of R: Resistivity, G: Gradiometry, B: Susceptibility data. Specific to this band combination, HIS transformation is applied and Intensity, Hue, and Saturation values are obtained for corresponding pixel values and displayed as separate datasets (Fig. 4). In this example, Intensity is mimicking the RGB as it is a mere representation of the brightness. Hue represents the actual color, and thus, immediately reveals color boundaries. This is helpful in delineating anomalies. Saturation distinguishes the purity of color so it shows areas with complex geophysical properties in comparison so more homogenous areas.

5.2. Binary Operations

Binary data represent any feature at a discrete state with two possible values: 0 is 'no information' and 1 is 'information. To state in geophysical terms, '0' is no detected anomaly and '1' indicates the presence of an anomaly. However, due to the nature of the geophysical data it is usually a challenging task to easily delineate an anomaly as its boundaries are never clearly defined. Therefore, it is not always possible to immediately assign '0' and '1' values as a transformation from continuous to binary data. The researcher either intuitively picks a threshold value or the value is determined using various statistical measures. This threshold value is the determinant of the classification; any value above (below) the threshold is assigned to '0' or vice versa. Once the classification is made for each geophysical dataset, Boolean operations can be applied for the integration of the data (Kvamme 2006).

To formalize the discussion, we employ various statistical methods to determine a threshold value. Hereby, we only examine Iso Data, Inter Modes, Niblack, Average, Otsu, and Modified Zone methods among many other automated thresholding techniques (for a review, see Trier & Taxt 1995, Kefali *et al.* 2010). These techniques provide

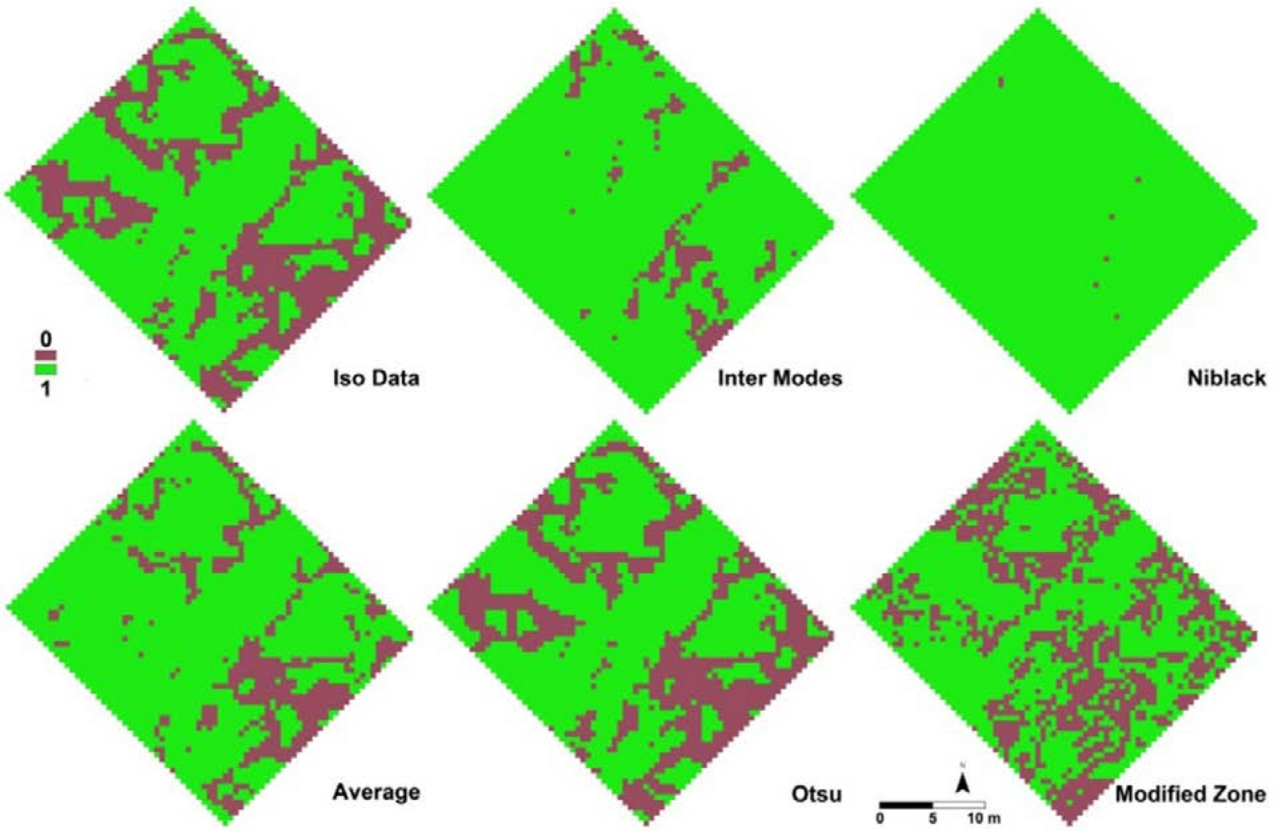

Figure 5. Different statistical measures (or 'thresholds') in binary conversion result in differences in unification results.

different results, raising the importance of threshold determination in binary conversions.

5.2.1. Boolean Union

For the Boolean Union, a pixel value is assigned to '1' if there is at least one corresponding pixel in any of the geophysical dataset that it is assigned to '1'. The resulting map compiles all 'thresholded' anomalies from all datasets where the assignment is technique-specific. All thresholding methodologies work in favor of 'anomaly generation' and create large areas of positive responses. Among experimented methodologies, Niblack transformation provides overtly optimistic results, and thus, remains not useful. Iso Data and Otsu methods appear as the most realistic transformation types for data integration based on Boolean Union operation (Fig. 5).

5.2.2. Boolean Intersection

Boolean Intersection determines if the anomaly is represented in all of the datasets. If a pixel contains an anomaly from each technique, the value of '1' is assigned to that pixel. If at least one geophysical technique does not contain the anomaly the pixel is assigned to '0'. For the given example (Fig. 6), Niblack transformation once again produces poor results. Iso Data technique is able to simultaneously capture some details from different geophysical datasets as in Boolean Union. However, Otsu technique also fails for Boolean Intersection, but the Average rises as a good binary transformation candidate for this particular example.

5.2.3. Boolean Sum

Boolean Sum algebraically adds all binary geophysical layers. Resulting data is not binary, but contains pixel values as much as the number of data layers with detected anomalies at that pixel location. For instance, if three geophysical techniques locate an anomaly, Boolean Sum for that pixel is assigned to three, and so forth. Therefore, it evaluates the accuracy of final interpretation – larger numbers indicating more secure interpretation for the existence of an anomaly

In Almyros 2, Boolean Sum fails for Niblack while Iso Data and Otsu transformations provide considerably good results; successfully delineating anomalies. which are visible in three different geophysical methods (Fig. 7). These techniques highlight magnetic anomalies, preserve the 'channel-like' feature at the center and provide a hint for the highly resistive areas.

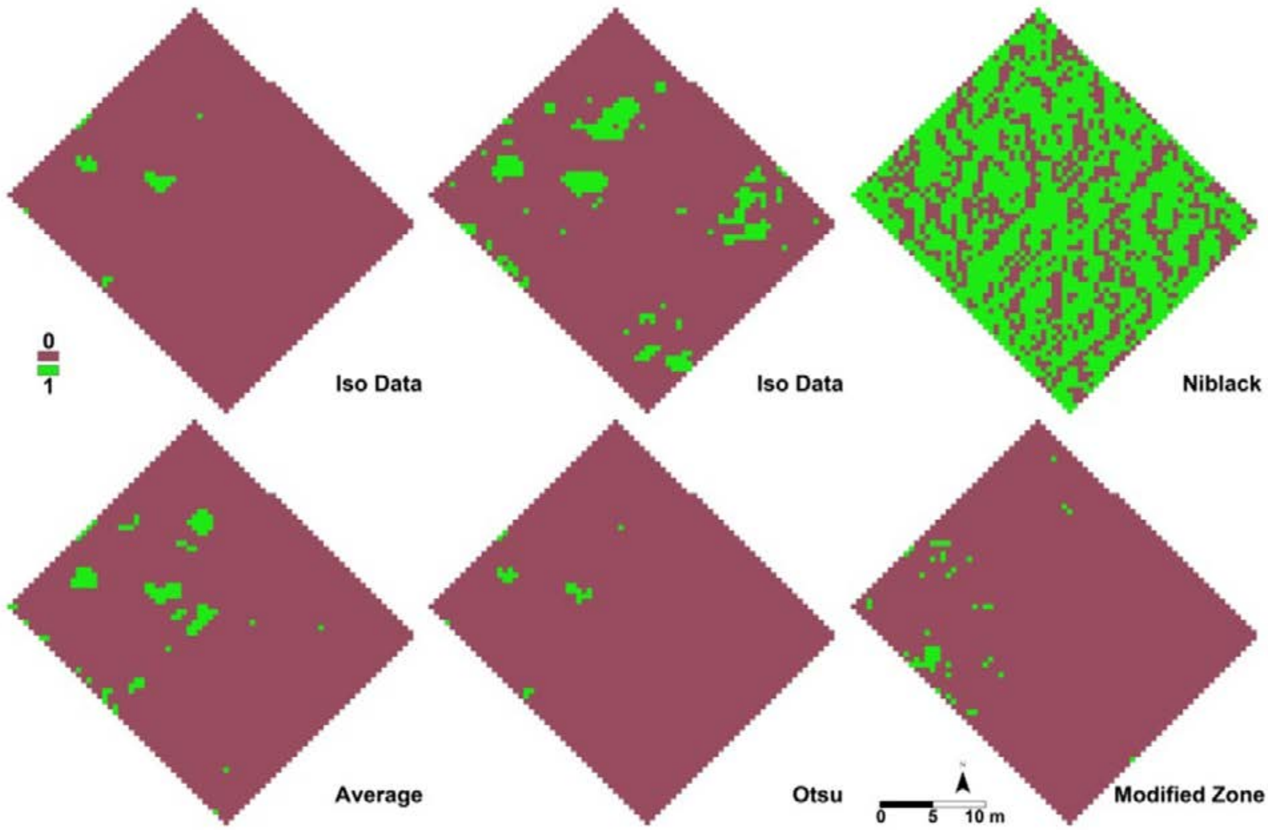

Figure 6. Different statistical measures (or 'thresholds') in binary conversion result in differences in intersection results.

Overall, we suggest Iso Data binary transformation performs superior to other techniques. However, we should also make it clear that this choice is case-specific and the results depend on the area under investigation as well as which geophysical methods were employed. Therefore, it remains as an empirical observation and do not have a theoretical basis. However, considering their algorithmic-efficiencies, these binary transformation routines can be applied to any dataset and the best candidate for data integration can be picked.

5.3. Continuous Data Operations

Without a transformation to binary data, it is also possible to perform simple algebraic operations on multiple geophysical data with the aim of integration (Kvamme 2006; Neubauer & Eder-Hinterleitner 1997). While the range of (normalized) data provides more variation in the final dataset, this final dataset inherently carries along the interpretation problems of each geophysical layer.

5.3.1. Numeric Combinations

Other than basic algebra operations, any user-defined function can be used to integrate geophysical datasets. In its simplest form, the researcher may assign weights to each geophysical layer with certain criteria and provide a linear combination of datasets. The complexity and power of the integrating function may depend on empirical observations, theoretical studies, or previous studies investigating similar concepts. For instance, von der Osten-Woldenburg (2005) reports an integrating function (for aerial archaeology and geophysical mapping) without any particular discussion of its origin:

$$C_{ij} = B_j + f / N^2 (A^2{}_j \times B_j - B^2{}_j \times A_j)$$

where A,B,C are the pixel positions at (i,j), f is the parameter controlling the strength of combination, and N is the depth of images. Researchers may experiment with such numeric combinations and modify them accordingly.

5.3.2. Data Product and Data Sum

With summing all geophysical data entering the process, it is possible to differentiate anomalies which provide higher signals than the ones with lower signals. It is important to note that the ways in which normalization is performed affects the summation. Furthermore, it is important to realize what higher (and lower) signals represent in archaeological terms so that interpretation remains still as a subjective task. If the researcher multiplies all geophysical data pixel-by-pixel a data product is achieved. Considering how multiplication operates, this technique tends to provide a larger range than summing data. Therefore, a higher variation is observed. Moreover, strong anomalies are further magnified.

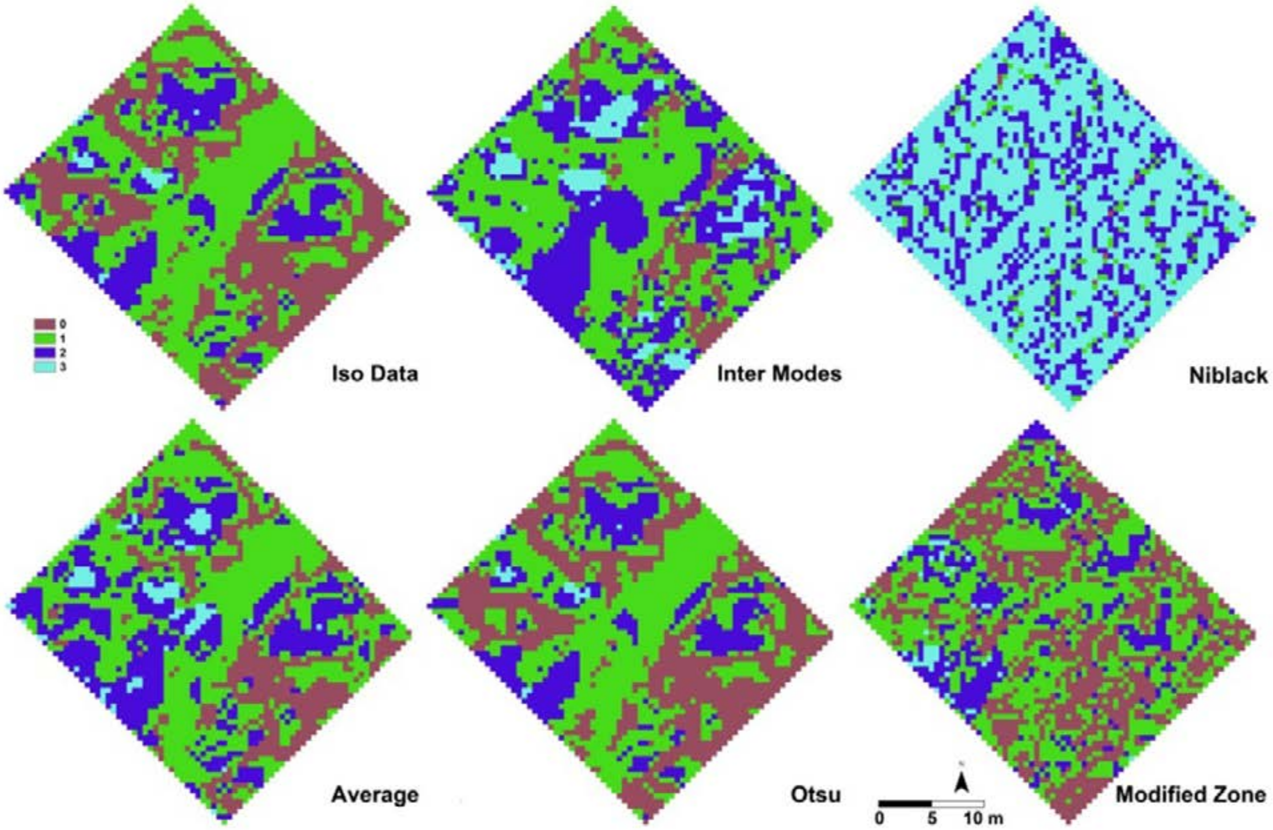

Figure 7. Different statistical measures (or 'thresholds') in binary conversion result in differences in summation results.

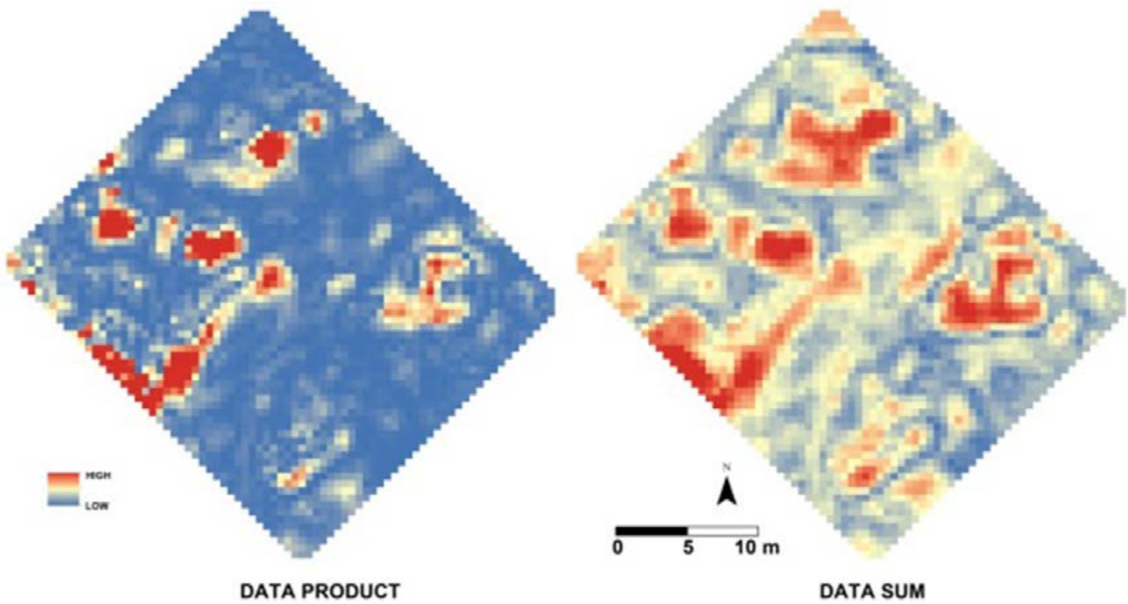

Figure 8. Easy-to-implement 'Data Product' and 'Data Sum' techniques are powerful integration tools. Especially, data summation provides akin results to the more complicated choices, such as Wavelet transformation.

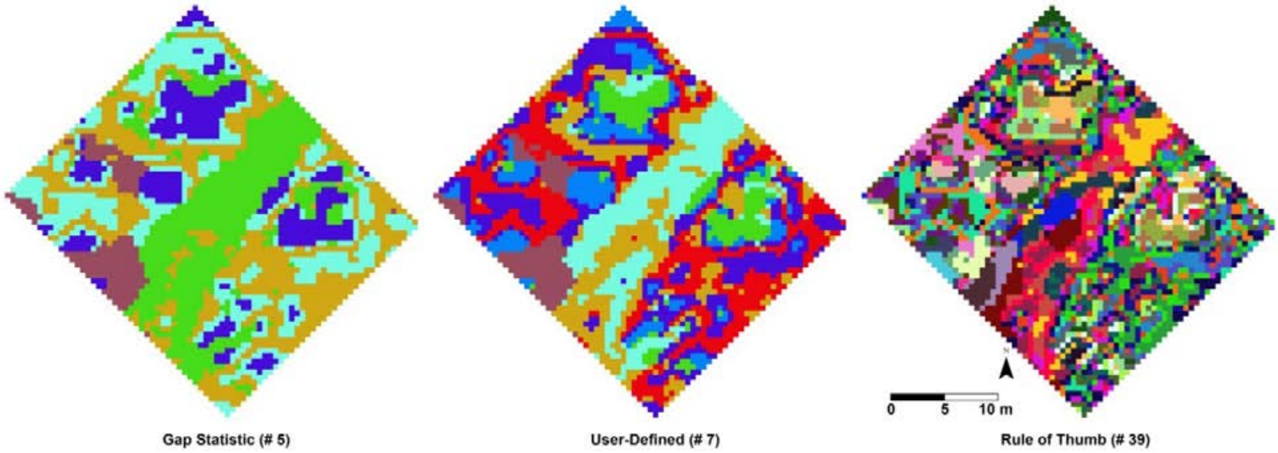

Figure 9. Different statistical and algebraic approaches may result in different number of clusters. The researcher may also determine how many clusters are required for the analysis.

In our example, Data Product preserves some details from resistance and gradiometry data (Fig.8). Especially, areas of interest in resistance map are nicely depicted. Furthermore, core areas of highly magnetic data are shown in the Data Product. However, the 'channel-like' anomaly is completely invisible, and thus, it remains as a poor data integration tool. Data Sum reveals more variation (Fig.8). Highly magnetic and resistive areas are preserved in this integration method, but once again 'channel-like' anomaly remains invisible. However, the channel area also provides some details which are invisible in the magnetic susceptibility data so that some extra information is obtained.

1.1. Statistical and Numerical Operations

Geophysical data integration is not only a data reduction problem for multi-dimensional data, but also a classification effort. Statistical operations can both provide this necessary data reduction and classification. They are the most useful when used in combination under the conditions that their constraints and assumptions are satisfied.

5.4.1. Cluster Analysis (Unsupervised Classification)

Cluster analysis is an unsupervised classification technique where the researcher can treat multiple geophysical datasets with the analysis and obtain a handful of classes (or clusters) based on a statistical measure (usually the Euclidean distance). These classes are most likely to represent anomalies which are visible (or hidden) in different datasets (Kvamme 2006; Ernenwein 2009). The main problem in this approach is the determination of the number of classes. The user can define the number of classes by intuition or can use a formal method, such as gap statistics.

Among other techniques, we use 'Gap Statistic', 'Rule of Thumb' for an automated selection of the number of clusters. A 'user-defined' number is also selected for comparative reasons (Fig. 9). Gap Statistic suggests five clusters should be assigned to data coming from three different geophysical datasets. In this case, 'channel-like' anomaly is delineated successfully. Highly resistive areas also appear as a distinct cluster. High magnetic areas and their boundaries are represented in two different clusters. However, the boundary cluster also includes other data so that it remains less-reliable. Rule of Thumb produces an excessive number of 39 clusters so that it does not provide a realist picture. User-defined cluster number (seven) performs worse than a cluster number determined by Gap Statistic. However, this statistic can provide guidance for user-defined analysis and improvements can be made.

5.4.2. Principle Component Analysis

Principle Component Analysis (PCA) reduces the dimension of data by exploring possibly correlated variables and by providing a new set of least correlated variables. In doing so, it is possible to create new datasets where the variation is stored in new layers of fewer dimensions (namely less number than the original datasets). Thus, the resulting sets are reduced in complexity and they are easier to interpret based on the loading readings from the principle components. Furthermore, datasets retaining most of the information can be treated with simpler graphical and algebraic integration methods, using the information based on calculated loadings (Kvamme 2006).

5.4.7. Mahalanobis Classification (Supervised Classification)

With Mahalanobis classification schema, we can determine classes over multiple geophysical datasets where these classes are based on pixel memberships (e.g. wall class, pit class, ditches class, etc.). Next, datasets are investigated in comparison to a training dataset for their Mahalanobis distances only to be compared by statistical measures. Results not only integrate multiple data into a single one, but also provide a classification of anomalies (Ernenwein 2009). As in any other classification efforts, the accuracy of classification depends on the purity of the training dataset which is a hard task to achieve in archaeological prospection.

5.4.4. Logistic Regression

Geophysical data can also be classified using a logistic regression where independent variables are composed of multiple data layers and the dependent variable predicts the anomaly (Kvamme 2006). It is a robust methodology and requires less strict assumptions than many other methods, providing a straightforward classification solution. On the other hand, as Lillesand *et al.* (2008:557) succinctly put forward, '[t]he quality of the training process determines the success of the classification stage, and therefore, the value of the information generated from the entire classification effort'. In rare cases, we can feed the model with the most accurate training datasets according to the complexity of geophysical data. Only with the help of ground-truthing such an accurate training dataset can be achieved. Results of the logistic regression can be used in two ways. First, we can explore the contribution of each geophysical method, using regression coefficients. These coefficients can be used as 'weights' and other integration analysis can be performed. Second, using a back transformation probability surfaces for anomalies can be created.

5.4.5. Cokriging

Kriging is an interpolation methodology, based on regression analysis. The values at unknown locations are predicted using surrounding measured values. These values contribute to prediction with weights, based on distance between observations, the spatial pattern of observations, and distance to prediction values. Cokriging is a variant of kriging where several attributes can be used simultaneously to interpolate the values of a primary variable; the integrated geophysical value in this case.

5.4.6. Wavelet Transformation

Wavelet transformation is a well-established choice for image fusion studies (Li *et al.* 1995; Pajares & Manuel de la Cruz 2004; Amolins *et al.* 2007). The transformation is a robust and scale-independent signal processing tool which discriminates high-level signals which are likely to contain most of the geophysical information from the low-level signals, dubbed as the noise. Once a separation is established, new data which is filtered for high-level signals can be back transformed and a 'clearer' picture of a dataset can be obtained. The integration is based on the combination of wavelet coefficients of input data (Rockinger 1996).

Wavelet transformation of three geophysical datasets successfully combines all *high* geophysical readings in a single dataset; highlighting the locations of anomalies (Fig. 10). On the other hand, their shapes are rather poorly preserved due to the complex interaction between different geophysical datasets. The channel-like feature is not visible after wavelet transformation —as in many other data integration methods, discussed above. Finally, the transformation registers all 'significant' features from three different datasets so that the interpretation of the integrated map remains as a challenging task.

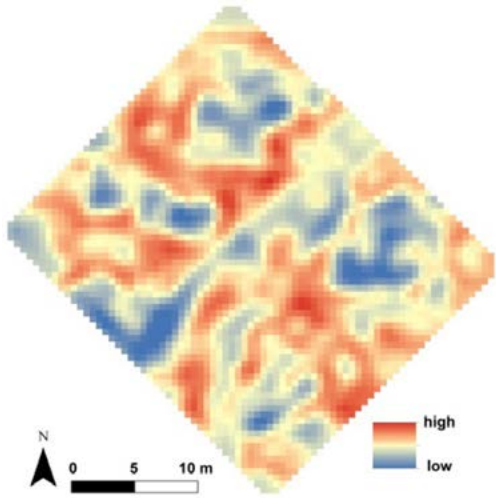

Figure 10. Data integration based on wavelet transformation.

5.4.7. Curvelet Transformation

One of the main disadvantages of wavelet transformation is its inability to retain spatial information. With their directional sensitivity curvelets preserves features better than wavelets. This provides a clear advantage in archaeological applications of geophysical data integration. To compute the transformation, first a Radon transformation is computed, and second, a one-dimensional wavelet transformation is applied to Radon slices (Choi *et al.* 2004).

5.4.8. Multi-scale Decompositions (Laplacian, Steerable, and Gradient)

With this approach, an image is recursively decomposed into sub-bands at different scales. The decomposition involves the use of basis functions in which a weighted sum of these basis functions represents the image. The weights, or the transformation coefficients, are computed by projecting data onto projection functions. In following, an image pyramid is a collection of these sub-band transformations (with convolving and subsampling) where basis and projection functions are translated at different levels with a factor of 2^j for an integer j. Subsampling results in size differences in sub-band images, creating a pyramid. A rule based cascading of pyramids of different data sources while keeping the most significant details provides integration (Heeger & Bergen 1995).

In the Laplacian pyramid, 'reduce' and 'expand' operations are applied. To 'reduce' a low-pass filter is applied to the image and subsampled with a factor of two. To 'expand' the image, data is upsampled by a factor of two and the same low-pass filter is applied. A combination of these 'expand' and 'reduce' operations form a level of the

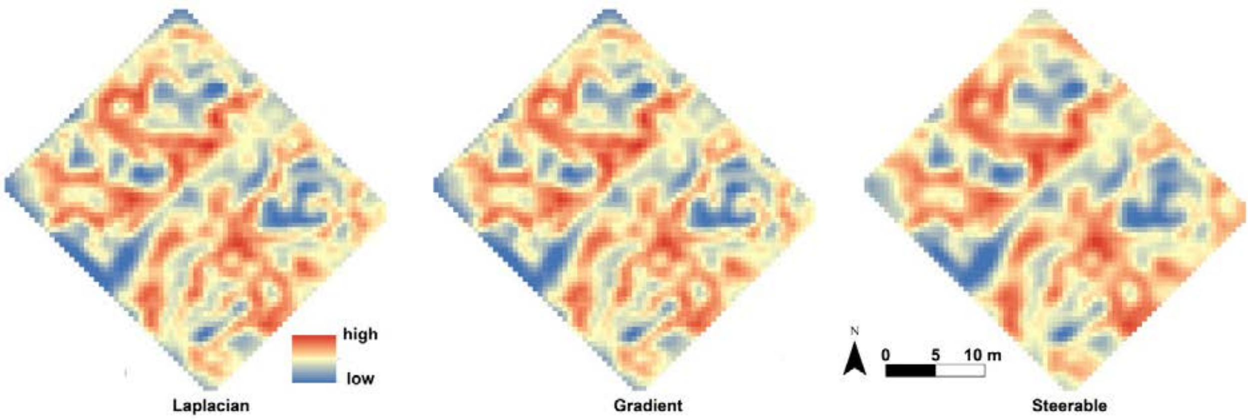

Figure 11. Different pyramid approaches did not provide differences in integration. Therefore, the researcher may choose the simplest algorithm for computational efficiency.

pyramid. After iterating, a full pyramid is obtained (Burt & Adelson 1983).

With a steerable pyramid, elongated features are also captured in the decomposition; a property which is missing in the Laplacian pyramids. On top of the Laplacian pyramid, a steerable pyramid further divides the bands into a set of orientation bands. In other words, the orientation is 'steerable' in such a way that it is superior to strictly orthogonal decompositions (Simoncelli & Freeman 1995).

A gradient pyramid is obtained if a gradient operator with four directions (i.e. horizontal, vertical, and two diagonals) is applied to each level of a Gaussian pyramid. The operator is successful in determining any directional change in color or intensity, and thus, potential features are preserved. The fused image is reconstructed by using a Laplacian pyramid (Petrovic & Xydeas 2004).

All three Multi-scale (MS) decomposition methods create similar results (Fig.11). Results also have close resemblance with Wavelet Transformation as MS methods also search for and pick significant features from each dataset and integrate these features in a single dataset. Therefore, the interpretation for Wavelet transformation provided above is also valid for MS decomposition.

5.5 Other Potential Approaches

Integration of geophysical methods through joint inversion has been also achieved in various cases. Inversion of electric resistance tomography (ERT) and GPR travel time (Doetsch *et al.* 2010), electromagnetic and seismic data inversion using structural constraints (Hu *et al.* 2009) are to name a few. JafarGandomi & Binley (2013) provide a Bayesian approach for geophysical data fusion. Royal *et al.* (2011) suggest an expert knowledge-based system in part with the fusion of sensor data. Data fusion studies in aerial/satellite remote sensing have been making a faster progress in comparison to geophysical prospection. In this respect, the ability to ground-truth gives a clear advantage for the betterment of the techniques. Neural-Statistical approaches (Bruzzone *et al.* 1999), Neural Networks (Jimenez *et al.* 1999) and Dempster-Shafer Evidence Theory (Hegarat-Mascle *et al.* 1997) reveal the early recognition of the need for data integration as well as the variety of techniques in use.

6. Conclusion

The goal of geophysical data integration is to obtain more information than the sum of information that individual sensors provide (1+1=3). For the data-level fusion this is established by comparing different datasets going into the fusion process pixel by pixel and selecting the most important information at a given pixel location. The collection of the most important information is the fused/integrated image.

Despite the ongoing advances in information sciences, studies on the true integration of archaeo-geophysical data are very few (e.g. Kvamme 2006; Ernenwein 2009) and most other studies with the intention of integration do not go beyond descriptive analysis of data, treated in complete isolation. This best practice guide is written in order to highlight this lack of attention in archaeological prospection.

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Overview of Underwater Archaeological Research with Advanced Technologies in Greece

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Abstract: Underwater archaeological salvage operations in Greece commenced with 'nude diving' in Lord Elgin's wrecked ship Mentor in 1802 at Kythera, continued with hard helmet diving at the Salamis straits in 1877, at Antikythera in 1900 and Madhia in 1907, and advanced with the introduction of SCUBA diving in the late 1950s. First underwater excavation took place at Grand Congloué in 1950 and from then on, salvage was transformed and developed into a separate discipline of archaeology, progressing today in using Closed Circuit Rebreathers and Atmospheric Diving Systems, as in the recent Antikythera project (2012- 2014). Except for SCUBA diving gear and visual observation, several other technological methods and equipment have been used after the mid-twentieth century, to locate and map submerged cultural remains, especially in deep waters. The article comprises an overview of innovative underwater archaeological research efforts in Greek territorial waters, distinct from the standard diving methods and technologies used in the field. The overview of the history of their use will lead, at the end,to the discussion of their efficiency and basic principles to be followed based on the experience acquired.

Keywords: archaeology, Greek archaeology, underwater archaeology, advanced technology, ocean research, underwater survey, ancient shipwrecks, ancient submerged sites

1. Introduction

Underwater archaeology was established in 1900, with the salvage of a Roman gulley cargo, known as Antikythera Shipwreck, by Symian sponge-divers, equipped with hard helmet diving gear. The Greek state placed the project under its auspices, becoming the first country to conduct such an operation (Throckmorton 1987: p.16). No other navy could have really achieved such a feat as the project owed a large part of its success to the heroic efforts of the tough and brave Symian sponge divers. The ship sank around the middle of 1st c. BC off the island of Antikythera while transferring pieces of art, namely bronze and marble statues, luxury goods, as wel as the famous Antikythera Mechanism.

Even before the beginning of the 20th century, the salvage of the cargo of *Mentor*, had already took place in 1802 (Lianos 1983 Kourkoumelis and Tourtas 2014 for further research and excavation of the site).The *Mentor* was one of Lord Elgin's ships loaded with some of Parthenon's marbles that sank in Kythera. The rescue was conducted by 'nude divers', their sole equipment being their breath. Besides the work on *Mentor*, a survey at the Straits of Salamis by sponge divers took also place in 1884, directed by Christos Tsountas of the Greek Archaeological Society (Koumanoudis 1885; Lolos 2003). The Society's Secretary Stephanos Koumanoudis' (1885:17) finally at the end of his report -describing the absence of significant findings- concluded: '*perhaps more convenient times will come for such difficult enterprises*'.

Part of another important cargo of art and building elements was also recovered by Greek sponge divers off the coast of Mahdia (Libya) in 1807 (Merlin 1908; Hellenkemper-Salies *et al.* 1994; for more recent research see: http://www.deguwa.org/?id=40 [Accessed: 23 Jan. 2012]). Those operations, though, were truly challenging for the means available at that time and were not repeated, thus the marine archaeological focus shifted to the easily accessed harbour remains, until the development of the regulator enabling SCUBA diving, by Jacques-Eves Cousteau and Émile Gagnan, in 1943. The excavation of the Roman shipwrecks of Grand Congloué in 1952, directed by Fernand Benoit and conducted by J.-Y. Cousteau's team was the first real underwater excavation –the previous efforts being in fact salvage operations. It was also the first operation during which a crude methodology was used, as opposed to the total lack of methodology during past efforts. Several others followed Grand Congloué's example around the Mediterranean. In 1960 at Cape Gelidonia, southern Turkey (Bass 2005) and from 1961 to 1964 at Yassi Ada, east of Kalymnos (Bass *et al.* 1982) George Bass transferred many land archaeology excavation techniques to underwater excavation, followed by M. Katchev at Kyrenia Hellenistic wreck (Katzev 1972; Katzev 2005 with relevant bibliography), in 1967-1969. Underwater archaeology was thus established as a distinct discipline and progressed perfecting its techniques, approach, tools and effectiveness in hundreds of sites all over the world, where shipwrecks, submerged sites, harbour installations or other objects of historical or archaeological significance could be found.

Greece, inevitably, could not stay out of this field. The first site to be surveyed was the bay of Marathon in 1950 by a French team (Braemer and Marcadé 1953). The first archaeologist – diver, Nikos Yalouris explored the Gulf of Pheia, western Peloponnese, in 1959 (Yialouris 1957: 31). The first excavation that was conducted in 1970 at the Byzantine shipwreck of St. Peter bay at Pelagos Island, in Northern Sporades complex, was directed by Charalambos Kritzas (Kritzas 1971; Throckmorton 1971). After that excavation, in 1973, the Hellenic Institute of Marine Archaeology (HIMA) was established (www.ienae.gr), a non-profit institution acting as a consultant of the Ministry of Culture. In fact, it was fulfilling the Ministry's needs for human resources for diving operations until 1976, when the Ephorate of Underwater Antiquities (EUA) was founded, the Greek State's institution, responsible for the protection, research and development of underwater cultural heritage (www.yppo.gr).

From then on, numerous sites have been investigated all over Greek territorial waters, many times in cooperation with other Greek and foreign institutions. The purpose of this article it is not to refer to all of these missions individually (for a general table of those up to 2011 see Theodoulou 2011a). Many of them were conducted with the use of modern mapping and survey equipment such as underwater photogrammetry, side scan sonar (SSS), sub-bottom profiler (SBP), multibeam (MB), marine magnetometer (MG), measuring of water column parameters (CTD), etc., or equipment of visual observation systems like autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), human operated vehicles (HOV). Simultaneously, diving proceeded to using more advanced methods including Nitrox, Trimix, closed circuit rebreathers (CCR) and recently atmospheric diving systems (ADS) during archaeological campaigns.

The article will mainly focus on the expeditions during which innovative methods to locate, map and investigate underwater archaeological sites were used. It will also discuss at the end the efficiency of these methods and basic principles to be followed based on the experienced acquired. The overview doesn't thrive to be thorough and detailed, but a tool to start with for further studying.

2. First efforts

From 1960s to the establishment of EUA in 1976 several pioneering missions used technology for archaeological investigation and recording. In 1953 J. Cousteau on board the legendary *Calypso* visited Greece accompanied by Harold Edgerton, inventor of the deep water cameras that Cousteau's team was using and experimenting at the time with SSS systems. Frederic Dumas (1972), who was on board too, describes the dives in Antikythera, Delos, Naxos and Navarino. H. Edgerton, though, remarks that he was finally not allowed to use his equipment at least in Antikythera, lacking the relevant official permission.

Under the direction of the Greek archaeologist Spyridon Marinatos in 1965, 1969 and 1970 H. Edgerton along with the pioneer of underwater archaeology Peter Throckmorton and E.T. Hall of the Research Laboratory for Archaeology at Oxford undertook a geophysical survey testing SSS, SBP, MG and coring at the harbour of Porto Longo, Peloponnese (Frey 1972). S. Marinatos, H. Edgerton and P. Throckmorton started also in 1967 to search for the lost city of ancient Helice in the Corinthian Gulf, using SSS. The city was submerged after a tsunami in the winter of 373 BC. However, no traces of the city were found (Edgerton 1966; Marinatos 1968; Edgerton and Throckmorton 1970). The expedition was repeated in 1972 with Ch. Kritzas as representative of Marinatos. The results were again negative (Edgerton 1981). Helice's location continued to be object of research –decades later- which finally proved that the remains of the city lay now inland due to the thick silting of Selinous river. A marine remote sensing survey was carried out by the Laboratory of Marine Geology and Physical Oceanography (MGPO) of the Department of Geology of the University of Patras (UPatras) at that area to examine a coastal landslide after a severe earthquake (6.2R) in 1995. The survey was conducted with SSS, SBP and ROV and the collected marine data along with onshore survey data led the researchers to suggest a new geological scenario for the disappearance of ancient city (Ferentinos *et al.* 2015).

In the meantime, in 1971, Ch. Kritzas supported by the American architect-archaeologist Julian Whittlesy used aerial photography to map the submerged buildings and harbour installations of Epidaurus (Kritzas 1972). Aerial photography was also used at the coast of the area between Nauplion and Tolo without significant results (cited in Kritzas 1978). The same year, as well as the following one, the harbour of Gytheion was surveyed by divers in combination with sonar survey conducted by H. Edgerton (Skoufopoulos and Edgerton 1972; Skoufopoulos and McKernan 1975). A huge formation 220x70m that was located was interpreted either as a harbour structure or a natural feature.

In 1971 and 1972, H. Edgerton and P. Throckmorton team searched also for remains of the Naval Battle of Lepanto, at the northern Gulf of Patras, which took place in 1571 among the Ottomans and the Holy League, a coalition of southern European Catholic maritime states. An EG&G SSS, an ELSEC 592 MG and a 5 kHz SBP were used (Fig. 1). The results of the survey, though, were again negative, although they spotted two areas with possible targets that they never visually checked (Throckmorton *et al.* 1973, Edgerton 1978; See also Papatheodorou *et al.* 2009 for a geological survey at the same area in 2008).

The Greek Tourism Organization and the Ministry of Culture and Science invited in late 1975 J.-Y. Cousteau to explore underwater sites with archaeological interest in order to promote Greece worldwide through his documentaries. Calypso was equipped with a helicopter for aerial pictures, a submersible, the *soucoupe* and SSS, operated by H. Edgerton. Most of the diving archaeologists of the Ministry and members of HIMA got familiarized with all this equipment inspecting or participating accordingly at the expeditions undertaken all over the Aegean (Kritzas 1978, 1988a, 1988b). Beyond

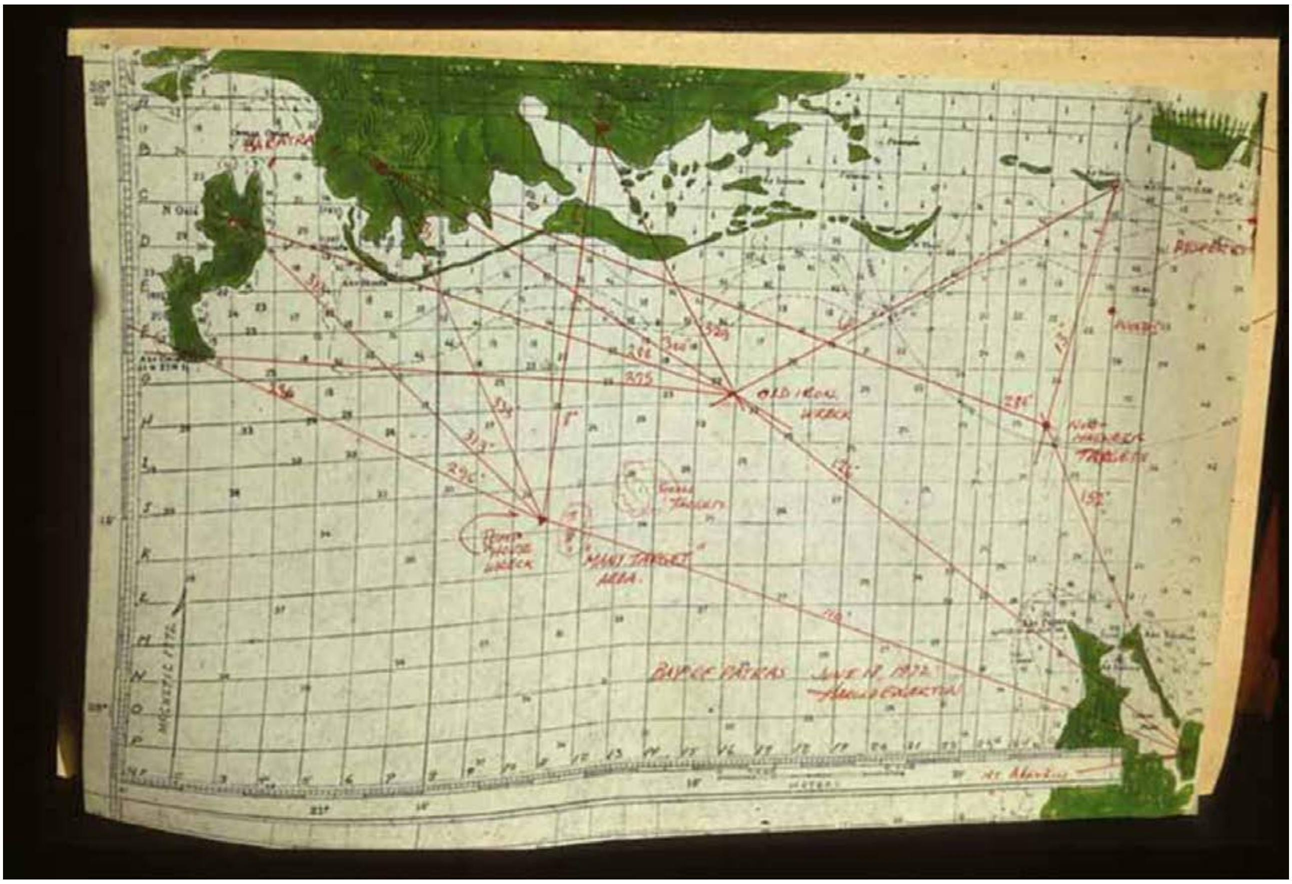

Figure1.Map of sonar survey targets in the Bay of Patras, site of the Battle of Lepanto; signed and dated June 18, 1972 by Harold E. Edgerton (online at: http://webmuseum.mit.edu/browser.php?m=objects&kv=93033&i=71120 [Accessed: 9 Feb. 2015]

the excavations that took place in Antikythera and Dhia islet off Herakleion, as well as diving in several other sites, SSS was used to search many areas. At gulf of Navarino, Peloponnese, the remains of Navarino Naval Battle (1827), among the Ottoman-Egyptian fleet and the French, British and Russian naval forces, were located and mapped. At the area of Cape Artemision they searched for possible relics of the Artemision shipwreck, from where the bronze statue of Poseidon or Zeus exhibited today in the National Archaeological museum was recovered, but with poor results. At Santorini they investigated the caldera without any archaeological results. Most fruitful was the scanning off Kea Island, Cyclades, where the wreck of HMHS *Britannic* the sister ship of *Titanic* that was sank during the 1st World War, was located and searched, 100m deep. In 2007, the Laboratory MGPO (UPatras) surveyed in detail the shipwreck and the surrounding debris field using an EG&G 272-TD SSS (Papatheodorou *et al.* 2008).

In 1979 Tjeerd van Andel and Nikolaos Lianos carried out a marine geophysical survey at the area of Koiladha bay, eastern Peloponnese with SSS and SBP revealing the topography of the historic and Prehistoric shorelines (van Andel *et al.* 1980). The survey was extended in 1982 to the broader southern Argolid peninsula in order to map the submerged palaeo-shorelines and to reconstruct the coastal palaeo-geography of the area (van Andel and Lianos 1983; 1984).

3. After Titanic

The location of *Titanic* by Robert Ballard in 1985 encouraged the broader use of deep water investigation technologies in searching for lost ships and therefore their employment in underwater archaeology. This tendency became stronger in the 1990s and 'exploded' after 2000 in Greece. In 1987 Ballard's team discovered in international waters near Skerki Bank, about 80 km NW of Sicily, a Roman shipwreck 750m deep (McCann and Freed 1994). The following year, Ballard's team returned to the site for the JASON Project. '*The project was designed to show how archaeologists might make use of the new technologies and to bring attention to the international problem of illicit excavation*' (McCann online). They returned to the site in 1997 with US Navy's nuclear research submarine, the NR-1 locating, recording and studying seven more shipwrecks (McCann and Oleson 2004) disposing the maximum use of new tools for underwater archaeology.

In Greece, in April 1988 HIMA investigated a 19th c. shipwreck off Chios, attributed most possibly to the flag ship of the Ottoman fleet under command of Kara Ali, that was set on fire and sank during Greek Revolution. The echo sounder of the Coast Guard vessel, disposed to the team, was used for the location of the relics at the seabed, along with a drop camera (Vichos1989). Some months later EUA returned to the site with the Greek Navy oceanographic vessel *Pytheas* and used SSS for the re-location of the site (Theodoulou *et al.* 2009).

From 1989 to 1992 the first systematic underwater excavation in Greece was undertaken by HIMA at the island of Dokos concerning an Early Helladic shipwreck (2200 BC), namely the oldest excavated shipwreck. For recording of the finds Sonic High Accuracy Ranging and Positioning System - SHARPS was firstly used (Vosyniotes 1990, Kyriakopoulou 1989, see also *Enalia* A: 11). The Laboratory MGPO (UPatras) was also invited to study the subbottom stratigraphy and the seafloor morphology of the site and attempt the reconstruction of the Prehistoric shorelines of the island. For the survey, a 3.5 kHz Geopulse SBP and an EG &G 272-TD SSS were used (Papatheodorou *et al.* 2008).

A team of the EUA directed by Katerina Dellaporta started in 1991 the excavation of a 16th century Spanish shipwreck out of Zakynthos port (Lefteris reef) in cooperation with the Oxford MARE Institute and British School at Athens. The excavation lasted up to 2000, though not continuously, and uncovered an important portion of the ship-shell as part of the cargo and its rigging. The investigation included photogrammetric recording of the site and underwater geophysics at the seabed (Dellaporta and Bound 1993; Koniordos *et al.* 1993; Dellaporta 1997, 2000, 2002a; see also Papatheodorou *et al.* 2001a).

The following year, at Peristera, Alonessos a Classical (420-400 BC) shipwreck started being excavated by EUA, under the direction of Elpida Hadjidaki (1992a; 1992b;1993a; 1995; 1996; 1997). The excavation lasted from 1992 to 2000, but not with field seasons on yearly basis. The cargo of the ship, more than 3000 thousand amphorae from Alonessos and Northern Greece (Mende) and the size of the ship proved to be very important for the study of Classical trade. For the recording of the site photogrammetry was used resulting in having one of the first general views of such an extended assemblage in Greece.

In 1993 EUA cooperated with Scripps Institution of Oceanography UC San Diego at the area of Artemision, in an attempt to employ oceanography methods and equipment for the location of underwater targets. E. Hadjidaki though remarks that '*The results of the fifteen days cooperation pointed that the use of these technology seek important development to be used for EUA purpose*s' (Hadjidaki 1993c).

That same year EUA initiated a SSS survey for the location of the possible relics of Actium Naval Battle among Caesar and Pompei (31 BC). The campaign continued in 1994 and repeated in 1997 (Murray 1993; 1994; 1997).The survey was conducted in cooperation with Florida and Miami Universities. SSS, metal detector, ROV and differential global positioning system (DGPS) were used. The results were not very encouraging. Two possible stone catapult projectiles and a possible metal object were located. The project finally stopped because works at the neighboring coast caused very bad visibility and silting of the seabed.

Due to the use of the gulf of Navarino, where the famous naval battle of the Greek Revolution took place (see above), for mooring and refueling of tankers and cargo ships, the Laboratory MGPO (UPatras) was asked, in 1996, to carry out a remote sensing survey of the area for mapping the remains in order to produce a plan for their protection. To achieve these aims the team used an EG&G Model 272-TD SSS, a 3.5 kHz SBP and a Benthos Mini-Rover MKII ROV. The positioning data were provided by a DGPS. The survey proved that shipwrecks relics were still obvious on seafloor while inconsistencies on the seabed might suggest further buried remains (Papatheodorou *et al.* 2005).

4. The new era of 21st century

By the end of 1990s EUA's new Director, K. Dellaporta, inaugurated an extroversive approach on behalf of the Ephorate, commissioning cooperation with Greek and foreign institutions handling advanced technology tools for ocean investigations. That led to the expanding of operational capacities in depth and space coverage, founding a new know-how as far as underwater archaeological survey is concerned, resulting to the survey of vast areas of Greek territorial waters, in addition to discovery and recording of dozens of ancient shipwrecks. What emphatically initiated the new era in Greek underwater archaeological research, as far as technology is concerned, was the establishment of a five year Cooperation Memorandum for archaeological exploration and mapping of extended areas in deep water, among EUA and the Hellenic Center of Marine Research (HCMR) that was signed among the two bodies in 2001 (Dellaporta and Sakellariou 2000, Kourkoumelis *et al.* 2005). The missions that followed were materialized not only by the two institutions but also along with the cooperation of other Greek and foreign bodies. HCMR followed by the Laboratory MGPO of the Department of Geology of the University of Patras have been proved to be the two Greek institutions that up to date have been leading the underwater survey, targeting cultural heritage, mapping and recording. The teams of the two institutions obtained experience that they have started sharing with other countries too (Chalari *et al.* 2003; Sakellariou *et al.* 2015; Bailey and Sakellariou 2012; Bailey and *et al.* 2012; Flemming and Sakellariou 2009; Papatheodorou *et al.* 2001b, 2001c)[1]. Meantime, EUA gained access and initiated projects that could not be employed before.

[1] In this framework D. Sakellariou of HCMR and experts from other eight European countries initiated in 2009 the European project Deukalion for a four-year period as COST Action TD0902 SPLASHCOS, 'Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf' (http://www.splashcos.org [Accessed: 26 Febr. 2015]) with main goals to (i) Investigate systematically the prehistoric archaeology and terrestrial landscapes now submerged on the European continental shelf, (ii) Integrate the skills of archaeological institutions and oceanographic agencies and use modern offshore, laboratory and computing technology and (iii) Illuminate long-term social response to sea level and climate change. The original aspirations of Deukalion Project remain in place up to date and the Deukalion Planning Group continues to meet to consider long-term strategic plans and research opportunities (Flemming &

In this framework, firstly in 1999, EUA, the Norwegian University of Science and Technology and the Norwegian Institute at Athens initiated a survey at the area of Northern Sporades (1999) and Ionian Sea, the straits of Cephalonia – Ithaca (2000, 2003). Throughout these expeditions they used a SeaScan PC high-resolution SSS system, two ROV systems, a Sub-Fighter 4500 ROV from Sperre AS and a Falcon ROV from SeaEye Marine. The positioning was due to DGPS. One of the project goals was to prove '*that it is possible to perform systematic large-area surveys in deeper waters using off-the-shelf equipment from available small ships, at relatively low cost with good results*' (Dellaporta *et al.* 2006:79). K. Dellaporta (1999:1022) was also noting that '*the employment of advanced technology poses queries, but also answers interesting issues of underwater archaeology*'. Five known shipwreck sites were re-located in Northern Sporades and three unknown ones were located at the Ionian sea, two of Roman and one of Hellenistic times (Dellaporta 1999; Spondilis and Theodoulou 2003; Dellaporta *et al.* 2006).

The initial common mission of EUA and HCMR took place in 2000 before the signing of the Memorandum, at the area of Kos-Kalymnos and Nisyros. A few years before, a complete woman bronze statue, known as *Maiden of Kalymnos* and other parts of bronze statues had delivered to the Ephorate by Kalymnian fishermen. Therefore, a campaign to the area was the first to be programmed, aiming to search for the spot where the statues were coming from. The expedition was carried out onboard Research Vessel (R/V) *Aegaeo,* disposing the HOV submersible *Thetis*, ROV *Super Achilles*, SSS, SBP and DGPS. However, the mystery of the statues was not resolved. Instead, another shipwreck was located, at the area of Nisyros Island with a cargo of 18th – 19th century Çanakkale plates, manufactured at the southeastern Hellespont Straits (Dellaporta and Sakellariou 2000).

During 2000, a team of HIMA surveyed selected areas of Argolic Gulf using an ROV, offered by a member of the Institute. It was used to survey mainly at the area of Trikeri islets and reef for assessment of the zone between -50 to -100m, operated from a slowly moving vessel. Christos Agourides suggests in his article about the project, that the ROV is a useful tool, though not as effective as the direct inspection. Nevertheless he remarks that it can definitely be improved in combination with SSS, magnetometers and more accurate navigation equipment (Agourides 2002).

R/V *Aegaeo*, returned to the site of Nisyros shipwreck the following year, 2001, for better recording and also for testing new equipment. On board were not only the scientists of the two institutions but also collaborating teams from National Technological University of Athens (NTUA) and Massachusetts Institute of Technology (MIT) which used AUV's to examine the site (Dellaporta 2001, 2005). The test indicated that low frequency, inconsistent seafloor with rocks and the dispersed ancient cargos presented significant challenges. On the other hand AUVs competence could easily be increased by adding more equipment to them such as cameras, magnetometers, metal detectors and so on. Moreover, AUVs proved to be able to operate deeper than sonars or ROVs. K. Dellaporta (2001: 555) closed her relevant article with an accurate foresight: '*The results of Nisyros survey are positive as experience is concerned, because big part of marine archaeology will be based in the future to the use of technology of this kind*'.

During 2002, two expeditions of EUA and HCMR took place. The first one continued the survey at the area of Kalymnos. The mystery of the statues, however, had not found its solution yet. Instead, four unknown ancient shipwrecks and a shipwreck of the Second World War were located deploying the means of HCMR and the locals' knowledge about their nearby seafloor. The ancient shipwrecks were found as follows: at Pezontas bay, Kalymnos, a cargo with amphorae of Pseudo-Koan type, dated to 1st c. AD; at the area of Aspronisia or Kalapodhia islets near Leipsi a cargo of Knidian amphorae, dated to 2nd - 3rd c. AD; at the area of Skrofadhes islets near Leros a cargo with Rhrodian amphorae, dated to 1st c. BC; and at cape Pnigmenos, Kalymnos a cargo of Rhodian amphorae, dated to 2nd c. BC (Dellaporta 2002b; Dellaporta *et al.* 2003). Many hours were spend in front of the monitors checking with *Super Achilles* SSS targets and many dives of *Thetis* gave archaeologists the chance to survey through its glass dome and locate the assemblages of the remains of ancient trade.

The second campaign directed to the small island of Syrna near Astypalaia. In 2000, a Kalymnian sponge diver had delivered to the Ephorate more than 30000 coins, dated to the end of 3rd c. AD. The site where they came from lay at about 50m deep. The divers of EUA were trained just for

Sakellariou, 2009; Bailey & Sakellariou, 2012). In this palaeogeogrpahic reconstruction context, the Laboratory MGPO (UPatras) suggested an exciting theory regarding the migration of the Neanderthals from mainland to the islands Lefkada, Kefalonia and Zakynthos, 100.000 years ago, based on marine geophysical data collected from Ionian Sea and taking into account the sea level rise, the tectonic movements and the sedimentation rate (Ferentinos *et al.* 2012).
In the same framework over the last fifteen years (1999-todate) the Laboratory MGPO (UPatras) in collaboration with Centre d' Etudes Alexandrines (CEA) under the direction of Jean-Yves Empereur, the Hellenic Institute of Ancient and Medieval Alexandrian Studies (H.I.A.M.A.S) and the Supreme Council of Egyptian Antiquities, has conducted marine geophysical survey examining the subsidence of the coastal zone of Alexandria (Egypt) and resulting in the palaeogeographic reconstruction of the Hellenistic Alexandria (Chalari *et al.* 2009, Papatheodorou *et al.* 2015). The Laboratory MGPO in collaboration with The University of Zadar and C.N.R.S is conducting a marine remote sensing survey at Pag Island (Croatia) since 2012. The marine data processing proposed a scenario of the evolution of the Pag island coastline configuration over the last 10kyrs based on seismic stratigraphy and the mapping of palaeoshorelines features and led to the detection of many targets of potential archaeological interest (Soura *et al.* 2013). In 2014 the Laboratory MGPO carried out two marine surveys: (i) in Corsica, for small-scale studying of ancient shipwrecks using marine geophysical means, in collaboration with DRASSM (Département des Recherches Archéologiques Subaquatiques et Sous-marines) and (ii) in Lebanon, for the coastal palaeogeographic evolution of ancient Byblos, in collaboration with College de France.
Furthermore in May-June 2013 the HCMR in collaboration with the University of York in the frame of the ERC project DISPERSE conducted a multi-national, multi-disciplinary, marine geo-archaeological survey of the continental shelf of Farasan Islands, in the Saudi Arabian sector of the southern Red Sea (Bailey *et al*, 2013; Sakellariou *et al.*, 2015).

a quick visit to the point with their air tanks (Dellaporta 2000). Therefore, taking advantage of the specialist skills of HCMR, the scientists of the two institutions returned to the site for better recording. With the support of HCMR technical divers and the continuous inspection trough *Super Achilles* even an excavation was ventured, although without much success due to problems of the dredging system. More coins and a lead sarcophagus recovered from the site. Meanwhile, dives with *Thetis* at the neighboring area resulted in the location of three more shipwrecks, two dated to Roman times and one to the Byzantine times (Dellaporta 2002c, 2002c, 2005; Kourkoumelis and Micha 2002).

Another expedition to the southwestern and southeastern coast of Kalymnos, in 2002, that used a private company's (Assodivers) ROV for the inspection of shallow waters located the site of an anchorage and possible remains of a Mycenaean cargo at Cape Atzipas (Theodoulou 2002; Evaggelistis and Theodoulou 2003).

In 2003, three more missions of EUA and HCMR took place. The first one was carried out around Kastellorizo with the use of *Aegaeo's* equipment but without *Thetis*. Five unknown ancient shipwrecks were found (Cape St. Stephanos, Limenari bay, Psomi islet) and the known Byzantine one at Cape Pounentis was re-located and recorded (Dellaporta 2002a[2], 2003; Philotheou and Michaelidou 1986; Papanikola-Bakirtzi 1999). The second mission to the area of Chalkidiki with the full equipment of HCMR, included *Thetis* re-found and recorded the sites of post-Byzantine shipwreck of Sani and the Hellenistic one at Porto Koufo. At the area of Porto Koufo bay, 90 and 105m deep, the team located and recorded the remains of two Byzantine shipwrecks, with amphorae cargo dated to 9-11th c. AD. The one of the two shipwrecks was preserving apart of the cargo, two assemblages with its metal 'Y' shaped anchors (Mela 2003).

The third campaign was employed in collaboration with the Canadian Archaeological Institute at Athens and the Institute of Nautical Archaeology of Texas A&M University. The mission was actually one of a series of the *Persian War Shipwreck Survey* project aiming to location of possible remains of Persian Wars fleets. 2003 campaign's goal was the survey at the area of Mt Athos for locating war shipwrecks of Darius fleet under Mardonius command that were lost at the area in 492 BC. The mission was repeated the next year at the same area disposing further than the usual equipment (SSS, SPP, *Thetis* and *Super Achilles*) the ROV *Max Rover,* capable to operate in depths of 2000m, and in 2006 at the Skiathos-Magnesia straits and eastern Euboea. With the exception of a 4th c. BC shipwreck cargo with Mendean amphorae that was located at Mt Athos area, the only indication for Persian War remains was a '*sauroter*' (=lizard killer in ancient Greek, literally a secondary-butt spike on the spear shaft) that was recovered. S. Wachsmann (2004: 598) notes bad weather conditions and equipment failures (Wachsmann 2004, Wachsmann *et al.* 2005, see also: http://nautarch.tamu.edu/pwss/homepage [Accessed: 9 Febr. 2015]).

In 2003 a team of the University of Athens, Department of Geology, under the direction of the E. Hadjidaki surveying Meramvellou Gulf at northeastern Crete located near Pseira Islet a dispersed assemblage of Middle Minoan pottery (1900-1700 BC), that was interpreted as the first cargo found of a Minoan shipwreck. For the survey SSS, SBP and a Sea-Eye ROV were used (Hadjidaki 2004, 2005, 2008, 2011; Hadjidaki and Betancourt 2005/2006).

During 2004, three more expeditions were organized by EUA and HCMR. The first one was conducted at the area of Kythera. It was, in fact, a continuation of the collaboration with NTUA and MIT using their AUV's. Apart from some remains of a possible Second World War shipwreck and an anchor no other relics were found. The rocky seabed once again negatively affected the result. At the same time the ability of the AUV to operate insignificant depths and photographically record artifacts offsets the disadvantage presented by the complex bathymetry (Dellaporta 2004). The second area to be surveyed by EUA and HCMR, in collaboration with HIMA this time, was that of Salamis. Survey base was again R/V *Aegaeo* from where SSS and *Super Achilles* ROV were operated. Three stone piles, interpreted as ship ballast, along with dispersed broken pottery fields were found (Lolos *et al.* 2005-06). The third mission of *Aegaeo* started at the area of Samos Island, where several areas were surveyed and a Roman shipwreck, with a cargo of Rhodian amphorae, was located and recorded near Samiopoula islet. The team moved then to the Chios – Oinousses straits where a late Classical shipwreck with Chian and a second type of amphorae was found, at 67m of depth (Kourkoumelis and Evaggelistis 2004; Sakellariou *et al.* 2007). The discovery of this shipwreck demonstrated the efficiency of the combined use and integrated interpretation of SSS and SBP data in the geologically reasonable evaluation of the geophysical recordings and in distinguishing targets of potential archaeological interest like shipwrecks from rock outcrops on the seafloor (Sakellariou *et al.*, 2007). Even though *Thetis* could not operate due to a failure, two amphora samples were recovered with the use of *Super Achilles* arm that hooked them on a line. The shipwreck, almost intact was a perfect target for further investigation.

In September of 2004 EUA organized a Conference in Athens focusing on deep water archaeology and its perceptions titled '*Deep water archaeological research. Technology and perspectives*'. Among the participants was B. Foley researcher of Woods Hole Oceanographic Institution (WHOI). EUA asked for his institution support in the recording of the Chios-Oinousses shipwreck. His consensus led to another expedition of R/V *Aegaeo* to Chios, with the teams of the three institutions on board in 2005. On the ideal flat, sandy sea floor WHOI's team deployed an AUV and three transponders. The AUV was

[2] The mission was conducted in 2003. The article is published both in 2002 and 2003 *Archaeologikon Deltion* obviously by mistake.

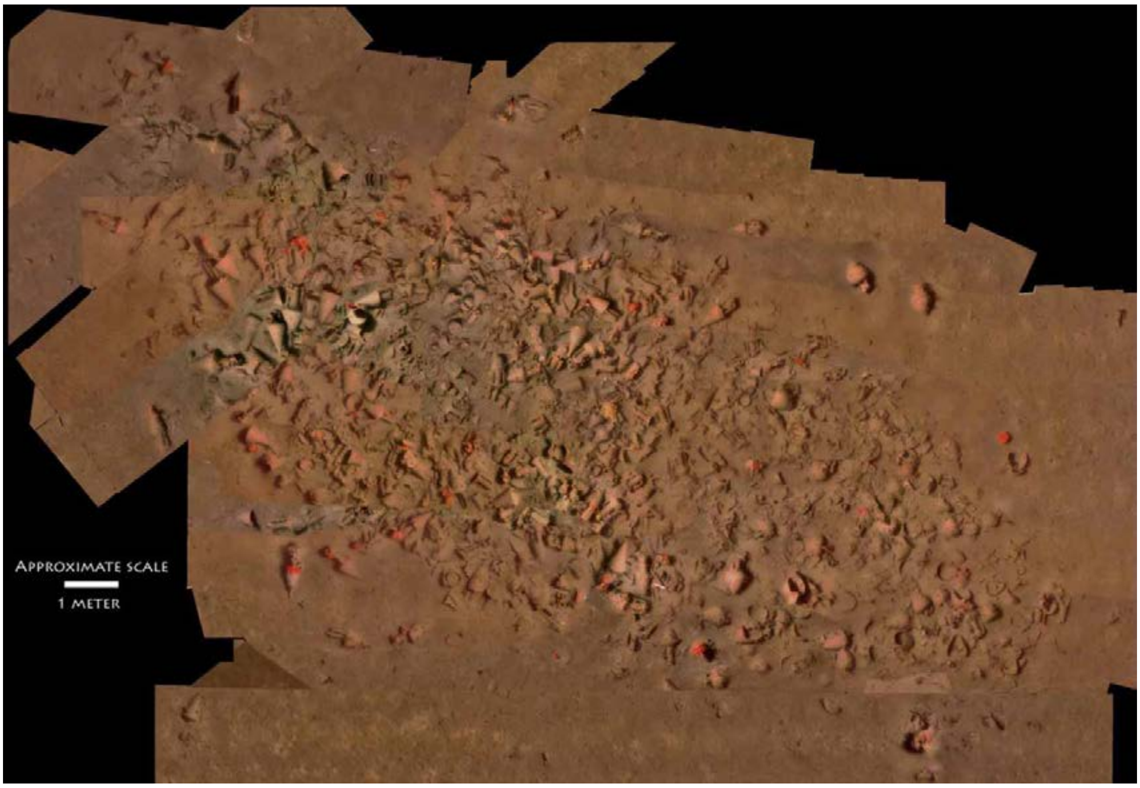

FIGURE 2: CHIOS – OINOUSSES CLASSICAL SHIPWRECK PHOTOMOSAIC AFTER FOLEY *ET AL.* 2009: 286

equipped with three types of sensors, navigation sensors for real-time positioning and guidance, optical and sonar sensors for mapping the seafloor and its features, and in situ chemical sensors for quantifying the oceanographic environment. A SSS, a MB and a digital camera with a synchronized strobe, all in a precisely navigated platform concluded the mapping of the wreck on an accurate 3D photo-mosaic in approximately 24 hours (Fig. 2). Besides the Classical wreck, a second Roman one was also mapped in western Chios and several other sites were investigated during the eight days of the mission. That was the first AUV photomosaic in a deep wreck site in Greece, second after Skerki bank (Foley *et al.* 2009, Dellaporta *et al.* 2005).

The same year EUA and HCMR surveyed an area off Kythnos Island from where a bronze statue of an athlete was delivered to the Ephorate by fishermen. Neither SSS nor SBP found any other statue. Instead, a cargo of amphorae, quite similar to the Chios – Oinousses one, as far as the provenance of the amphorae is concerned, was located at a depth of 500m. Archaeologist of EUA Paraskevi Micha was the first archaeologist diving in such a depth with *Thetis* to inspect it (Dellaporta *et al.* 2005).

The five year Memorandum came to end in 2005 with a last mission at the area of Santorini and Andros Islands where WHOI was also invited. During the campaign one more post-Byzantine shipwreck was found and recorded off Andros. A general report for the wrecks found during the years of EUA and HCMR cooperation can be found in P. Micha's relevant article (2005/06). Despite, the official end of the Five Years Memorandum the two institutions established a relation that is still alive and productive.

In 2006 Shelley Wachsmann of the Institute of Nautical Archaeology of Texas A&M University, along with HCMR and the Greek Institute for the Study of Ancient Alexandria conducted a research at international waters south of Crete that lasted for two years. R/V Aegaeo and its equipment were used. The result was to find several isolated amphorae (Wachsmann 2008, Wachsmann *et al.* 2009, Wachsmann 2010, see also: http://inadiscover.com/danaos/index.html [Accessed: 9 Febr. 2015])

That same year, the Laboratory MGPO (UPatras) along with University of Peloponnese carried out a quick survey at the front shore remains at cape Sounion. SSS and high resolution SBP data were collected resulting to a geomorphological map of the gulf based on the configuration of the seafloor stratigraphy and morphology. Unknown ancient remains were detected on the sonographs and correlated with the existing knowledge for the site (Papatheodorou *et al.* 2014).

The Finnish Institute at Athens in collaboration with EUA and the University of Peloponnese started also in 2007 a archaeological survey at the gulf of Glarentza, Kyllene for the recording of the remains of the Crusaders harbour (13-14th c.) and the location of the harbour of ancient Kyllene. Within the framework of the Kyllene Harbour Project, the Laboratory MGPO (UPatras) carried out a marine remote sensing survey at the submerged harbour and the surrounding area in order to reconstruct the coastal palaeogeography of the area (Pakkanen *et al.* 2010). Moreover, a marine magnetometer was tested in the very shallow waters of the harbour remains, the first time it has been employed for harbour studies in Greece (see:http://www.finninstitute.gr/en/kyllene and http://www.yppo.gr/5/g5111.jsp?obj_id=55513 [Accessed: 9 Febr. 2015]).

During 2005 mission to Chios and following missions in collaboration with WHOI significant discussions were had to determine the capabilities required for future surveys. The principal identified need was to transfer the capability of photo-mosaics from AUVs to human hand, given that most of the shipwrecks are situated in dive-able waters and rocky slopes where AUVs and SSS are not really effective. In this framework a joint team of EUA and WHOI returned to Chios in 2008, where, in ten days fifteen shipwreck sites, three of modern and twelve of ancient ships, dated from 7th century BC to Byzantine times, were recorded with high resolution digital images. In most of the cases, depending always in the dispersion of the cargo, photo mosaics gave the chance of a low cost, quick and accurate recording of the sites for better protection of them. Two Nikon D300 still cameras were used with ordinary SCUBA diving gear. The data were further processed by a photo-mosaic software (Theodoulou *et al.* 2009, Theodoulou *et al.* 2013).

2008 was in fact the year of photo-mosaics. EUA used the technique for shipwrecks at Northern Sporades (Preka-Alexandri 2008), when a more advanced technique including photogrammetry was conducted at Mazotos shipwreck in Cyprus by the University of Cyprus and members of HIMA (Demesticha and Vlachaki 2008; Demesticha 2010). The technique has been even more advanced recently in a 3D mapping, applied by the Cyprus University of Technology (Demesticha *et al.* 2014). In the context of applying magnetometer to ancient shipwreck sites, a very detailed geophysical survey was conducted in the Mazotos shipwreck by the Laboratory MGPO (UPatras). An intensive magnetometer survey carried out using Overhauser magnetometer in order to detect the buried part of the cargo. Preliminary results indicate that a significant part of the wreck extends beyond the southern end of the amphora assemblage (Geraga *et al.*, *in preparation*). A year later a team of EUA attempted the photo mosaicing of the 350m ancient breakwater of Mytilene commercial harbor at Epano Skala (Theodoulou 2011b). Photomosaics became from then on the usual process especially as far as shipwrecks are concerned (see for example Kourkoumelis and Tourtas 2014: 6).

Throughout 2009 two more projects started with technological interest at Pavlopetri, Laconia and Ramnous, Attica. At Pavlopetri, a submerged Mycenaean (~1200 BC) settlement, EUA collaborated with British School at Athens and Nottingham University, along with HCMR and the Australian Center for Field Robotics conducted a shallow water survey on shallow submerged archaeological remains. During 2010-2011 AUV, sector-scanning sonar, parametric MB and other techniques were used successfully for the detailed documentation and imaging of the site (Sakellariou *et al.* 2011, Henderson *et al.* 2013). Moreover, in the wider region of Pavlopetri, the Neapoli bay, a marine remote sensing survey took place for the palaeogeographic evolution of the coastal zone of bay for the last 20ka (Papatheodorou *et al.* 2013). The marine survey was conducted by the Laboratory MGPO (UPatras) in partnership with Faculty of History and Archaeology (National and Kapodestrian University of Athens, Prof. E. Mantzourani).

At Rhamnous, Attica in collaboration with The Archaeological Society, harbour expert David Blackman and geology prof. Michael Dermitzakis (University of Athens) started a geophysics exploration for the definition of the two harbours now located in partly silted basins (Petrakos 2009, 2010; Simossi 2009; see also: \http://www.archetai.gr/site/content.php?sel=165 [Accessed: 9 Febr. 2015]).

In that same year (2009), HIMA started a full scale underwater excavation at a Late Bronze Age shipwreck which is located off the north rocky slopes of Modi islet, Saronic Gulf. The following seasons (2010, 2011, 2012 and 2013) focused on the systematic underwater excavation and on the conservation and study of the material recovered (Agouridis 2011). In addition a systematic marine geoarchaeological survey was carried out by the Laboratory MGPO (UPatras) (2009, 2010 and 2013). The collected data suggest a scenario for the palaeogeographic evolution of Poros area and particularly the Modi islet while a number of potential archaeological targets has been detected (Geraga *et al.* 2015).

In 2010 EUA and WHOI collaborated in a survey at the area of Alonessos. The investigation focused on areas among the islands Alonessos, Kyra Panayia and Peristera and was carried out both by scuba diving and the Remus 100 AUV operations. The AUV is equipped with SSS and a low-light video camera. The project marked the first use of the Remus 100 AUV for underwater archaeological investigation. The AUV mapped an extensive area of 8 sq. kms, at depths ranging from 40 to 85m. A new type of scuba diver thruster (Pegasus Thrusters) was also used. The Pegasus thrusters attach directly to the divers' tanks, leaving their hands free for photography or other tasks. The thrusters significantly increased –at least doubling– the area searched by divers in the steep near-shore terrain unsuited to AUV survey. Finally, several shipwrecks were re-located and mapped. An amphora from a Byzantine shipwreck was recovered and samples were taken in order to detect DNA of the vessel's content, a technique that the team initiated after Chios-Oinousses shipwreck exploration in collaboration with Lund University (see: http://www.yppo.gr/2/g22.jsp?obj_id=41552 [Accessed: 9 Feb. 2015] and also Foley *et al.* 2012).

Remus 100 AUV of WHOI was also used the following year, 2011 at the Herakleion Gulf, Crete. HCMR was participating offering its research vessel *Alkyon*, as AUV's

Figure 3: AUV Remus 100 of WHOI onboard R/V Alkyon of HCMR in the port of Herakleion, Crete, 2011.

operational base, equipped with MB, SBP and CTD (Fig. 3). Moving beyond SCUBA diving scientists of EUA and WHOI were also trained in Closed Circuit Rebreather diving (CCR) which was the first use of this equipment for archaeology in Greece. About 30 sq. kilometers off Herakleion port and the south bays of Dhia Islet were surveyed and mapped as well as part of Ayia Pelagia Bay. Four unknown ancient shipwrecks, three modern ones and four anchorages were located and investigated along with the relocation of one of the shipwrecks that J. Cousteau partly excavated in 1976 at Dhia islet (Theodoulou 2013, see also: http://www.yppo.gr/2/g22.jsp?obj_id=49372 [Accessed: 9 Feb. 2015]).

The same team, diving CCRs, aided by diver propulsion vehicles (DPVs) circumnavigated Antikythera Island in 2012, surveying the zone down to the contour of -40min only eight operational days. Underwater digital still and video cameras, along with GoPro cameras mounted on DPVs were also used for complete recording of dives. Isolated anchors and pottery were found. In addition, the team located the area of the famous Antikythera Shipwreck a site with pottery and anchors of contemporary chronology and same geophysical configuration at -43m. The site had been initially considered as the Antikythera Shipwreck one, but the study proved later that this was probably not the site from where the Symian sponge divers recovered the statues in 1900. Thus, Antikythera Shipwreck site was still to be found (see: http://www.yppo.gr/2/g22.jsp?obj_id=52532 [Accessed: 9 Feb. 2015]).

In 2011 and 2012, the Laboratory MGPO (UPatras) carried out a marine geophysical survey at ancient harbours of Zea and Mounichia in collaboration of Zea Harbour Project (ZHP) (Lovén, 2011). The ZHP operates under the auspices of the Danish Institute at Athens, is directed by Dr. Bjørn Lovén and the project is supervised by the Ephorate of Underwater Antiquities and the 26th Ephorate of Prehistoric and Classical Antiquities. The marine geophysical survey defined the entrance and the geomorphology of the basins of the ancient harbours and detected many targets of potential archaeological significance (Papatheodorou *et al.* 2012).

In 2012, at the area of Frachthi cave, Eastern Peloponnese, EUA along with Swiss School of Archaeology in Greece carried out a survey including bathymetric mapping in order to locate remnants of the settlement that was linked with the cave during Late Neolithic era. The mapping was conducted with the use of a single beam echo sounder (see: http://www.yppo.gr/2/g22.jsp?obj_id=51492 [Accessed: 9 Feb. 2015]). The survey was continued in 2014 with the collaboration of HCMR and the University of Geneva. Two SBP (Boomer 0,7-3kHz and Chirp 2¬7kHz), a SSS (100/400kHz) and a MB (200/400kHz) were used on board the two-vessel campaign - HCMR's research vessel *Alkyon* and *Turannor Planet Solar*, a solar-powered catamaran - in August 2014, collecting high-resolution swath bathymetric, acoustic and subbottom profiling data for the reconstruction of the palaeo-enviroment of the area (see Sakellariou *et al.* 2015a; http://www.yppo.gr/2/g22.jsp?obj_id=58292 [Accessed: 10 Feb. 2015]

The third campaign of 2012, Poseidon Project, was conducted at the Ionian Sea, as to prove clearly the know-how that EUA and HCMR gained throughout their collaboration after 2000. The survey took place in order to examine the route of a natural gas pipeline programmed to link Greece and Italy. The interested company provided the two institutions with the MB, SSS and SBP data acquired during the detailed marine survey of the route conducted by FUGRO survey company the previous year. In a total area of 180 km length by1 km width the scientists of the two institutions prioritized twelve targets out of the thousands features recorded on the sonographs and interpreted them as of potential archaeological interest. Out of the twelve targets three proved to be shipwrecks. The first one was located at a depth of 1180m, quite well preserved with obvious amphorae, anchors, ballast and even part of the ship-shell. Two amphora necks were recovered with the use of the ROV arm. The second one was resting at 1375m, consisted of amphorae, cooking and table ware as well as part of the ballast. From the third one, laying at 1290m the ship-shell, iron anchors and several transport and table vessels were recorded. These three were the deepest shipwrecks ever found in Greek territorial waters (Kourkoumelis - Sakellariou 2015; Sakellariou *et al.* 2015b,see also: http://www.yppo.gr/2/g22.jsp?obj_id=50694 [Accessed: 9 Feb. 2015]).

In 2013 EUA and WHOI programmed their next mission to western Crete, namely Kissamos Gulf and the peninsulas of Rodhopos and Gramvousa, plus the neighboring Antikythera. Apart from diving survey equipment, a second team for geological and seismic investigation from WHOI was cooperating, using dual-mode sonar provided by corporate partner, EdgeTech (USA). The model 4600 integrating bathymetric and SSS data recorded an area of 65 km around the coasts of the two peninsulas to around 120 meters depth. The team also mapped the entire perimeter of Antikythera (30 km) with the sonar, with special attention to the area of Antikythera Shipwreck. After that, it became clear that there are two sites similar in configuration and artifacts but in different depths (-43 and 53m respectively), about 200m away from each other. Archaeological discoveries around the two peninsulas of western Crete included remnants of six ancient shipwrecks. Three of these wrecks date to the Roman period, including one with a load of about 100 tons of quarried stone building blocks. Two Byzantine-era wrecks located by the team carried amphorae. The final ancient wreck located during the project is marked by a cargo of mysterious perforated stones, function unknown. The team also documented the wreck of a modern steel vessel and the remains of a 19th century warship off southern Gramvousa islets. In addition to the shipwrecks, the team investigated five anchorages. These have been used from the Classical period to present, indicating long historical patterns of navigation through the rough waters of western Crete. The team investigated the seismically uplifted ancient port of Kissamos and studied the geological history of western Crete and Antikythera. The sonar map revealed submarine earthquake faults throughout the region (Theodoulou 2013).

As a result of the previous missions, Antikythera Shipwreck became the point of interest of the EUA and WHOI team's next mission in 2014. The University of Sydney, Australia supported the mission with its *Sirius* AUV (Fig. 4). Antikythera Shipwreck site was, thus, thoroughly mapped and a three-dimensional model of the wreck site was created based on bathymetric and photogrammetric data. The bathymetric data were inserted into a GIS data base, along with metal detection targets and observed sea floor artifacts to outline the dispersal of the cargo under the sediments. The harsh weather conditions permitted just four dives at the site, so the relationship between the two wrecks remains unanswered. Nevertheless, parts of the ship's rigging, a bronze spear of a statue and pottery was recovered from the site for further study. Members of the team were trained to pilot the Atmosphere Diving System (ADS), *Exosuit*, which was scheduled to dive on site and aid the research. *Exosuit*, was, finally, able to conduct just test dives in the area for only one day due to the hostile weather conditions (see: http://www.yppo.gr/2/g22.jsp?obj_id=58772 [Accessed: 9 Feb. 2015]). Excavation of the site have been scheduled for 2015.

The same year (2014), a marine remote sensing survey was carried out, in the bay around Mitrou islet near Atalante, by the Laboratory MGPO (UPatras) in co-operation with Prof. Aleydis Van de Moortel of the University of Tennessee (Department of Classics) under the directorship of Dr. A. Simossi, Director of the EUA. The marine remote sensing survey was designed: (i) to evaluate the coastal palaeogeographic evolution development around Mitrou islet and the surrounding area in prehistoric times by studying the seismic stratigraphy of the recent sediments and (ii) to detect possible targets (mainly subsurface) of potential archaeological interest. The very promising results of the first phase suggest the continuation of the survey for the next year (Simossi *et al.* 2015).

The year 2014 ended with EUA (Department of Crete) collaborating with the Institute of Mediterranean Studies (IMS) of the Foundation for Research and Technology in employing a geophysical survey at the area of Ayioi Theodoroi, Herakleion, Crete (Nirou/Kokkini Chani). A Late Minoan (~1500 BC) building on the coast was excavated in 1920s by S. Marinatos. A series of rocky islets that were used as a quarry and a large carving have been interpreted as a Minoan ship-shed lay just north of the building. The geophysics survey of the site started with Electric Resistance Tomography, Seismic Reflection and Seismic Tomography, along with Multiple Surface Wave Analysis. The survey was carried out in a 40X30m grid in the sea and 25X20m grid on shore. Preliminary results show that more buildings lay submerged and buried under the sand. The survey lasted for just three days and the goal of the two institutions is to undertake further research at this and other sites in the area (Papadopoulos *et al.* 2015).

5. Conclusions

The preceding overview indicates that new methods and equipment were adopted to increase the effectiveness and accuracy of underwater archaeological operations. That happened in accordance to the need to transform underwater exploration to a discipline, namely a branch of archaeological science, following the same professional principles and terms. What is inevitably unique in underwater archaeology and differentiates it from land archaeology is that it cannot really progress without adopting methods and using equipment from other sciences related to marine/underwater environment, oceanography, marine geology, etc. The process and mentality of both land and underwater archaeology are in fact the same. However, the approach of underwater sites, monuments or relics seeks methods and equipment that is under continuous revision in order to ensure improved safety, effectiveness, duration and space coverage. From this point of view underwater archaeology is obliged to follow the quick pace of technological change and development. Just a glance at the overview above is enough to shed some light on the rapid development in underwater archaeology techniques compared to land archaeology.

SCUBA diving equipment can give access to only the shallowest fraction of the seafloor, approximately 2% as estimated by Foley *et al.* (2009: 270). Eventually most navigation in the past took place in waters that allowed a

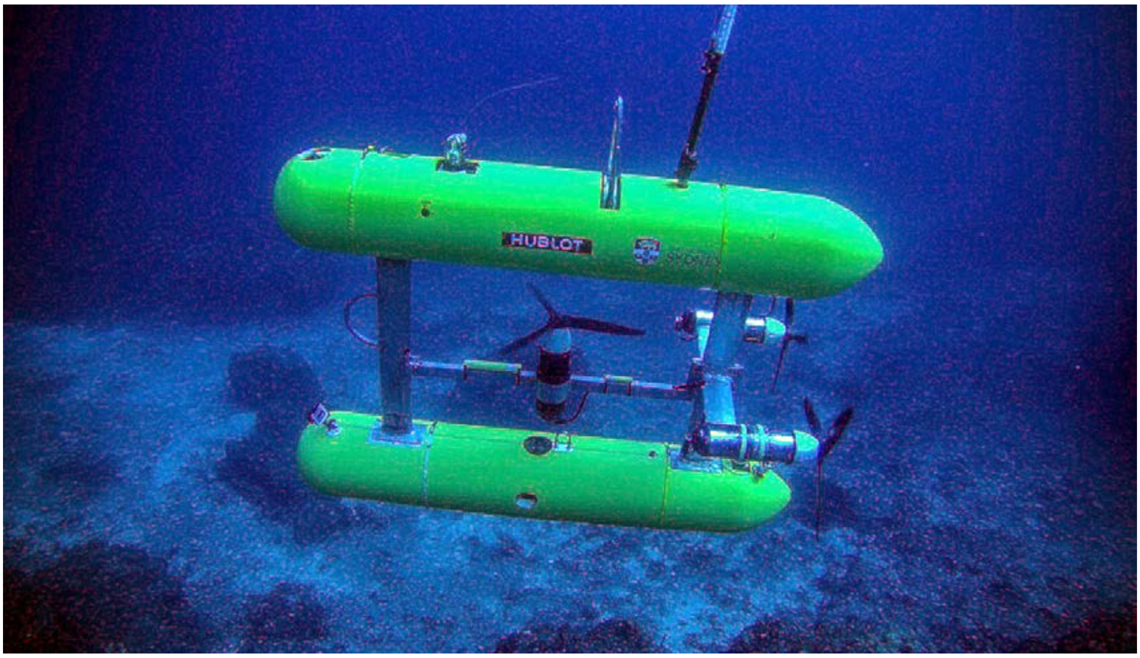

Figure 4: AUV Sirius of Sydney University mapping Antikythera shipwreck site, 2014.

view of the coast. Of course this does not mean that open water navigation was not existent, with Skerki bank and Ionian Sea shipwrecks being a proof of that. It is, therefore, reasonable to conclude that most of ancient shipwrecks, as well as submerged human structures remains, can be found in the SCUBA diving zone. Unfortunately this area is also the most affected by looting, waves, currents and siltation that negatively impact the condition of archaeological sites. In the adjacent zone to 1000m depth archaeological sites are less affected by natural factors, but still suffering by human activities, especially trawling for fishing. Thus, the deeper part of the ocean is the only area where shipwrecks can probably be found fully undisturbed from human and natural factors (see relevant discussion in Foley and Mindell 2002).

Given the above mentioned facts, it is clear that remote-sensing techniques (SSS, SBP, MG, MB) comprise a perfect tool for locating and studying undisturbed shipwreck remains in deep or very deep waters. These techniques, originally used for the study of the natural features of the seabed, proved in time to be powerful tools for archaeological survey, as well as mapping and recording (Ballard *et al.* 2000; Quinn *et al.* 2002b; Chalari *et al.* 2003; Blondel and Pouliquen 2004; Papatheodorou 2005; Sakellariou *et al.* 2006; Sakellariou *et al.* 2007; Sakellariou 2007a; Papatheodorou *et al.* 2001d, 2011). These methods have the advantage of extended depth range, fast survey speed and integration with high quality positioning data. In this perspective, even seemingly large costs for research vessels and equipment can easily be compared to those needed for similar operations when traditional methods are used. In our days access to reliable remote sensing equipment becomes cheaper and such surveys can be conducted from small vessels, diminishing vessel and crew costs. Such examples are the use of the EUA's inflatable vessel for Remus 100 AUV operations at Northern Sporades in 2010, the operations at Gulf of Herakleion, Crete in 2011 conducted from the small R/V *Alkyon* of HCMR and the mapping of Rodhopou and Gramvousa peninsulas along with Antikythera in 2013, where a cruise vessel 17.3m long was used for mapping operations (personal participation; for the same issue see also Dellaporta 2006). Another apparent advantage is the ability of locating even buried targets (Papatheodorou *et al.* 2005:95), thanks to SBP, MG or geophysics (Electric Resistance Tomography, Seismic Reflection and Seismic Tomography, etc.).

Visual observation from trained and experienced archaeologists is insuperable. HOVs and ADS can easily substitute divers giving archaeologists ample time for survey and recording in deep waters (Mallios 2006). ROVs are very productive when research identified targets. Far more effective are AUVs with incorporated MB, MG, etc. that can collect swiftly accurate data. Generally, the development and wide availability of photomosaic software has allowed sites to be recorded and modeled in 3D from a range of survey platforms much more accurately than was previously possible with SCUBA surveys using traditional archaeological methods. Modern archaeological diving and recording are also quite more effective allowing the safe extension of time and depth with Nitrox, Normoxic, Trimix or CCR diving.

It is apparent that any of the above mentioned means and technologies needs a multidisciplinary approach and the collaboration of archaeologists with other scientists, experts, technicians, divers and crews. This is really an excellent opportunity for underwater archaeology to take advantage of achievements from other scientific fields. Furthermore, taking under consideration that archaeology although intriguing is not a sector where financing can be easily secured, the opportunity to use technology from other disciplines is an added value (and vice-versa). Nevertheless, no matter if in deep or shallow waters high professional standards must be kept for both divers and vehicles, compared to land archaeology. This can be accomplished if certain principles are taken into consideration:

Careful planning of operations. Marine archaeological operations, must be well organized in order to succeed. Before fieldwork begins, a number of issues have to be very well-thought and the necessary preparations must include the securing of permissions, skilled personnel, collaborations, appropriate vessels and equipment, logistical support and management of results. Study of natural factors and history of the area under survey is also an important prerequisite.

Suitable instrumentation/equipment. Depending on the type of seabed to be surveyed, appropriate equipment must be chosen. For example, AUVs or SSS are good for flat, sandy seafloors but not as effective yet in rocky seabed or rocky coasts where ROVs, HOVs and divers are more effective. Depending on the depth that should be reached, the appropriate type of ROV, AUV or other kind of equipment or diving method must be selected.

Appropriate method to be used. For surveying flat sandy areas, AUVs and SSS along with SBP and MB can produce similar results. Nevertheless, AUVs can operate from smaller, less stable vessels. AUVs are more suitable for great depths and detailed recording of sites that have already been located. For surveying inclining areas ROV is a good alternative as they will consistently follow a particular contour. Any artifacts, which could be dispersed on a slope, would be eventually located in some pass. For visual target observation ROVs are excellent tools especially in deep waters. Diver and HOV's are very effective in shallow water and their effectiveness can be easily improved with DPVs, the correct diving equipment, as well as with appropriate cameras and video-cameras for fast recording.

Comparative data analysis. The nature of the construction and cargo of shipwrecks strongly affects the ability of geophysical and surveying techniques to distinguish them from the sea floor. Modern or pre-modern metal shipwrecks and medieval shipwrecks with cannons are easily identifiable due to their strong contrast from geological materials. In contrast, ancient shipwrecks often contain ceramic or building materials which can be easily mistaken for rocks. In this case the use of MB or SBP enhances the ability of discerning natural seabed formations from amphorae and worked stones. This clearly indicates the importance of applying conventional marine geophysical methods when seeking underwater archaeological targets. Nevertheless, identification of targets seeks also comparison of their depiction with depictions of known sites.

Accurate navigation of sensors and vehicles. In the vast marine space any operation of sensors and vehicles need accurate and precise navigation so that areas searched and targets located can be plotted and re-found. DGPSs and tracking sensors for vehicles are the most suitable positioning systems as they are widely available and provide high accuracy.

Archaeological procedure. Lastly, it is important to note that when targets are located, recording of them must be detailed, precise and focus on both the artifacts and the geomorphic processes active of the site. Any well-established or innovative method and equipment used should not put artifacts or structures in any danger and has to be non-destructive and non-intrusive. In the event of an excavation, complete removal of an entire assemblage is not permitted. Parts of the sites/assemblages must stay intact to allow future generations to glimpse part of the site in its original condition and perhaps allow future scientists to apply more advance methods of surveying. The importance of this assumption is portrayed by the two subsequent campaigns in Dhia Islet, Crete. During 1976, Cousteau's team with the most advanced technology available of his age located four shipwrecks at the south side of the islet in a coast of 7 km, after a very thorough survey. At the same area in 2011, EUA and WHOI team with the assistance of modern technology located four more shipwrecks, making evident that new means can produce new results and that 'advance' is indeed a relevant term.

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Aerial Reconnaissance in Archaeology – from Archives to Digital Photogrammetry

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Abstract: Most human interactions with the landscape have left and continue leaving traces around us in different forms. Field boundaries, land divisions, monumental buildings and communication systems or water management infrastructures characterize our surroundings in a constantly changing multi-stratified environment. Whatever photograph we take, it captures a single moment, a specific time or it freezes a unique memory. If we look back to that photograph after some time, we are probably going to recognize the place we visited, the history of the monument in the background but also the renewed house close by. Aerial photographs do the same, just from a different perspective. It has been said that 'there is every possibility that a single aerial image will record information that spans time from the fraction of a second it was taken to millennia in the past' (Cowley and Palmer 2009:129). And the job of the photo-interpreter is to 'read' as many details as possible of that frame and to try and reconstruct a history behind it, making sense of images by constantly isolating and merging time phases, relative and (ideally) absolute chronology of the depicted objects as for a non-destructive archaeological excavation. Dating is not an easy task and it is usually strictly linked with the self-training and experience of the air-photo-interpreter (API for short). New technologies, sensors and software are today supporting and largely helping the interpretative process; this paper pinpoints some of the most important steps to achieve a possible understanding of the area under investigation, presenting an ideal bridge that spans from historical archives to digital photogrammetry.

Keywords: Aerial Remote Sensing, archive photographs, landscape archaeology, Remotely Piloted Aerial Systems (RPAS, also known as Unmanned Aerial Vehicles –UAV– or drones), photogrammetry.

The bird eye view of the pioneers

Aerial images have been taken since the very early times of photography around the second half of the 19th century. The eclectic Gaspard-Félix Tournachon (also known as Nadar, as he nicknamed himself), a bohemian artist and inventor open to new ideas and discoveries, can be considered as the first aerial photographer (1858) with his images of Paris from the basket of an ascendant balloon (Rosenblum 1997). Later, Nadar invested efforts in the creation of a larger balloon from which he could monitor enemy troops, photograph them, print the photographs while still in the air and send the prints to the ground for strategic countermeasures. The American Civil War also saw a massive use of balloons for surveillance and reconnaissance for both sides, but it is not known if a photograph was ever taken because no vertical or oblique aerial images have been found.

Various other 'platforms' were tested for aerial image acquisition with various fortunes: in 1889 Arthur Batut put a camera on a kite together with an altimeter (which would make it possible to scale the image) and a slow burning fuse for timing; the German Ludwig Rahrmann patented in 1891 a camera fitted inside a large caliber projectile to be fired high in the air (Newhall 1969:41); the Bavarian army first though of equipping carrier pigeons, already a vital part of military communications, with small light weight cameras with 30 seconds timer (Julius Neubronne patented the 'breast mounted pigeon camera' in 1903). The rapidly increasing interest and advances in technology in aerial photography made it possible for the first aerial motion pictures (https://www.youtube.com/watch?v=8osZHhkp-cM) to be recorded a few years later (April 24th , 1909), when Wilbur Wright demonstrated his 'heavier-than-air' aircraft invention before the King of Italy and shot a video at Centocelle Airport, Rome-Italy. In 1911, during the Balkan War, an aircraft flew over Ottoman lines for reconnaissance and identified targets were bombed the day after with dirigibles.

Between the two main events -the first airborne photograph and the first aerial video- sit the earliest experiments of aerial image capture for archaeological purposes: F. Stoltze documented the excavations at Persepolis in 1879 (Stolze 1882); G. Boni photographed the Roman forum (Boni 1900, fig. 1–5; Piccarreta 1987:5) in 1899; Stonehenge was photographed for the first time from above in 1906 by R.H. Sharpe. A few years later, pioneering works with aerial photographs for the documentation of the complex archaeology of Rome was translated in a manual with theoretic principles, required equipment, practical background and techniques for an aerial survey. Here the topographic reconstruction with aerial photography is defined as a mean to achieve an 'objective portrait of the landscape' (Tardivo 1911:89–90).

Despite these early attempts of a systematic use of aerial photography in archaeology, the main driving force for collecting aerial images was intelligence. The First World War was indeed the occasion for the development of systematic air-photo-interpretation, often with makeshift

Figure 1: Dummy Sherman tanks in the Anzio bridgehead (Italy, 1944). War Office - Second World War Official Collection at Imperial War Museum (http://www.iwm.org.uk/collections/item/object/205204567, 205204568 and 205204641)

darkroom facilities being built in the very proximities of airfields (Shepherd *et al.* 2012, fig. 12, 13, 14). In this way reconnaissance flights could document the state of art of the targets to be bombed the following days after a quick photo-printing and military interpretation. Such an aerial reconnaissance was so much in use that even specific dummy items were built and positioned on the ground to trick air-photo-interpreter (see examples in Fig. 1).

The large amount of aerial images collected during the two World Wars made it possible to examine photographs from different perspectives and for different purposes. Intelligence officers of the Royal Air Force, routinely dealing with countless vertical frames, started to notice interesting 'lines' in specific field-plots. John Bredford, for instance among others, hypothesized a link between these lines and possible buried archaeological remains. These traces were indeed indirect indicators of archaeological remains due to localized differences in soil moisture or composition, or to local micro-topography (see lately Brophy and Cowley 2005)

Archaeologists tried to enter the loop of military aerial reconnaissance by commissioning –when and where possible– targeted flight (or deviations from planned flight track) over ongoing archaeological excavations or areas of interest: it is the case of Troy in 1915, Macedonia between 1916 and 1919, Palestine and Sinai in 1919, Mesopotamia and Syria again in 1919. On the other side, many archaeologists were employed as intelligence air photo interpreters during the war, and sometimes they were able to make successful requests to the Air Forces for reconnaissance flights to record (mainly) crop-marks.

The discipline development was also boosted by the French priest Antoine Poidebard, with his systematic approach to aerial photography for understanding visibility principles (Poidebard 1934:36). He was among the first to demonstrate with an actual example the principle of a bird-eye view, noticing that sometimes traces or patterns are clearly visible during aerial survey but are not perceivable at ground level.

In general, the major development of the technique of aerial photo-interpretation took place between the two World Wars with a number of British, French and German scholars in Europe, the Middle East and the Mediterranean who all experimented with different methodological approaches.

The scientific bases for archaeological air-photo-interpretation were set, although most of the applications seemed to underline the potential of such an approach only in deserted or scarcely inhabited areas. British aviation at this time played an essential role in extending the applicability of the bird-eye view to complex stratified and densely populated contexts of Europe, starting in 1922 (Allen *et al.* 1984). The research of O.G.S. Crawford during the first half of the 20th century probably laid the foundations for the future development of aerial archaeology. Around the same period targeted excavations were undertaken as a form of ground-truthing (Alvisi, 1989:26, 39), looking for correspondences between traces identified on aerial photographs and archaeological structures. A particular merit of Crawford was his attitude of transferring his photo-interpretation directly to maps.

Photo-interpretation

From an overview on the foundations of aerial archaeology, the unsystematic approach of most archaeological discoveries in the early phases of the discipline is clear. Indeed, pioneer aerial archaeologists dealt largely with reconnaissance photographs that targeted specific sensitive or strategic military objectives and only incidentally captured features of archaeological or historic interest. This has been defined as the 'serendipity effect' (Brugioni 1989).

It is self-evident how a proper training in photo-interpretation was required and necessary for intelligence purposes. The same applies to archaeological interpretation of aerial images, whether black and white prints from archive collections or recently acquired digital raw files. Recent neurological studies tried to identify the cortical circuits critically involved in extracting signals and discriminating features in aerial reconnaissance, and they determined how training modifies these circuits (Chang *et al.* 2014). In other words, as Andrew Welchman says, 'by analogy to the World War II analysts, the parietal cortex helped them spot suspect objects while the ventral cortex helped them distinguish the weapons from the pylons. But training these operatives to identify the weapons will have improved their ability to spot potential weapons in the first place' (University of Cambridge 2014).

And although training is very important in archaeological photo-interpretation (it was definitely more important in war time for other reasons), at the point that specific units (such as the well-known 'RAF Chicksands', the Cambridge University Committee for Aerial Photography –CUCAP– and the RCHME's Air Photography Unit or the Italian *Scuola di Aerocooperazione* at Guidonia) were created for this purpose (Downing 2011), 'specialist knowledge comes from a specialist background and is able to produce specialist output' (Cowley and Palmer 2009:130).

All images come with some level of intrinsic bias, the knowledge of which should be part of the interpretation as well. Indeed, aerial archaeology draws mainly on two different kinds of aerial photographs: oblique and vertical. The first, most common for archaeological aerial reconnaissance since the 1930s, are generally taken with hand-held cameras with a kind of observer-directed ratio. The latter, with longer tradition, are generally taken with automated cameras fixed in position within the aircraft, the lens pointing straight down at the ground (on this topic, read 'The vertical debate' in Verhoeven *et al.* 2013:33). Although oblique photographs (or just 'obliques') are certainly more biased, because of the photographer selection (or the pilot's ability to put the airplane where the photographer would need), also vertical images (or 'verticals') are the result of a selection and they respond to different goals (Brophy 2005). Aerial photographs taken by archaeologists are records of things understood at the moment of photography to be of heritage significance, and these concerns should be considered also during the image interpretation.

A very important synthesis, on the actual debate on aerial archaeology as a research method on its own, has been made by C. Musson: 'it has sometimes been argued that the techniques (namely API, Air-Photo-Interpretation) which are so successful north of the Alps will […] only work for a small proportion of the landscape, that they will not work because the ground is under cultivation, or the wrong kind of cultivation, […] that free-ranging survey will simply produce more sites […], that cropmarks reveal little about the function or date of the sites they represent […] And so on, and so on. All of these objections are true to one extent or another, but similar things can be said about every other method of archaeological investigation. In reality no individual technique gives us better than 'peepholes on the past'' (Musson *et al.* 2013: 43).

By contrast, especially for endangered past (or even present) landscapes, recording from the air at defined intervals is the only realistic means of documenting traces from their rapid and irreversible change. There are also ancient sites that survive almost exclusively as traces visible only from above. Modern computer technologies (see later) may also provide unique information based on the measurable landscape's transformations across time. At the same time, the availability of new and more affordable platforms for photo-capturing (such as the remotely piloted aerial systems, or RPAS) should help achieving cultural heritage monitoring and change detection analysis on larger scale.

Aerial imagery: from archives to 3d models

Although aerial archaeology is commonly associated with airborne cameras, most effort occurs on the ground and indoors, making the most of imagery (mostly in sequences across space and -ideally- time) that is years or even decades old. Aerial photo interpretation (API) for archaeology is concerned with attention to detail and in the continuous exercise of (trained or 'informed') judgment within a framework of systematic procedures (Fig. 2).

This protocol should start from correct archiving procedure, keeping in good account the following requirements:

- uniform and consistent archiving structure
- separation between raw and edited data
- objective information separated by interpretative deduction
- complete metadata (possibly in software independent format, such as txt or xml)

The above minimum level of documentation is often essential although hard to achieve, but it may be easily sided by supplementary information, when available, from characteristics and state of conservation of the source data to the mathematical algorithms which were used to process individual images. The important note to stress is that some types of documentation are absolutely 'essential' while other types are only 'recommended', and a good database should consider a modular structure that will mirror the above schema and should be open to possible technological developments. For example, single overlapping images may be processed in photogrammetry to generate new images, such as orthophoto and Digital Terrain Model (DTM): these new records, although not being properly raw data (because derived from processing of other data), can be treated as raw only if properly and extensively described (source images used – with link to their metadata –, level of interpolation, algorithm used to generate the surface, type of seamless merging for single frames, draping method and so on). No special difference should be made between archive photographs and newly acquired images, since every photograph taken today, in this sense, becomes an immediate historical record as much as the images of World War II. One advantage of new imagery is undoubtedly their native digital format and

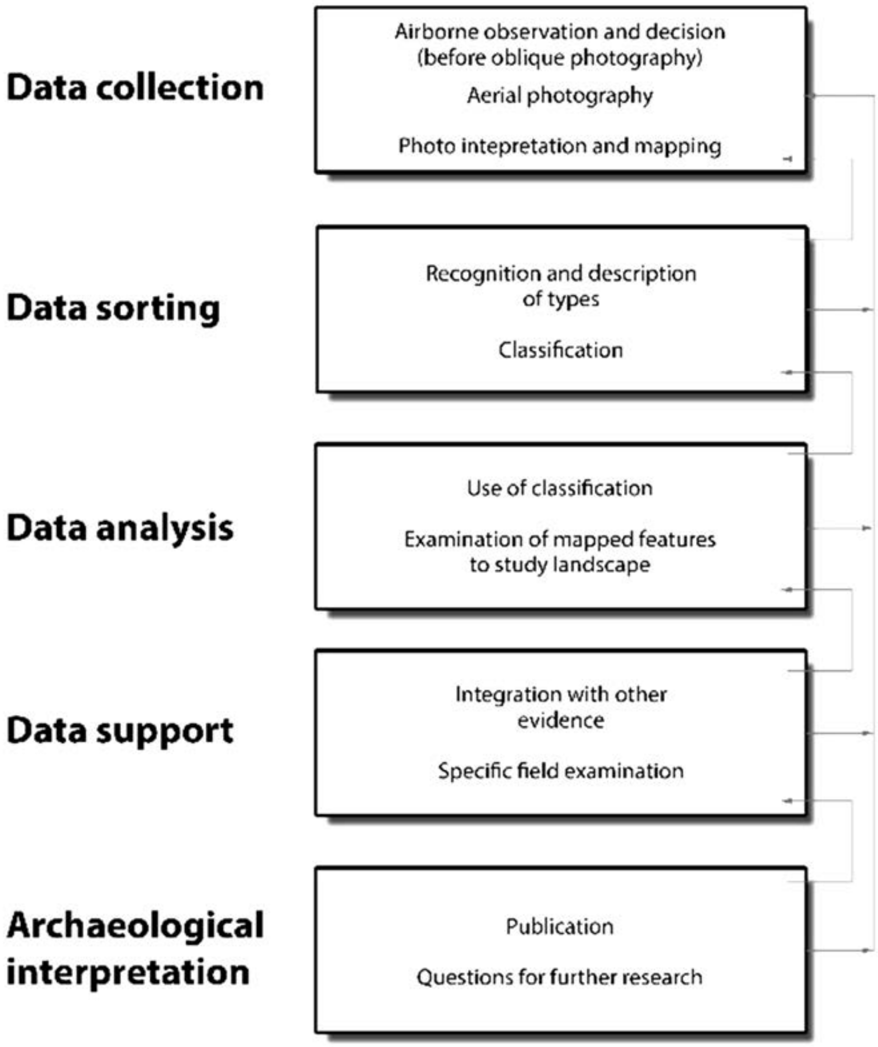

Figure 2: Diagram showing the workflow connecting aerial photographs to archaeology in a continuous flux. (Adapted from Musson *et al.* 2013:, fig. 9.2).

the added value of EXIF (Exchangeable image file format) metadata.

As mentioned above, the main (but not unique) source of information for API comes in two shapes: vertical and oblique photographs. Obliques are generally taken with hand-held cameras, whilst verticals are generally taken with automated fixed or gyro-stabilized cameras mounted (or housed) on flying platforms, pointing vertically at the ground. Because of budgetary or military (or other sort of) restrictions, new oblique photographs may be more hardly obtainable. At the same time, they are not always indispensable since most likely any country has available or has access to archive historical images, at least for part of the territory. Chances are that also other neighboring countries (involved in international conflicts or systematic mapping programs) may hold or share part of the collections for specific areas (see for instance the NARA archive in USA).

There is not a unique way of starting a photo-interpretative session. Below, a parallel with other visual work exam is suggested. When approaching a piece of art, for example, a critical method should consider the following:

- commission/sponsor: who promotes or wants the creation of the specific product;
- message/motivation: what is the message that the artefact should transmit to the recipient;
- recipient: who is going to benefit from the product;
- context: spatio-temporal situation in which all the above take place;
- medium: what is the support that permits the transmission of the message to the recipient.

Aerial photography should be approached the same way, with open mind about its potential but with a clear consciousness of its limitation. In the specific case, most of the verticals were commissioned by army or national geographic institutes (commission/sponsor); they were needed for monitoring sensitive areas (complex of

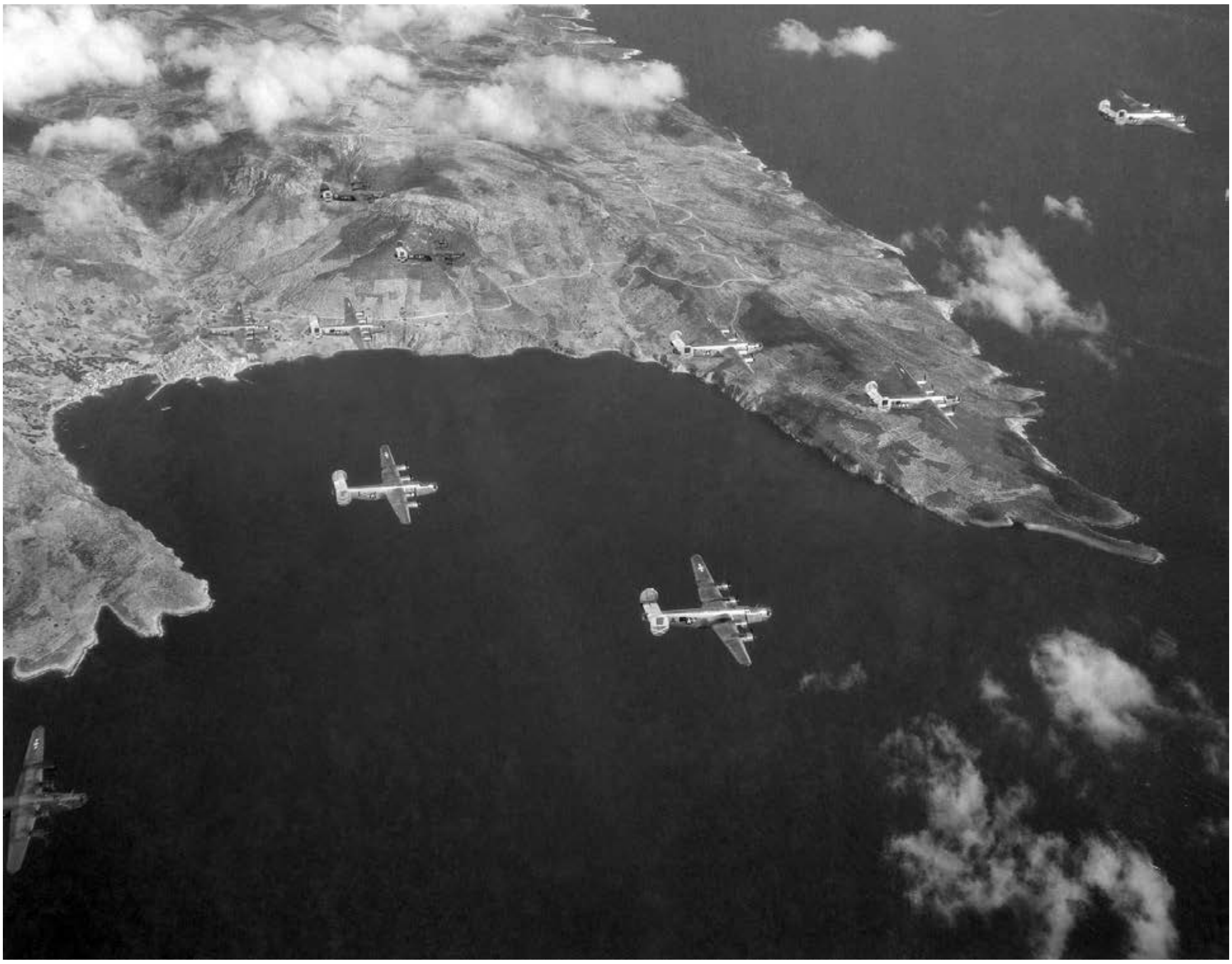

Figure 3: Air-to-air oblique photograph of Komiza (Croatia) coastline with the 485th Bomb Group fleet returning to Venosa (Italy) airfield from a mission during WWII.
(Courtesy of the 485th Bomb Group, Laura Sharpe)

buildings or large communication infrastructures such as roads, bridges, airports, ports or coastlines in general) or for mapping the entire territory (thanks to photographs overlapping and analogue photogrammetry); photographs were given to army's photo-interpreter specialists or mapping experts (recipient); images were mostly shot during the First and Second World War (context), so they depict a landscape still not so much affected by the agrarian revolution (with the introduction of large cultivation machinery and deep ploughing) that started with the 1950s and 1960s. It is more likely that obliques are taken by archaeologists (commission/sponsor) or for archaeological purposes (message/motivation), although there are countless examples of non-archaeological oblique photographs such as the air-to-air photographs (Fig. 3).

Verticals and obliques each have their merits and limitations, neither being a substitute for the other. They are most effective when used in combination, each offsetting the limitations of the other. Even their available format, digital or printed, doesn't necessarily equate better or worse image. Printed aerial photographs from film cameras normally provide more readable outputs than (and are often preferable to) their digital scanned version, even when the scanning has been done with professional photogrammetric drum scanners. It has been calculated than a 35mm film can equate the resolution of digital camera of between 12 and 20 Megapixels (Clark 2008, Vitale 2009).

Based on the consolidated teaching experience from the Aerial Archaeology Research Group and (more recently) from the training schools organized in the framework of ArchaeoLandscapes Europe, Rog Palmer proposed a few basic questions to be answered to achieve a good understanding of the methodology and (finally) of the landscape itself (for the example he proposes, Palmer 2010:284). He suggested, after the description of the main component in the specific photograph have been attempted, to answer the following: A) what time of year do you think the photograph was taken? B) And what was the time of day? C) Can you see any shape to the ground? Are there

Table 1: Detailed comparison of dpi resolutions and pixels measures. (Adapted from Linder 2006:28).

Resolution [dpi]	**150**	**300**	**600**	**1200**	**2400**	**4800**
Image size ca. [MB]	**2**	**8**	**32**	**128**	**512**	**2018**
Photo scale						
1: 5000	0.847	0.423	0.212	0.106	0.053	0.026
1: 7500	1.270	0.635	0.318	0.159	0.079	0.040
1:10000	1.693	0.847	0.423	0.212	0.106	0.053
1:12500	2.117	1.058	0.529	0.265	0.133	0.066
1:15000	2.540	1.270	0.635	0.317	0.159	0.079
1:17500	2.963	1.482	0.741	0.370	0.175	0.093
1:20000	3.386	1.693	0.846	0.424	0.212	0.106
1:25000	4.233	2.117	1.058	0.529	0.265	0.132
1:30000	5.080	2.540	1.270	0.634	0.318	0.159
1:40000	6.772	3.386	1.693	0.846	0.424	0.212
1:50000	8.466	4.234	2.116	1.059	0.530	0.265
	Pixel size in terrain units ca. [m]					

high or low places? And so on. This assisted photo-reading exercise exemplifies the need for ‘learning to see’ and how one can train him/herself to extract information from a single frame.

The current practice of API has an immediate and sometimes essential link with Geographical Information Systems (GIS), because of the essence of the depicted landscape being geographically located, oriented and scaled. For the same reason, most modern aerial photo-archives make use of web-GIS system to allow users, looking for historical aerial coverage for their area of interest, to topographically explore the database with polygon or toponym/punctual spatial query. If the GIS is not available for online users, an enquiry can normally be submitted on the base of geographical maps or (more recently) Google Earth files (KML or KMZ format).

Once all the archives have been explored for material of interest (as said, also other countries involved in the world conflicts may hold parallel collections of photographs), according to the specific budget and goals of the project, images can be acquired. Special attention should be given to the following: it is essential (although not always allowed or possible) to view the original images before ordering anything. Screen previews of the prints may not be sufficient to appreciate the real potential of the area. They may also give the impression of ‘false positives’ or they may show traces potentially belonging to archaeological remains but instead being the result of pixel redundancies; finally, original prints may have been scanned for screen preview with sunlight in incorrect direction (for example, in order to facilitate the reading of image IDs on the photo frame, the North may be actually on the right hand side): if photographs are not properly oriented during visualization (e.g. with light casting from top-left corner), they may provide sort of optical illusions, with mountains perceived as canyons (Palmer 2010:24.3).

The choice of which image to select is not an easy task, since it is sometimes hard to define a ‘reasonable’ area around the point of interest. Roads are normally done to connect far away locations; modern administrative divisions do not always match with historical ones; modern coastline does not necessarily match the one of some decades ago and so on. The above are typical cases where the definition of the area of interest, or the choice of the minimum number of photographs to be acquired, becomes hard.

As a general direction, the level of details the photographs may potentially contain, constitutes a valid support for first image selection. Vertical photographs are normally recorded with approximate indication of scale to the ground or altitude of the airplane: large scale (usually available scale 1:3.000, 1:5.000, 1:6.000) depict smaller portions of lands with potential of representing larger number of details; small scale (such as 1:15.000 or 1:45.000) shows entire regions and may be optimal for larger pattern recognition.

Since most of the aerial images are normally processed in digital environment, it may be important to considering also the above Table 1.

Another factor to consider when selecting the appropriate photographs to collect in specific scale, is the presence of landmarks and control points to be used for photographs geo-referencing and thereafter mapping. Stereoscopic view is also an important (if not essential) way of understanding the landscape, thus if possible it is always a good practice to acquire stereo pairs of images (if not entire stripes, see below about photogrammetry). Indeed 'stereoscopic viewing may show a settlement to be located on a local high spot that is too slight to be visible on conventionally mapped contours, or specific site may be situated next to the deeper soil of a former watercourse' (Musson *et al.* 2013:213).

When a large set of images is available for the same area, a relatively easy step to undertake for the understanding of the specific landscape consists in mosaicking the individual frames into a single one. This is usually done by assigning precise coordinates to pixels in each image. Sometimes, ground coordinates can be measured in the field or they can be extracted by already geo-referenced ortho-photos or maps. When at least three points have been assigned to a single frame (more are normally required for not flat landscapes and anyway for better accuracy), an algorithm is applied to the image to match with the digitally depicted in GIS system. This operation has also the implicit goal of eliminating, minimizing or diminishing the lens distortions 'hidden' in any remotely sensed image. But if this is a relatively easy operation when dealing with almost flat terrains, the registration of vertical or oblique images to reflect a perfectly orthographic view of a hilly or mountainous landscape is a challenging task. No algorithm can accomplish a proper registration in such a condition, preserving the uniform quality of the input image.

This is where photogrammetry can really make a difference. Non-metric, off-the-shelf digital cameras (Waldhäusl and Ogleby 1994, D'Ayala and Smars 2003) can be often used to extract accurate and detailed 3D models of real-world objects at almost any height or platform, from orbiting satellite (aerial) to tripod (close-range photogrammetry). Aerial photogrammetry in particular takes advantage of the overlapping (usually around 60% forward and 30% sidewise) of large-format imagery to numerically recreate a portion of the earth in a virtual environment (Fig. 4).

Here, horizontal (X and Y or Longitude and Latitude) measurements can be made and recorded directly into a geospatial data file. Also the elevation of the same portion can be recorded, given that few basic conditions are met:

- a number of images with a certain degree of overlapping covers the area of interest;
- the precise coordinates of at least three points (Almagro 2001) are known;
- the above points can be identified in at least two adjacent images.

While the identification of the same feature (a crossroad, the corner of a building, the edge of a field-plot and so on) in neighboring overlapping images is quite an easy task for human-eye/brain, the same operation requires a complex set of procedures for the computer: it has to a) view, b) describe, c) match and d) convert two (or more) raster files (whether a still picture from digital camera or a scanned version of an old print) to obtain a three-dimensional reproduction of the depicted terrain. Indeed the 2D-to-3D conversion involves the branch of IT called Computer Vision.

In 1999 David Lowe, Canadian professor in Computer Science, discovered a way to 'give eyes to computer' and to allow it to sense and describe real world object from images (Lowe 1999). His approach, known under the acronym SIFT (Scale Invariant Feature Transform), converted in computer software and freely distributed online, became the base for large variants and improved algorithms for image matching (Cantoro 2012:759–760). These image descriptors have been differently exploited (Khvedchenia 2011, Wu *et al.* 2013) in several structure-from-motion applications: given the ability for humans to perceive the third dimension and the reciprocal size and position of object from different images converging to the brain during movements (ours or of the environment around us), computer vision tries to simulate this attitude by uniquely identifying an object in a scene and recognize the same object (through Euclidean distances computation) in the next one, having this way the possibility to track its position and reconstruct its size and location in 3D real world.

The growing availability of commercial and cost-effective or free photogrammetric software (in computer clouds online or for offline users processing), together with the higher resolution and quality of cheap digital cameras and high performance computers are between the main causes of the sudden spreading of 3D reconstructions of archaeological landscapes via photographs. The use of photogrammetry is often considered as a more efficient, less labor-intensive, and more cost-effective method of field 3D data collection than other types. The level of detail and accuracy that can be reached, can hardly match with other technologies (Birch 2006).

In recent years, the number of papers and reports on technical applications of photogrammetry in archaeology is quickly growing (Ioannidis *et al.* 2000, Guidi *et al.* 2009, Matsumoto and Ono 2009, Remondino 2011, Opitz and Nowlin 2012, Verhoeven *et al.* 2013 to name a few). In cultural heritage contexts, the applications are not only limited to new discoveries documentation but they extend to accurate reconstructions of earlier conservation status of specific artifacts (Gruen *et al.* 2003) or of past landscapes, making so this technology unrivaled and priceless.

With specific reference to landscape studies, aerial acquisitions are normally designed and planned according to the intended deliverable, with special attention to scale. The required final resolution dictates the height at which to fly according to a simple equation where scale is the result of the focal length divided by the flying height above terrain (Hussain and Bethel 2004). For example,

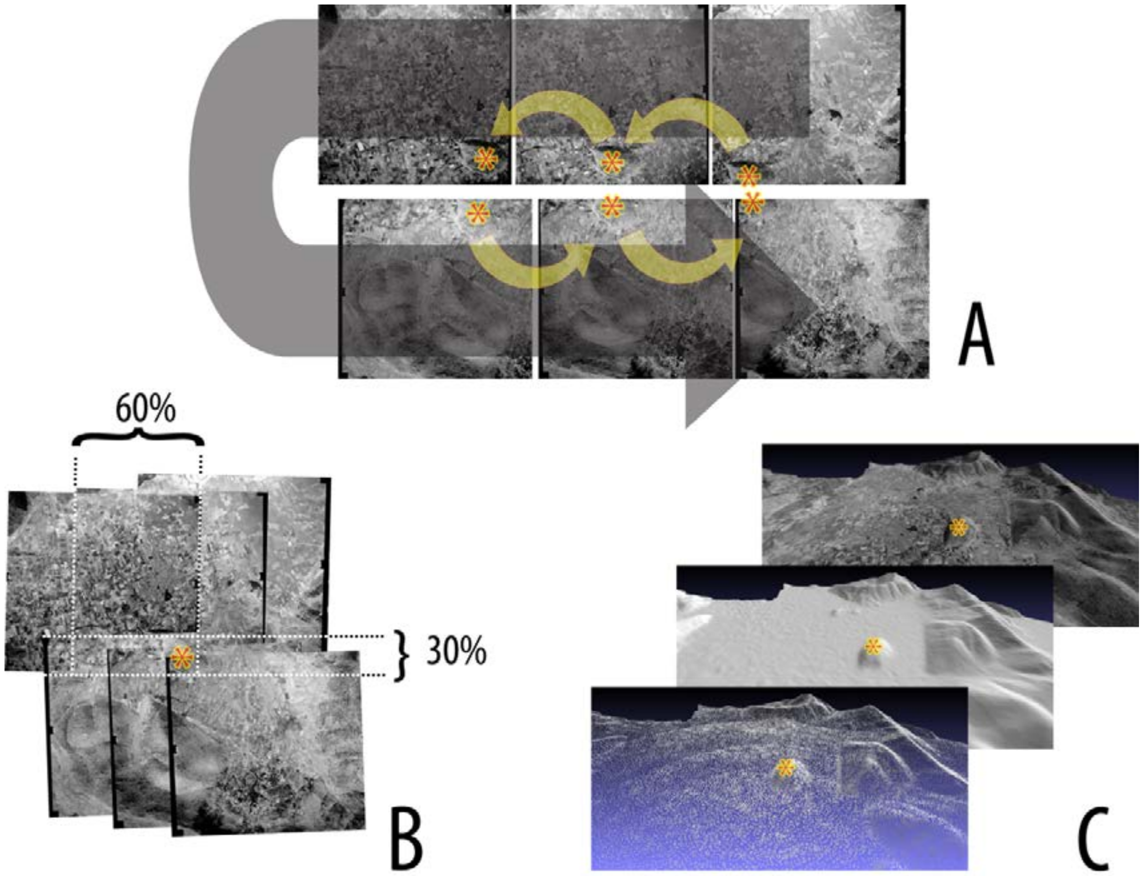

Figure 4: The photogrammetric process: a) image sortie from archives (the red star shows our reference point in each frame); b) visualization of the overlapping (normally around 60% in forward direction and 30% on the side); c) photogrammetric outputs (point-cloud, digital surface and textured surface/ortho-photo).

an airborne camera with a 6inch focal lens at 300 meters above the ground produces photography at 1:2.000 scale, allowing the detection of objects as small as 5cm. And certainly the easy accessibility and usability of remotely piloted devices makes the production of high-resolution output more and more affordable and on-demand. So, for instance, not only a specific photogrammetric model of an area can be created on specific season or time of the day, but also several models of the same area can be overlaid for change detection (Hesse 2014 and Stal *et al.* 2013) and conservation purposes.

The great potential of digital photogrammetry

Despite the fact that most of the API have been historically done on original prints or digital files without excessive image processing (with the exception of some expedients to improve the color contrasts at photo-printing stage), traces visibility may be easily enhanced with basic or specific image editing software (for the application of some methods, see for instance Musson *et al.* 2013 fig. 6.3 and 6.4). Interesting results can be obtained also thanks to channel mixing of visible and near-infrared images (for example, for the production of NDVI index to enhance vegetation' stresses visualization; see for instance the Infragram project and related material at the Public Laboratory http://infragram.org/). As said, numerous advantages may come from proper photogrammetric reconstruction, the most important of which being the possibility to convert in a few steps a printed photograph into a three-dimensional surface. This, in a way, simulates (or enhances) the traditional stereoscopic vision, with the additional possibility to remove the colors (texture) from the surface, especially useful in bare-land analysis.

The model of Fig. 5 shows a quick example of the many potentials embedded into photogrammetric approaches, such as the possibility to: obtain 3D measurements all over the site; get a digital elevation model with high and uniform ground resolution (also on the side of the small hill); create a single mosaic ortho-photo; visualize the 3D model as simple surface (without texture) and apply on it specific algorithms to enhance minor details; monitor the erosion of the site with repeated flights and overlapping photogrammetric reconstruction.

Given few ground control points from precision instruments, the entire photogrammetric digital model can be geo-referenced and so each pixel depicted in the images can get its X, Y and Z coordinates. At the same time, altimetry variations can be numerically studied or even enhanced or exaggerated through the use of specific filters. Subtle relief features on the ground may be missed or even filtered out during processing, but a number of algorithms may convert complex operation in easily obtained output. In cases like this, the simple air-photo-interpretation has to face a sort of algorithm output interpretation, which obviously requires the knowledge of the specific filter applied to the area of interest. These operations, quite common for laser scanning datasets, need some extra attention in photogrammetry because of the possibility that isolated non-real features are created during the processing due to light condition or lenses distortions. There is anyway, an important difference between aerial photogrammetry point-clouds and airborne laser scanning datasets. The ground resolution of modern laser scanning is normally calculated on an ideal flat surface. This means that the steepest the side of the hill (or of the artifact in general), the less points will be available to document its shape. Imagine for example the extreme case of a top-down LiDAR (Light Detection and Ranging or Laser Imaging Detection and Ranging) scanning of the city of Pisa in Italy: no declared ground resolution could ever be able to document the leaning side of the famous Tower because of its being out-of-plumb. An obvious solution to this problem could be to integrate an azimuthal with a ground laser scanning. On the contrary, oblique photographs, processed in photogrammetry, may be sufficient for the documentation of the entire object or at least of a larger part of it and with a homogeneous distribution of points.

If large number of overlapping images is good pre-requisite for correct three dimensional restitution of give object, it is also true that, to be correctly interpreted in real scale, all these photographs need to be correctly positioned to the ground with the minimum grade of distortion. Geo-referencing single frames may be a time consuming operation and results in hilly/mountainous fields may be often unsatisfactory. Also, some of the aerial photographs are normally taken to document specific details of the area of interest and they do not always keep into account the visibility of possible ground references for geo-registering: often only few frames can be properly geo-referenced onto available maps. This problem can be solved with two possible photogrammetric approaches, according to the specific typology of photographs. For example, if the images are taken with sufficient overlapping, they can be processed altogether to produce an intermediate product, such as an ortho-photo or a Digital Elevation Model (DEM). This product can be then geo-referenced onto given base map or reference system. If the dataset is made of isolated frames without overlapping, a possible road to follow consists in the automatic matching of each newly acquired image with a base ortho-photo (for both approaches, see the free software AutoGR-Toolkit (Cantoro 2012)). The successfully matched aerial image can then be overlaid into a GIS project or 'draped' on the top of a digital surface.

There are also times when a specific texture may trick our eyes and make us unable to appreciate the real shape of objects. The availability of un-textured models may help us reading the landscape on its real shape. Minor variations on surface may be highlighted with artificial shade. Specific shaded relief (such as the directional illumination from a point light source or specified azimuth and elevation) can be nowadays recreated in any GIS software so that shallow features may be highlighted in the final results.

Small but important changes may characterize the post-depositional life of archaeological artefacts. With photogrammetry the ability to detect (and graphically visualize by means of surface subtraction operations) small changes in soil movement can provide valuable insight in assessing effects of surface activities (Matthews *et al.* 2007). Alternatively, one single 3D model can be compared with a processed version of that same surface to enhance altimetry variations: typical examples are the 'trend removal' and the 'local relief model' filters, consisting in the subtraction of a smoothed (low-pass-filtered) version from the original DEM.

Conclusions

Aerial photography is widely considered valid and cost-effective support to the archaeological investigation, sometimes able to provide unique information not or hardly obtainable with other methods, sometimes completing the understanding of the wider area of investigation in combination with field research. The focus of aerial archaeology has broadened from a primary concern with crop-marks to a larger application, arriving till the documentation of 20th century constructions of the so-called industrial archaeology. In such applications, structures associated with the Second World War such as hangars, decoys, camps etc., are not mapped from photographs of their currently extant remains but from photographs taken while they were in use. More recently, historic aerial photographs have been employed also in new ways, such as: the creation of computer games set into WWII scenarios; aerial photographs draped on virtual models for 3D reconstruction of historical events; disputes on boundaries at precise dates; land-use change and cultural heritage monitoring; explosive ordnance disposal (for areas bombed during world conflicts). But aerial survey is not photography in general (see Rączkowski 2002:321–322, Baines 2009); certainly some aerial photographers intentionally captured some kind of artistic views, but on their own such images misrepresent aerial survey. The techniques of aerial survey are based on relations among images rather than on isolated photographs.

In a way, digital photogrammetry brings us to the consciousness of this character of aerial archaeology, as a discipline dealing with sequences of images. If the invention of photography gave visual form to 'time space compression', driving us to declare that 'time and space had ceased to exist' (Schwartz and Ryan 2003:2), digital photogrammetry (and stereoscopy before that) gives

Figure 5: Perspective view of the photogrammetrically reconstructed 3D model of the Byzantine Castle at Profitis Elias, Heraklion - Crete (Greece)

volume to space and materializes time, allowing time-related changes to be visualized and measured in a digital environment.

The increasing availability and diffusion of affordable photogrammetric suites gave a new direction to landscape studies and to the possibility to reconstruct pieces of lands just with the use of regular cameras (and few ground control points). In parallel, this development pushed also the needs for more affordable and 'real-time' images of specific contexts. This market niche was quickly occupied by new consumer grade devices for image capturing at low and mid-altitudes. The decreasing costs of auto-stabilizing and navigation devices for RPAS drastically compressed the learning curve for piloting such devices (generally estimated in 2 years of daily practice to get good command of remotely controlled helicopter), so that a complete system equipped with autopilot and GPS flight path programming capabilities can be acquired with few hundred euros in a ready-to-fly solution. Obviously, taking photographs above the ground does not equate with making aerial archaeology. And the possibility to survey an area any time of the year and with the most disparate sensors does not mean that aerial photography will ever substitute other field activities connected with archaeological research. It is definitely an important opportunity and an invaluable source of new information, but if this new data is not properly approached, processed and studied, it will be little more than a pretty picture for a screen presentation. Surely a picture is worth a thousand words, but we will still need someone to revert the process and get some words (information) from the specific photograph.

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On the Use of Satellite Remote Sensing in Archeology

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Abstract: Remote sensing has been successfully used in the past for the exposure of shallow buried antiquities. The detection of these remains is mainly based on the photo interpretation of high-resolution satellite or aerial imagery. This procedure is focused on the identification of crop marks using visible and near infrared (VNIR) spectrum response (e.g. vegetation indices), which is sensitive to vegetation stress. Although several studies are usually performed based on adequate spatial resolution datasets, the use of freely available satellite data or ground spectral signatures for the detection of crop marks is quite limited. This study presents three different approaches and case studies on the use of such remote sensing in archaeological applications. The first part introduces the so-call 'Archaeological Index', an index sensitive to crop marks developed for detecting archaeological antiquities based on the optimal spectral bands of satellite images. This is followed by an image-based method intended for the detection of crop marks using satellite data of inadequate spatial resolution (medium spatial resolution). Finally, the potential applications of the forthcoming European Space Agency's (ESA) satellite sensor, Sentinel-2, for archaeological studies is examined. The results outlined here reveal the potential use of satellite remote sensing and ground spectroscopy for the identification of buried archaeological remains through crop marks.

Keywords: Satellite Remote Sensing, Archaeology, crop marks, spectroscopy, Thessaly, Cyprus

Introduction

Archaeology is defined as the systematic approach for uncovering the human past and its environment. Nowadays, archaeology has moved from traditional systematic excavations and surveys to a multidisciplinary approach aiming to the collection of landscape data and image or samples processing. Modern studies in archaeology engage a series of other sciences such as geology, information systems, chemistry, statistics, etc. In the last decades remote sensing has received considerable attention since it can assist archaeological research, along with other sciences, in order to understand archaeological landscapes and detect unexcavated buried remains.

Remote sensing is the acquisition of information about an object or phenomenon without making any physical contact with the object (Levin 1999, Parcak 2009). According to Sabins (1997), remote sensing involves all the methods that allow the use of electromagnetic radiation in order to identify and detect various phenomena. Based on this definition, other techniques such as satellite remote sensing, aerial photography, geophysical surveys, ground spectroscopy or even terrestrial laser scanners, can be considered as remote sensing techniques.

Currently, the cultural heritage sector seeks innovative and cost effective tools for systematic monitoring to better understand cultural heritage sites, monuments and landscapes. In this framework, gathering data of vast areas can be time consuming and expensive, while sometimes data collection procedures might not be possible due to a lack of appropriate equipment and tools. Therefore, remote sensing may be used to minimize fieldwork, as well as to cover areas of large dimensions. In many parts of the world, several researchers have been able to identify crop marks related to buried archaeological remains using aerial and satellite images. However, as several researches have commented, such marks are difficult to be modeled and studied, since they constitute a complicated phenomenon (Kaimaris and Patias 2012, Agapiou *et al.* 2012b, 2012c, Winton and Horne 2010, Mills and Palmer 2007). Further details regarding how crop marks are formed as well as improvements of image analysis are needed in order to enhance the photo interpretation of images.

This study presents three different approaches for the use of satellite remote sensing in archaeological applications for the detection of crop marks. The first approach is focused on data mining for the extraction of the most suitable spectral regions which are sensitive to crop marks. The potentials of the new European Space Agency's (ESA) satellite sensor, Sentinel-2, for archaeological studies are examined in the second research approach. The third approach addresses the problem and illustrates an image-based method intended for the detection of crop marks using satellite data of inadequate spatial resolution. The overall methodology consists of seven separate steps. The method initially begins with two areas of interest preferably in close proximity to one another. The first area is characterized as the 'archaeological area under investigation' while the second is a known vegetated non-archaeological area.

In all case studies presented here, research has focused on the Neolithic tell settlements ('magoules') located in the

Thessalian plain of central Greece and in archaeological test fields developed in Cyprus. *Magoules* are typically low hills, one to five meters in height above the surrounding plain. Numerous *magoules* are dispersed throughout Thessaly and can be found within different kinds of vegetation. Furthermore, extensive field surveys took place in the area during the last years (Alexakis *et al.* 2009; 2011). The need for systematic monitoring of the spectral signatures of crop marks that relate to subsurface remains led to the creation of archaeological test fields in Cyprus (Agapiou *et al.* 2012c). For this purpose, local stone was placed at different depths and then covered with soil. Then, the topsoil was cultivated with dense vegetation (barley and wheat) in order to study the variations of the spectral signature of the crops as a result of the existence of subsurface remains. The main purpose of this field was to explore further characteristics of the spectral signature profiles of the crops throughout the phenological cycle of vegetation.

Archaeological index

The development of an Archaeological Index aims to enhance crop marks that relate to buried archaeological remains, since it records data from multispectral/ hyperspectral remote sensing images. For this reason spectral regions which are capable of distinguishing the spectral diversity of vegetation due to archaeological remains were examined. Such spectral regions can be used for hyperspectral satellite images while in a future step these characteristics can be implemented for sensors specifically designed for the detection of crop marks.

Initially, ground measurements were recorded in the test field sites in Cyprus during the complete phenological cycle of barley and wheat crops. In each campaign hyperspectral measurements were taken over the ‘archaeological control site’ and over ‘healthy vegetation’ from the surrounding area. In total more than twenty *in situ* spectroradiometric campaigns were performed using the GER 1500 spectroradiometer, during the sowing period until harvesting (i.e. complete phenological cycle). The GER 1500 instrument has the capability to record spectral signatures in the visible (Vis) and very near infrared (VNIR) part of the spectrum (450–900 nm). Moreover, this specific spectroradiometer can record electromagnetic radiation within a bandwidth sampling of ~1.5 nm. In total, more than 3000 ground measurements were collected over vegetation marks and the surrounding vegetated area (healthy area). A reference spectralon panel was also used in each campaign to measure the incoming solar radiation and therefore calibrate the *in situ* measurements during the campaigns.

After data collection, three main separability indices were evaluated using (a) Euclidean distance, (b) Mahalanobis distance and (c) Cosine similarity, in order to study the separability of reflectance values from ‘healthy vegetation’ and ‘archaeological areas’. The first method calculates the Euclidean distance between a pair of observations (i.e. healthy site and archaeological site) (Hastie and Tibshirani 1996), while the Mahalanobis distance exploits also the covariance matrix of the measurements (De Maesschalck *et al.* 2000). Finally the Cosine similarity refers to the similarity between two vectors by calculating the Cosine of the angle formed by these vectors (Kruse *et al.* 1993). The whole dataset from the two study areas (barley and wheat crops) was analysed separately and the final outcome was reached to similar conclusions regarding the optimum spectral regions where crop marks photointerpretation is maximized. Fig. 1 indicates the correlation coefficient between ‘healthy vegetation’ and ‘archaeological areas’ per wavelength.

Multispectral sensors sensitive to near infrared wavelengths are very promising in recording crop reflectance variations due to buried archaeological remains. This observation is already widely known for vegetation studies using the VNIR part of the spectrum. In addition, based on the results it was found that spectral regions around 700 nm and 800 nm (near infrared and red edge) are very promising for the detection of crop marks. These spectral regions demonstrated the highest separability (see Agapiou *et al.* 2012c). High separability values were also recorded and for the VNIR and blue part of the spectrum. However, the use of the blue part of the spectrum could be found very problematic for satellite images due to the Rayleigh scattering phenomenon. Therefore the Archaeological Index could follow the following function:

$$AI = f\,(p_{800,}\, p_{700})$$

Where

A.I.: Archaeological Index
p_{800}: reflectance at 800 nm
p_{700}: reflectance at 700 nm

Having taken into account the observations of the phenological cycles of barley and wheat crops, the Normalized Archaeological Index was evaluated in terms of interpretation using hyperspectral images (EO-1, Hyperion sensor) (see Agapiou *et al.* 2013a). The case study area of this application was the Thessalian plain in central Greece. In Figures 2-3 the results of this evaluation are presented. Besides Hyperion images, several other multispectral Landsat TM/ ETM images were used. Besides the Archaeological Index, other known image analysis techniques were also applied to the satellite images. A true colour composite (RGB) was constructed for Landsat images along with the NIR-R-G composite for both set of images (Hyperion and Landsat). Additionally the $NDVI_{multispectral}$ and $NDVI_{hyperspectral}$ indices were also evaluated. The Simple Ratio (SR) index which uses the characteristic curve of vegetation canopies at the red and near infrared spectrum (red edge) was applied. Finally, Tasseled Cap images and Principal Component Analysis (PCA) were tested. Figures 2 and 3 depicted that the proposed Archaeological Index distinguishes the Neolithic tell of ‘Anagennisi’ and ‘Stefanovikeio 5,’ in contrast to

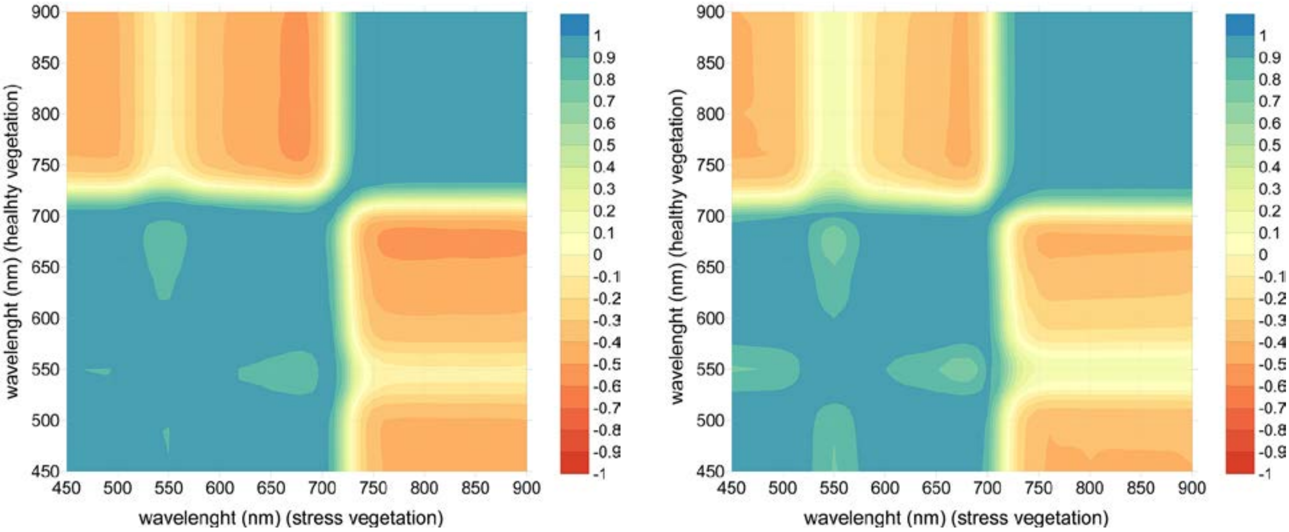


Figure 1. Correlation analysis (R^2) (450 -900 nm; visible- near infrared spectrum) of reflectance values from stress vegetation against reflectance of healthy vegetation from Alampra test field -barley crops- (left) and Acheleia case study -wheat crops- (right) (Agapiou *et al.* 2012c). High correlation values are indicated with blue colour while lower correlation colours are shown with red colour. Optimum regions are considered those which have the less correlation coefficient (i.e. higher variance of the initial dataset is explained)

any other analysis. Anagennisi had been inhabited during Middle and Late Neolithic period and Stefanovikeio 5 from Early to Late Neolithic period. Other tells were also examined with promising results. Each tell's crop mark was enhanced better after the application of the Archaeological Index and the trace of both tells was highlighted. In contrast, concerning the application of other techniques including pseudo colour composites, NDVI, SR, Tasseled Cap and PCA analysis, the Neolithic tells were not clearly visible and they were difficult to distinguish from the surrounding cultivated area. Indeed a circular crop mark was visible for both areas using the Archaeological Index while in several other indices and algorithms applied these crop marks could not be recognized. Several Landsat images were analysed in order to examine if the tells were able to be detected in different periods, without any result.

Hyperion hyperspectral images can better enhance the final outcome compared to the multispectral Landsat images, having the same spatial resolution (30 m). The analysis performed (PCA, Tasselled Cap) on Landsat 5 TM dataset resulted in very poor results similar to those reported in the same region by Alexakis (2009). To quantify the contrast between crop marks of the *magoules* and the surrounding area, a direct comparison was made for the different algorithms applied to the above images. Hence several measurements from the images were made both on the top of the *magoula* and the surrounding area. The results have shown that the proposed Archaeological Index was able to distinguish better the *magoules*, with a relative contrast of 27% and 60% compared to the surrounding area of the *magoulas* 'Anagennisi' and 'Stefanovikeio 5' respectively. Similarly, Simple Ratio's contrast was estimated only at 14% and 18%, while the NDVI hyperspectral was calculated to 8% and 44%. Finally the relative contrast for $NDVI_2$ hyperspectral index was estimated at 11% and 33%. These results are also compatible with visual interpretation. Concerning the Landsat images these were not examined since their interpretation was inconclusive, being unable to recognize traces of the *magoules*.

Development of an image based method for the detection of archaeological buried antiquities using multitemporal satellite imagery

In several archaeological investigations, there is a lack of accessibility of very high resolution multispectral satellite images while the area of interest may suffer from high cloud coverage at the particular time of acquisition that may be needed. Additionally, in archaeological research, the use of freely distributed archive data such as those of Landsat TM/ETM+, or data with low cost (e.g. CORONA), is essential in order to examine the geomorphology of the site before any significant changes due to human presence in the area (e.g. urban expansion). In this section an image-based approach for archaeological investigations is presented for the detection of crop marks using satellite data of inferior spatial resolution. The evaluation of crop marks is based on the comparison of spectral characteristics for two areas of 'archaeological site under investigation' (Site A) and 'vegetation site under investigation' (Site H). These sites are directly compared using spectral signatures, soil lines, and their phenological cycle characteristics. The approach aims to identify any spectral difference from Site A and Site H based on phenological observations in order to minimize this heterogeneous nature of crop marks.

The proposed methodology is based on a set of time-series multispectral satellite imagery taken during a complete phenological crop cycle (about 1 year). The overall

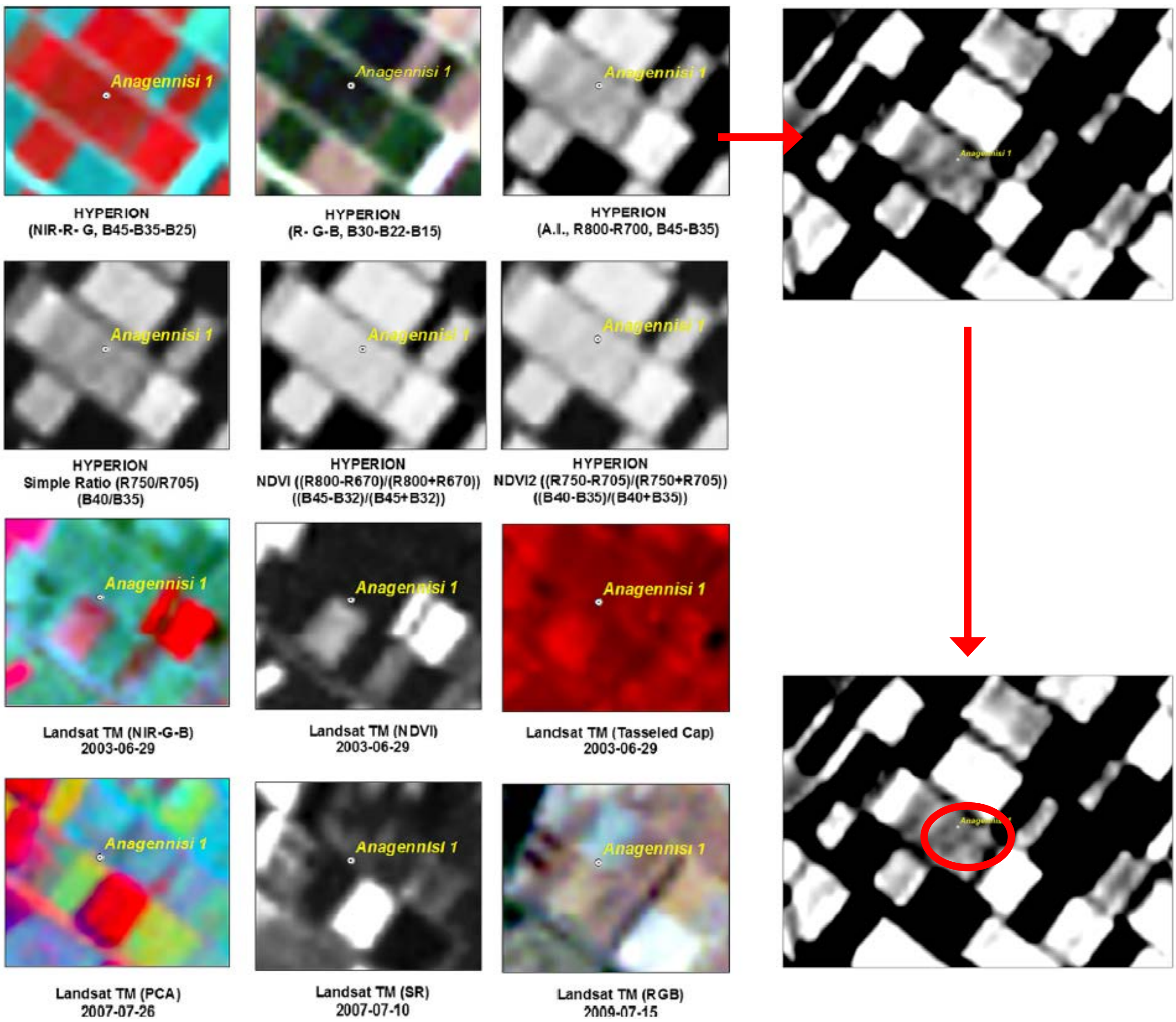


Figure 2. Results of the hyperspectral image of Hyperion (03-09-2001) and Landsat TM (29-06-2003/10-07-2007/26-07-2007/15-07-2009), for the archaeological site 'Anagennisi 1'. The application of the Archaeological Index (A.I.) is shown in the first row, third column. The date and the algorithm used for each image are mentioned below of the each image (Agapiou *et al.* 2013a). Although its medium resolution of Hyperion images (30 m pixel size) the circular crop mark was able to be detected using the Archaeological Index (right section of the figure)

methodology is summarized into seven steps, where two areas of interest are selected in the image (Site A and Site H). The methodology is presented below, where the first three steps (Steps 1–3) address the preprocessing steps of the satellite dataset, while Step 4 is focused on the selection of the two areas. Steps 5–7 concern the post-processing stages of the proposed methodology.

Step 1 - Geometric correction. The first step includes the geometric correction of the satellite images. Geometric correction is an important preprocessing step, essential for many image-based applications such as remote sensing. Raw satellite images usually contain significant geometric distortions. These distortions might be a result of the satellite sensor's velocity, earth curvature, atmosphere refraction, relief displacement, etc.

Step 2 - Radiometric correction. Radiometric correction is crucial to satellite images, since changes of illumination (e.g. earth-to-sun distance correction) and viewing geometry (e.g. sun-elevation correction) should be minimized in time-series datasets. Radiometric correction is usually applied in two different steps: first the conversion of the image's raw digital numbers (DN) to radiance units and then to reflectance.

Step 3 - Image-based atmospheric correction. Atmospheric correction is considered to be one of the most difficult techniques since the distributions and intensities of these effects are often inadequately known. Despite the variety of techniques, used to estimate the atmospheric effect, the atmospheric correction remains a hard task in the preprocessing of image data. As shown by several studies (Hadjimitsis, Clayton and Hope 2004, Hadjimitsis,

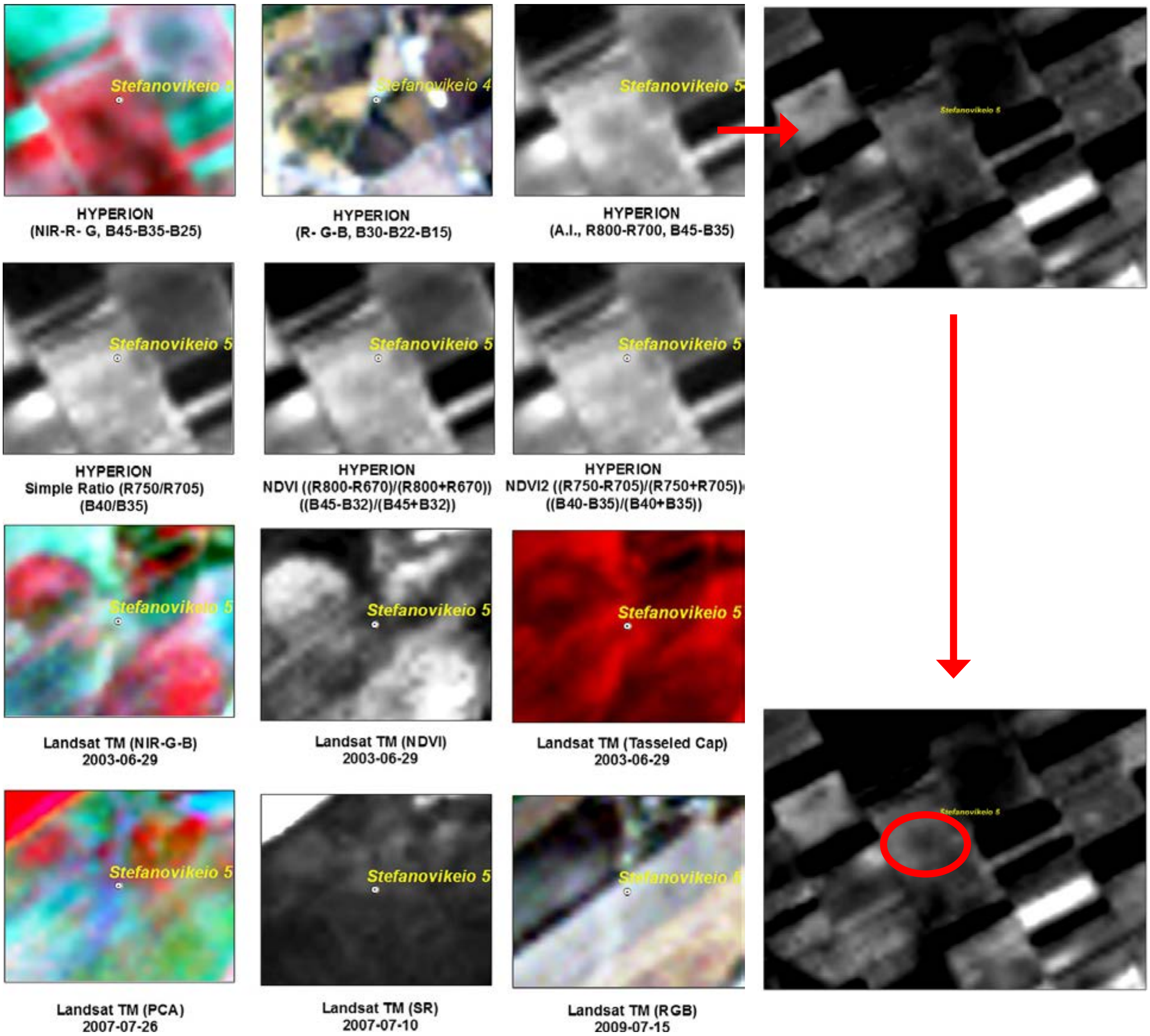


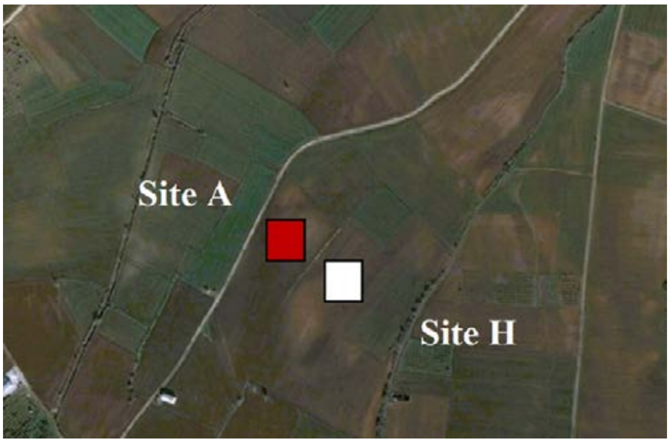
FIGURE 3. RESULTS OF THE HYPERSPECTRAL IMAGE OF HYPERION (19-09-2001) AND LANDSAT TM (29-06-2003/10-07-2007/26-07-2007/15-07-2009), FOR THE ARCHAEOLOGICAL SITE 'STEFANOVIKEIO 5'. THE APPLICATION OF THE ARCHAEOLOGICAL INDEX IS SHOWN IN THE FIRST ROW, THIRD COLUMN. THE DATE AND THE ALGORITHM USED FOR EACH IMAGE ARE MENTIONED BELOW OF THE EACH IMAGE (AGAPIOU *ET AL.* 2013A). ALTHOUGH ITS MEDIUM RESOLUTION OF HYPERION IMAGES (30 M PIXEL SIZE) THE CIRCULAR CROP MARK WAS ABLE TO BE DETECTED USING THE ARCHAEOLOGICAL INDEX (RIGHT SECTION OF THE FIGURE)

Clayton and Toulios 2010, Agapiou *et al.* 2011a), the darkest pixel (DP) atmospheric correction methodology can be easily applied either by selecting non-variant targets on the image or using dark targets (e.g. dams or reservoirs).

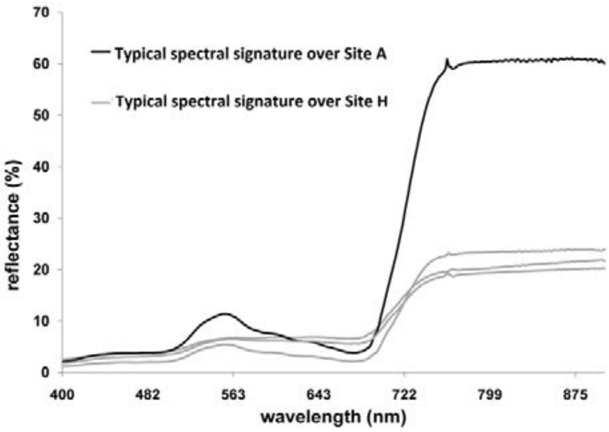
Step 4 - Selection of areas. Step 4 is considered to be the most critical of the proposed methodology. Two areas of interest are selected in the image: the first is the 'archaeological site under investigation' (Site A) while the second is a 'non-archaeological site under investigation' (Site H). Although this is a very simple step, further analysis should be performed before the selection of Site H in order to verify that both sites have similar soil characteristics; similar climatic conditions; same crop cultivation; and similar methods of cultivation.

Step 5 - Spectral signature. Evaluation of the spectral signatures for both sites is the first step of post-processing analysis in the satellite images. The aim of this step is to identify any spectral signatures or 'anomalies'. Such 'anomalies' can be easily recognized, especially in the VNIR part of the spectrum. As shown by other studies (Agapiou *et al.* 2010, Agapiou *et al.* 2012, Agapiou and Hadjimitsis 2011), spectral signatures can be used for detection of crop marks formed by a difference in soil moisture deficit, which is mitigated by buried archaeological features.

Step 6 - Phenological cycle. Step 6 includes a detailed examination of the crops, phenological cycles for Site A and Site H. As McCloy (2010) mentioned, the phenological cycle can be defined as the trace or record of the changes



A



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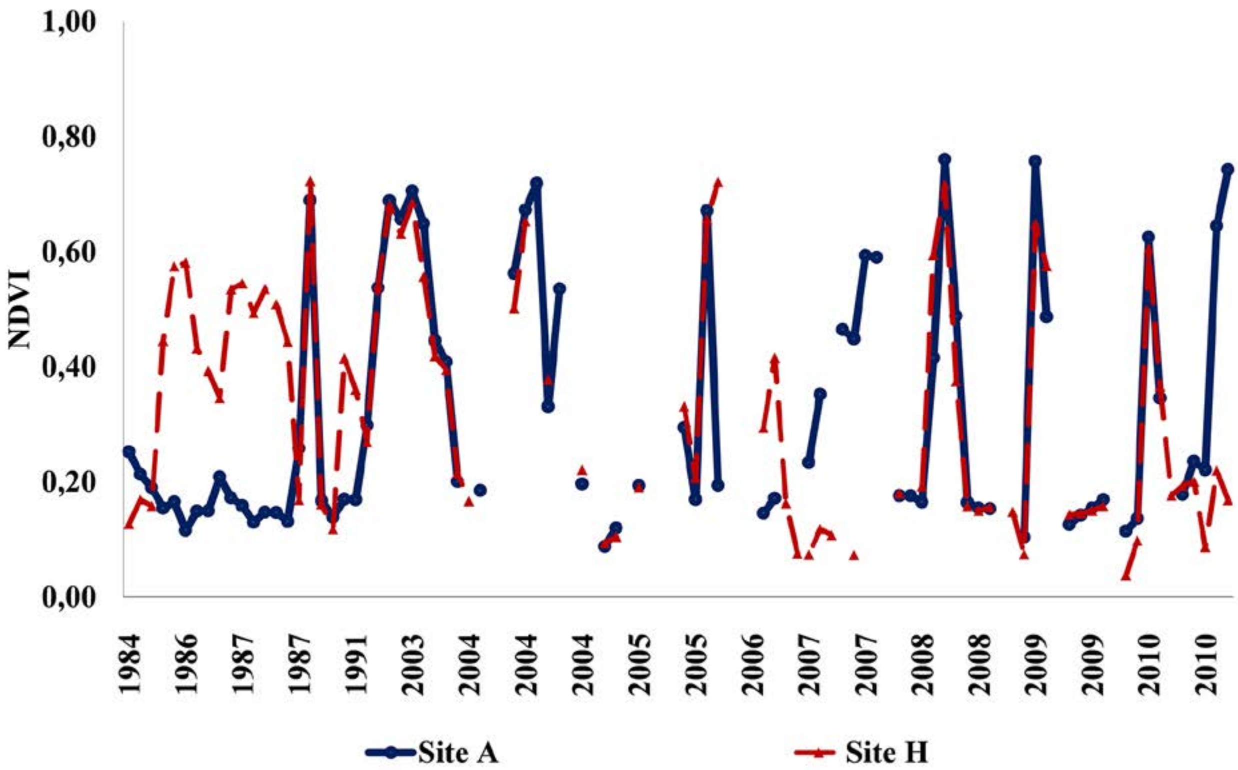

C

Figure 4. a) Site A and Site H selected in the Almyros locality at Thessaly (Google Earth ©). b) Spectral signatures over the archaeological site of Almyros *magoula* (A) and non archaeological site (H) (Agapiou *et al.* 2012). c) Phenological cycle as recorded from the Landsat satellite imagery (1984-2011). In several cases the phenological cycle of Site A is higher than Site H (Agapiou, *et al.* 2013b).

in a variable or attribute over the phenological period, while a phenophase is defined as an observable stage or phase in the seasonal cycle of a plant that can be defined by start and end points.

Step 7 - Hypothesis accepted or rejected. The final step is the acceptance or rejection of the hypothesis for Site A based on the previous results. Moreover, it should be noticed that all these steps can be applied to more than one vegetation sites in order to verify the results.

The above mentioned methodology was applied at the Thessalian plain. An extensive dataset consisting of 97 multispectral Landsat multispectral scanner MSS/TM/ETM+ was examined in order to detect a Neolithic settlement (*magoula*) in the Almyros locality of Thessaly. The period examined was from 1984 until 2011. The site was surveyed and the results showed a high density of ceramics at the top of the *magoula* (≈10 ceramics/m^2). Additionally, ground spectroradiometric measurements were retrieved in this area. After the necessary preprocessing steps (Steps

1–3), two areas were selected: Site A and Site H (shown in Fig. 4a from Google Earth).

These areas were in close proximity (nearby parcels) and therefore errors from hypothesis A and H were minimized. Spectral signatures (Step 5) have managed to distinguish the archaeological site of Almyros II from the surrounding area. Almyros II had been inhabited during Early and Middle Neolithic Period. As is shown in Fig. 4b, Site A (Almyros II) tends to give higher reflectance values, especially in the near infrared part of the spectrum, compared to Site H. This differentiates the signature found in the spectral profiles of crops cultivated in Site A, which can be related to the presence of the Neolithic settlement. The latest seems to differentiate soil moisture or soil nutrients, compared to the background area.

The phenological cycle (Step 6), as plotted from the 96 multispectral Landsat datasets, confirmed the spectral signature results. After searching many phenological cycles, Site A tends to give higher NDVI values in contrast to Site H (Fig. 4c). Such positive crop marks systematically observed in Fig. 4c for many phenological cycles can be therefore associated to the Neolithic settlement. This is compatible with the results of relevant archaeological surveys in the Almyros II site carried out by Vouzaksakis (2009). The results have shown a high density of sherds at the top of the *magoula* (around 10 pieces of ceramic per square meter).

Evaluating the potential of Sentinel-2 for archaeological research

This section explores the capabilities of remote sensing sensors for the detection of new archaeological sites using simulated Sentinel-2 data. The Sentinel-2 sensor aims to provide continuity to services relying on multi-spectral, high-spatial-resolution optical observations over global terrestrial surfaces. It should be noted that the design of the Sentinel-2 mission aims at an operational multi-spectral earth-observation system that complements the Landsat and SPOT observations and improves data availability for users.

The performance of Sentinel-2 sensor to distinguish vegetation marks was examined using several existing broadband vegetation indices. As is known, vegetation indices intend to explore vegetation's spectral signature characteristics, using the visible and near infrared parts of the spectrum. Canopy reflectance in the visible and near infrared is strongly dependent on both structural (*i.e.*, amount of leaves per area, leaf orientation, canopy structure) and biochemical properties (*i.e.*, chlorophylls, carotenoids) of the canopy (Stagakis *et al.* 2010). Vegetation stress associated with sub-surface soil disturbance may be observed as visual symptoms, stunted growth, and sparse vegetation cover.

For the needs of the study, several ground spectroradiometric measurements were taken during the whole crops phenological cycle in Alampra test field (Cyprus) using the GER 1500 handheld spectroradiometer (see section 2). Even though several indices exist in the relevant literature only a small number of them has been practically used or evaluated for remote sensing archaeology applications. As was found, although NDVI is considered to be the most widely used index for archaeological studies, other existing vegetation indices might be also used successfully for the detection of buried archaeological antiquities. Indeed more than hundred vegetation indices have been presented in the relevant literature, either using narrow-band or broad-band reflection. In this section, some widely used vegetation indices applied for the enhancement of vegetation mark using satellite imagery have been evaluated (see Table 1). All these indices have been calculated for all sensors mentioned in this this study: Sentinel-2 (Bands 4–8); Sentinel-2 (Bands 5–7); Landsat 5 TM (Bands 3–4); ASTER (Bands 2–3); IKONOS (Bands 3–4); Landsat 4 TM (Bands 3–4); Landsat 7 ETM+ (Bands 3–4); QuickBird (Bands 3–4); SPOT (Bands 2–3); and WorldView-2 (Bands 5–7). The aim of this evaluation was to assess the potential of the new spectral characteristics of Sentinel-2 to further expand the capabilities of remote sensing techniques for the detection of buried archaeological features. Following, the relative difference between vegetation marks and the surrounding healthy vegetation using different vegetation indices was calculated (Table 2). It becomes clear that Sentinel-2 distinguished better the vegetation marks compared to the remaining sensors. Spectral characteristics of the forthcoming sensor seem to improve photointerpretation using either simple or more advance vegetation indices. It is interesting to note that for the majority of indices examined in this study (~85%) the Sentinel-2 was the most suitable sensor for the detection of buried archaeological features. Moreover, Bands 5 and 7 of Sentinel-2, which were closed to the optimum spectral region for the detection of crop marks (700nm and 800nm) tend to give high relative differences between vegetation marks and the surrounding healthy vegetation.

Finally, one EO-Hyperion image over the *Thessalian* plain (Central Greece) has been used. The EO-Hyperion narrow bands were resampled into the specific bandwidths of Bands 5 and 7 of the Sentinel-2 sensor using the relevant RSR filters. Specifically, the Hyperion Bands 33–36 and Bands 39–45 were resampled to Sentinel-2 Band 5 and 7, respectively. In addition, the spatial resolution of the EO-Hyperion was resampled to 20 m as in Sentinel-2. For this purpose, a high-resolution IKONOS image of the same area was acquired. A high relative geometric correction between the EO-Hyperion and the IKONOS image was achieved (Total Root Mean Square Error (TRMSE) < 2 m) using 2nd order polynomial order correction algorithm. Then, the IKONOS image was merged into the EO-Hyperion dataset using the PCA approach. This procedure was used in order to merge the high-resolution image (IKONOS, 1 m pixel size) with the lower-resolution image (EO-Hyperion, 30 m). Finally, the end product was resampled to 20 m as the Sentinel-2 spatial resolution.

Table 1. Vegetation Indices used in this study

No	Vegetation Index	Equation
1	NDVI (Normalized Difference Vegetation Index)	$(p_{NIR} - p_{red})/(p_{NIR} + p_{red})$
2	Green NDVI (Green Normalized Difference Vegetation Index)	$(p_{NIR} - p_{green})/(p_{NIR} + p_{green})$
3	SR (Simple Ration)	p_{NIR}/p_{red}
4	MSR (Modified Simple Ratio)	$p_{red}/(p_{NIR} / p_{red} + 1)^{0.5}$
5	MTVI2 (Modified Triangular Vegetation Index)	$[1.5(1.2 * (p_{NIR} - p_{green}) - 2.5(p_{Red} - p_{green})]/ [(2 p_{NIR} + 1)^2 - (6 p_{NIR} - 5 p_{Red}^{0.5}) - 0.5]^{0.5}$
6	RDVI (Renormalized Difference Vegetation Index)	$(p_{NIR} - p_{red})/(p_{NIR} + p_{red})^{1/2}$
7	IRG (Red Green Ratio Index)	$p_{Red} - p_{green}$
8	PVI (Perpendicular Vegetation Index)	$(p_{NIR} - \alpha p_{red} - b)/(1 + \alpha^2)$ $p_{NIR,soil} = \alpha p_{red,soil} + b$
9	RVI (Ratio Vegetation Index)	p_{red} / p_{NIR}
10	TSAVI (Transformed Soil Adjusted Vegetation Index)	$[\alpha(p_{NIR} - \alpha p_{NIR} - b)]/$ $[(p_{red} + \alpha p_{NIR} - \alpha b + 0.08(1 + \alpha^2))]$; $p_{NIR,soil} = \alpha p_{red,soil} + b$
11	MSAVI (Modified Soil Adjusted Vegetation Index)	$[2 p_{NIR} + 1 - [(2 p_{NIR} + 1)^2 - 8(p_{NIR} - p_{red})]^{1/2}]/2$
12	OSAVI (Optimized Soil Adjusted Vegetation Index)	$(p_{NIR} - p_{red})/(p_{NIR} + p_{red} + 0.16)$
13	DVI (Difference Vegetation Index)	$p_{NIR} - p_{red}$

Table 2. Relative difference between vegetation marks and the surrounding healthy vegetation using different vegetation indices. The maximum difference for each index is highlighted.

Vegetation Index Sensor	NDVI	Green NDVI	SR	MSR	MTVI2	RDVI	IRG	PVI	RVI	TSAVI	MSAVI	OSAVI	DVI
Landsat 5 TM	6	8	37	25	3	18	9	30	6	7	2	6	29
Sentinel-2 (Bands 4 and 8)	31	21	**56**	53	32	35	**29**	46	49	38	25	31	40
Sentinel-2 (Bands 5 and7)	**38**	22	39	**54**	**64**	**42**	3	**61**	30	**54**	**31**	**38**	**48**
ASTER	32	22	54	48	34	36	20	48	46	40	25	32	41
GeoEye	32	20	56	54	36	36	28	47	**49**	39	25	32	41
IKONOS	33	22	44	40	38	36	14	49	41	42	26	33	41
Landsat 4 TM	31	**23**	55	50	30	35	21	47	47	38	24	31	40
Landsat 7 ETM+	31	22	56	51	31	35	24	46	48	38	24	31	40
QuickBird	31	22	56	51	32	35	24	47	47	38	24	31	40
SPOT	30	20	54	47	33	34	20	46	45	38	24	30	40
WorldView-2	31	20	56	50	34	35	25	46	47	38	24	31	40

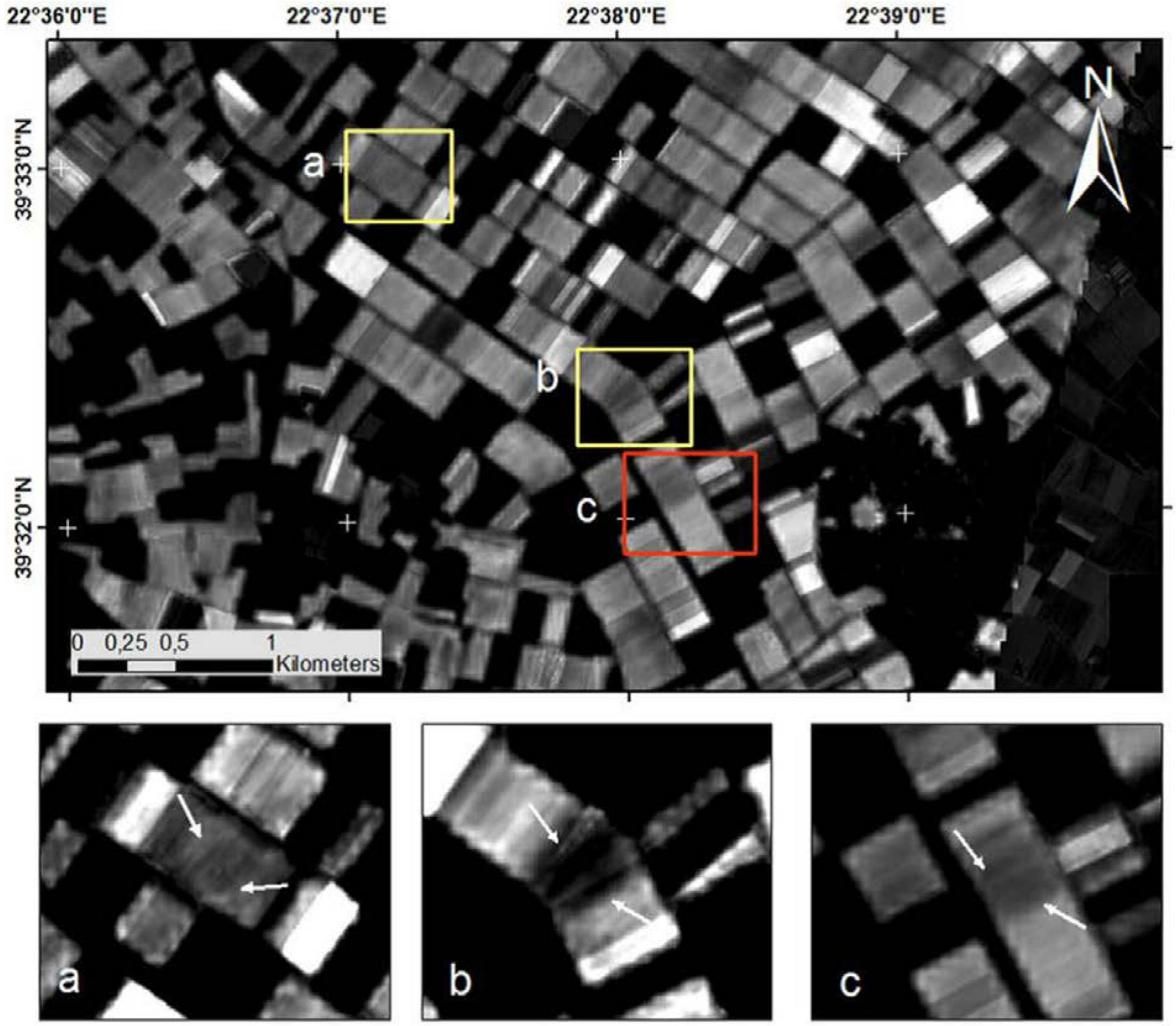

Figure 5. The simulated Sentinel-2 image over the Thessalian plain, based on the EO-Hyperion dataset. Known archaeological vegetation marks are indicated with yellow color (a: Anagennisi 1; b: Melissa 1), while another unknown vegetation mark is indicated in a red square (Agapiou *et al.* 2014).

As shown in Fig. 5, some already known *magoules* (indicated with yellow color) were detected using simple photointerpretation of the image. These archaeological vegetation marks can be detected mainly due to the difference of the vegetation mark against the surrounding area, but also based on their circular shape. However, the most promising attribute of this analysis was the detection of still unknown archaeological crops marks. Indeed, as demonstrated in Fig. 5, at least another one potential site has been found in the same area. The site (indicated with red color) is in very close proximity to the existing known sites.

Conclusions

Remote sensing can contribute in several ways archaeological research, from site detection to cultural heritage management. This article presented some results from different cases studies in Cyprus and Greece using several techniques of remote sensing, including satellite images, archive aerial images and ground spectroscopy. The results have shown the potential use of satellite remote sensing and ground spectroscopy for the identification of buried archaeological remains through crop marks.

The first approach proved that spectral regions around the red edge and NIR spectrum (700 and 800 nm respectively) are able to distinguish crop marks. The above conclusion was evaluated successfully at the Thessalian plain, for the detection of Neolithic tells, using Hyperion images. The results of the application of the proposed Archaeological Index were evaluated with other techniques such as colour composites, vegetation indices, PCA, Tasseled Cap, etc.

The second approach introduced an alternative image-based methodology for the detection of vegetation anomalies that might be attributable to buried archaeological features. For this reason three different case studies were selected and thoroughly examined. The methodology discussed, consisting of seven consecutive steps, can be applied in any multispectral/hyperspectral satellite image. The first three steps concern image basic preprocessing procedures while the next three steps constitute the post processing procedure. The final step is the acceptance or rejection of the initial hypotheses. Although four main parameters influence this approach (concerning similar soil characteristics, climatic conditions, type of cultivation, and method of cultivation), the potential user has the ability to minimize any possible errors by using either image data information or other auxiliary data (e.g. meteorological data). Indeed, although several hypotheses are essential to fulfil for the selection of two initial areas under investigation (Site A and Site H), this step can be simplified by just selecting areas in a very close proximity. In this way the proposed methodology can have a wide application and evaluation in several archaeological environments.

Concerning the third approach, it was proved that Sentinel-2 will assist further archaeological research. It is also important to highlight that the Sentinel-2 mission will provide us with important satellite products, freely available to scientific community, continuing the heritage missions of Landsat and SPOT space programs.

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Cities and Satellites: Discovering Ancient Urban Landscapes through Remote Sensing Applications

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Abstract: Satellite remote sensing at ancient Greek cities on Mainland Greece has identified an extensive network of near-surface orthogonal streets and sections of city-blocks. This new and valuable information reveals the general organization of urban space and its parameters at Mantinea and Elis in the Peloponnese and Pherai in Thessaly, showing that these cities were planned settlements. It is the first time on mainland Greece that a planned settlement has been identified only through satellite remote sensing applications. In presenting the evidence for buried archaeological features, the paper highlights the advantages of these methodologies in the archaeological sciences where they are sparsely used compared to traditional methods of fieldwork.

Keywords: satellite remote sensing, urban history, land use patterns, Mediterranean archaeology

1. Introduction

This paper outlines some of the ways in which satellite imagery can be used as a primary or complimentary tool of archaeological research to explore the human past. The archaeological sciences in the second decade of the twenty-first century are a rich mixture of various scientific and humanistic undertakings. Satellite remote sensing is just one field among many cross-disciplinary applications trying to make sense of our culture heritage. Compared to other modes of archaeological research, such as excavation, field survey, and geophysics, satellite remote sensing is still at an early phase of integration, leaving room for expansion. One clear advantage is its ability to explore large contexts covering in some cases hundreds of square kilometers. The tremendous range in scale is ideally suited for exploring large sites and whole regions in timely sequence. An image high above the Earth's surface gives a completely different perspective from which to explore the past, and the newest generation of satellite sensors do so at a resolution around a half meter. This is enough to identify even the smallest of ground targets on an archaeological site. In addition, (passive) satellite sensors record the spectral information reflected/emitted from the Earth's surface. Therefore, one can recognize ground features in true color images and in combinations, such as infrared, that are impossible for the human eye to detect. Satellite remote sensing quite literally opens up new horizons of visualizing the Earth and its human and environmental characteristics.

My intention in this volume is to highlight a few possible uses of satellite remote sensing in Archaeology. More specifically, I demonstrate how satellite image processing has helped someone like me, trained as a Mediterranean archaeologist, to realize and enhance features of the ancient landscape that would otherwise have been challenging to achieve with traditional methodologies. I have had success using satellite imagery to investigate the spatial organization and geographical extent of ancient Greek cities, such as the arrangement of streets and city-blocks, the interconnection between urban and rural space, and the potential transformation of urban patterns under changing conditions. The case-studies that I showcase here are Mantinea and Elis in the Peloponnese and Pherai in Thessaly. In classical antiquity they were large and prominent Greek cities, but up to the present archaeological exploration remains limited. In particular, their urban structure is poorly understood even after decades of recurrent investigations. Archaeological fieldwork from excavations and small scale geophysics had found little evidence of town planning, but satellite remote sensing methods have been able to positively identify them as planned cities with relative ease. Compared to other subfields of Archaeology, Greek Archaeology is a conservative discipline taking pride in meticulous excavation and artifact analysis in light of its rich artistic and ancient literary traditions. Until now satellite remote sensing has played a minimal role, even with the broad adoption of field survey, GIS, and geophysics in Greek Archaeology over the past few decades. Its devalued role is perhaps partly due to the lack of relevant studies that demonstrate its benefits and how to implement it from a practical standpoint.

2. Satellite remote sensing within Mediterranean Archaeology

The organization of cities and rural land was a distinctive feature of Greek and Roman culture. Throughout the ancient Mediterranean and its periphery, many settlements, especially those that were new and redeveloped, were influenced by conceptual approaches in cohabitation, such as the logical arrangement of streets, city blocks, and farmland (Greco and Torelli 1983; Hoepfner and Schwandner 1994; Donati 2014a). The Greek and Roman city was a concept that could be planned from the very beginning to suit the needs of a specific population at a determined geographic location. Greek colonization in South Italy (Magna Graecia) and Sicily was the original catalyst for planned settlements in classical antiquity. Archaeological excavations in these regions have found extensive evidence for cities with orderly streets and well-defined public and private zones beginning in the seventh century BCE (De Angelis 2003; Gras, Tréziny, and Broise 2004). In numerous cases, urban grid systems were also extended into the surrounding countryside to divide up agricultural farmland. Well-documented examples of this practice include the Greek settlement of Metapontum in South Italy and the rural territory in the Crimea on the Black Sea (Carter 2006; Smekalova and Smekalov 2006), as well as the Roman centuriation of Corinth in the Peloponnese (Romano 2003). One likely purpose of urban and rural planning was to regulate the distribution of residential property and agricultural land to the citizen body in a logical manner (Boyd and Jameson 1981). In addition, ancient authors, such as Aristotle (*Politics* 7.1330a-1331a), commented on the benefits of regular streets placed at specific angles to take advantage of the sun and the direction of the wind currents.

Up to the present, the identification of urban and rural land divisions has been dependent on three separate methodologies: (1) archaeological fieldwork and survey revealing physical evidence for road networks, buildings, and farmsteads, (2) geophysical prospection identifying subsurface features, and (3) photo interpretation of aerial photographs and satellite imagery distinguishing patterns of the ancient landscape that are still preserved in modern times or associating linear 'crop marks' on the surface with buried roads and boundary walls. There are benefits and limitations in each of these applications. In general, archaeological excavations and ground-based geophysical prospection are better suited at identifying ancient features on a targeted level. Two recent geophysical surveys at Sikyon in the Peloponnese (Lolos and Gourley 2011) and Plataea in Boeotia (Konecny *et al.* 2012), both on Mainland Greece, found good evidence for extensive street systems, city-blocks, and even the layouts of individual buildings. On the other hand, aerial photography and satellite imagery, used in tandem with historical maps, have made a bigger impact in the detection of rural land divisions, because of their capacity to explore a much greater area (Castagnoli 1971; Montufo 1997). Specifically, the identification of Roman centuriation systems from the orthogonal alignments of modern agricultural fields has been a long established field of research (Clavel-Lévêque 1983; Chouquer and Favory 2000). Beyond photo interpretation, methods to develop computer-based applications to study the morphological dimensions of ancient agrarian landscapes from aerial images were first explored by the Optics Laboratory of the University of Besançon (France) in the 1970s and 1980s, when aerial photographs of southern France were subjected to directional filters from light beams to calculate the dominant orientations of fields and record them as histograms (Charraut, Favory and Raynaud 1992; Charraut and Favory 1993). The target then was in the identification of Roman centuriation. Over the past two decades, remote sensing and GIS have been used to process aerial and satellite images through automated filters in order to study ancient landscape forms (Donati 2014b). Here, there has been particular success in documenting Roman centuriation on an extensive scale in regions of France and northern Italy where ancient rural landscapes often retain their original proportions and orientations (Charraut and Favory 2000; Brigand 2010; Favory, Nuninger and Sanders 2013). Still, satellite remote sensing remains very much marginalized in Mediterranean Archaeology, especially on mainland Greece and the Aegean Islands, where a more rocky landscape deters its widespread use. The Minnesota Archaeological Researches in the Western Peloponnese (MARWP) was one of the first projects in Greece to adopt satellite remote sensing, using Landsat images to study the vernacular architecture and medieval sites of the Peloponnese (Cooper, Bauer, and Cullen 1991). More recently, various satellite platforms were used to identify prehistoric settlement mounds in Thessaly (Alexakis *et al.* 2010; Agapiou *et al.* 2012) or details of Hellenistic settlements (Rowlands and Sarris 2007).

3. Methodologies and data processing

Satellite images from three different sensors (GeoEye-1, Quickbird, and WorldView-2) form the main data sets for my research (Table 1). Quickbird in 2001 was a pioneer in providing high-resolution multispectral satellite imagery at submeter resolution. It was followed by GeoEye-1 in 2008 and WorldView-2 in 2009. These three, along with WorldView-3 launched in August 2014, are the most advanced multispectral satellite sensors of submeter resolution commercially available to date for archaeological projects. Imagery comes in the form of a panchromatic (grayscale) image of superior spatial resolution, and a bundle of either 4-band or 8-band multispectral images of lower spatial resolution. As an example, WorldView-3 has an optimum ground sampling distance of 0.31 m panchromatic and 1.24 m multispectral. In 4-band imagery, multispectral data is delivered in blue, green, red, and infrared wavelengths of the visible and invisible spectrum. 8-band imagery includes a more expansive suite of spectral wavelengths. If possible, an archaeological project should use several satellite images acquired in different years and in different seasons. Because the results of satellite remote sensing are highly dependent on local and seasonal climatic conditions (rainfall, heat, angle of the sun, soil moisture) and the growth of vegetation, a ground target or subsurface feature might be undetectable during a specific season of the year. It is difficult to predict the successful results of the satellite images beforehand; therefore, diversification is recommended. Of course sometimes only a few images with little or no cloud cover are commercially accessible.

Table 1. Satellite sensors used in the present study and some of their specifications.

Satellite sensor	Extraction date	Resolution (m)	Off-nadir angle
Mantinea			
Quickbird	13 September 2003	Pan 0.63; MS 2.50	9.4°
Quickbird	10 June 2009	Pan 0.64; MS 2.56	14.8°
Quickbird	3 June 2012	Pan 0.66; MS 2.65	14.8°
WorldView-2	11 September 2013	Pan 0.50; MS 1.90	10.1°
Pherai			
Quickbird	15 June 2009	Pan 0.62; MS 2.49	7.6°
GeoEye-1	4 May 2010	Pan 0.50; MS 1.98	14.0°
Elis			
GeoEye-1	20 July 2009	Pan 0.50; MS 1.86	9.1°
Quickbird	30 April 2010	Pan 0.63; MS 2.50	8.9°
WorldView-2	13 December 2012	Pan 0.50; MS 2.03	18.2°

One can make arrangements for a sensor to take a new acquisition within a predetermined date range, but this process is limited to the collection of recent images.

A series of pre-processing techniques are usually applied to satellite images for further data processing and analysis. Depending on the type of data used, the pre-processing steps can include radiometric and geometric corrections to the satellite images and image fusion of the lower resolution multispectral bands with the higher resolution panchromatic image. In relatively flat regions, the geospatial accuracy of Quickbird, GeoEye, and WorldView imagery has a margin of error of around 5 meters or less. Errors increase in more mountainous terrain. For better accuracy, further imagery corrections are possible with ground control points taken on site or with a digital elevation model (DEM). Image fusion, or 'pansharpening,' is a process that increases the spatial resolution of a satellite image by using another image of superior spatial resolution. This can occur as long as any two images are geometrically corrected with one another. Image fusion is frequently used to increase the spatial resolution of multispectral bands with a higher resolution panchromatic (grayscale) image. The difference in resolution quality between color and grayscale imagery is significant and without supplementary feature enhancement an image will have limited range in distinguishing fine surface details. Image fusion creates a high-resolution real color (R,G,B) or pseudocolor image (with infrared wavelengths) even though the raw multispectral data from the satellite sensor is of lesser quality. In the case of Quickbird, the 2.5 m resolution multispectral image becomes a much sharper 0.6 m resolution image.

The capacity to enhance archaeological features from satellite images rests largely on post-processing techniques. Specific algorithms are applied to the imagery to measure and magnify the range of spectral signatures reflected from ground targets. Vegetation in agricultural fields is especially important, because the chlorophyll in plants absorbs and reflects spectral wavelengths differently depending on the climatic conditions and the health of vegetation. A subsurface feature of archaeological value, such as the stone walls of a buried building, might put stress on the vegetation growth directly above. This stress can alter the spectral signature of ground vegetation and create surface anomalies or 'crop marks' that betray the presence of a feature. Although it is possible to identify surface anomalies using true color images and different combinations of the multispectral bands, feature enhancement maximizes feature detection. In my case, I apply a combination of vegetation indices to the multispectral satellite images (Table 2). The new data sets display a versatile range of surface details partly or wholly indiscernible in the original multispectral band combinations, and from them image interpretation of an archaeological context follows. There are many different avenues to explore at this stage of research, such as classifications and automated feature detection, but in many instances direct image interpretation of the feature enhancement indices can be the most reliable (and most straightforward) method.

4. Mantinea

Mantinea is a classical Greek city in Arcadia with a long and rich history dating from its foundation in the late sixth or early fifth century BCE through the Roman period (Hodkinson and Hodkinson 1981). The settlement was destroyed and rebuilt on two separate occasions. In an episode described by the contemporary historian Xenophon (*Hellenica* 5.2.1-7), Sparta sacked Mantinea in

Table 2. Feature enhancement indices applied to the satellite imagery.

Feature enhancement	Algorithm
ARVI	$(P_{NIR} - (2 [P_{RED} - P_{BLUE}])) / (P_{NIR} + (2 [P_{RED} - P_{BLUE}]))$
EVI	$((P_{NIR} - P_{RED}) / (P_{NIR} + 6(P_{RED}) - 7.5(P_{BLUE}) + 1))$
Green NDVI	$(P_{NIR} - P_{GREEN}) / (P_{NIR} + P_{GREEN})$
IR/R	P_{NIR} / P_{RED}
MSAVI	$((P_{NIR} - P_{RED}) / (P_{NIR} + P_{RED} - L)) (1 + L)$
MSR	P_{NIR} / SQRT($(P_{RED} / P_{NIR} + 0.1) +1$)
NDVI	$(P_{NIR} - P_{RED}) / (P_{NIR} + P_{RED})$
SAVI	$((P_{NIR} - P_{RED}) / (P_{NIR} + P_{RED} + 0.5)) (1.5)$
SQRT IR/R	SQRT(P_{NIR} / P_{RED})
TSAVI	$(s (P_{NIR} - s * P_{RED} - a)) / (a * P_{NIR} + P_{RED} - a * s + 0.08 (L - s * s))$
WDVI	$P_{NIR} - P_{RED} * s$
a = soil line intercept s = soil line slope L = 1 - 2 * s * NDVI * WDVI	

385 BCE by damning a river flowing through the town which then flooded the urban center. A forced depopulation was enacted and the city was left abandoned for fifteen years until its reestablishment in 370 BCE A similar event of destruction befell the city in 222 BCE, when the Macedonian army led by Antigonos Doson attacked. As far as the urban history of Mantinea is concerned, the episodes of destruction and reconstruction make for an interesting case-study in how the inhabitants imagined their city and rebuilt it following catastrophes. The only extensive archaeological investigations at Mantinea were conducted by the French School at Athens from 1887-1889 (Fougères 1898). The French focused on the agora and its public monuments, including the theater. They discovered civic and religious buildings and porticos arranged around a rectangular square with phases spanning from the Classical to Roman periods. Many of these buildings have since been reburied by seasonal flooding. Beyond the agora, the most significant architectural feature at Mantinea is the elliptical fortification walls, approximately 4 km in circumference (Winter 1989). Today, the walls and gates are in a remarkable state of preservation and constitute an exceptional illustration of a near complete Greek defensive circuit. As a result, the urban boundaries of Mantinea are well defined comprising an area of 119 ha. Little else of the remaining settlement has been studied and today the site is predominantly cultivated for wheat and vegetables. The target for satellite remote sensing was to identify details of the huge urban environment, since virtually nothing of the ancient city is known beyond the central agora and fortifications.

Feature enhancement filters were applied to four high-resolution multispectral satellite images in order to optimize the spectral signatures reflected from ground targets (Donati and Sarris forthcoming). At Mantinea, this method proved valuable in identifying an extensive system of linear surface anomalies that mark the location of buried orthogonal streets, showing that the city was a planned settlement. The frequency, ordered arrangement, and metrology of anomalies are clear, and many begin to form the outlines of long rectangles presumably from city-blocks. South of the agora there is evidence for four parallel streets of prolonged dimensions spaced between 87-91 m (Figure 1). The westernmost can be traced in the satellite imagery for almost 700 m from a gate to the theater. A similar arrangement and metrology of streets in the northern half of the city was noted. East-west anomalies that mark buried streets are also apparent, with many intersecting the north-south anomalies at right angles. Regions to the northwest and east of the agora best demonstrate this with average spacings of 59-60 m.

Mantinea is an excellent example of the benefits of using satellite remote sensing during an initial phase of site exploration. The city was not previous known to have been a planned settlement, but now a partial reconstruction of the grid system is possible (Figure 2). The central zone of Mantinea, as reconstructed, is defined by a series of extended north-south streets at 89 m intervals. Two-thirds of street lengths (62%) are verified by linear anomalies. The ones in the southern zone are positioned 23 m further east. I suspect that the reason for the shift was to optimize the communication between city gates and the agora. The two northern gates are not on axis with the two southern gates; therefore, a slight modification to the arrangement of the southern streets was required for proper circulation. Completing the north-south roads, a string of east-west streets are dispersed throughout Mantinea at 60 m intervals. One-quarter of the street lengths (27%) are verified by

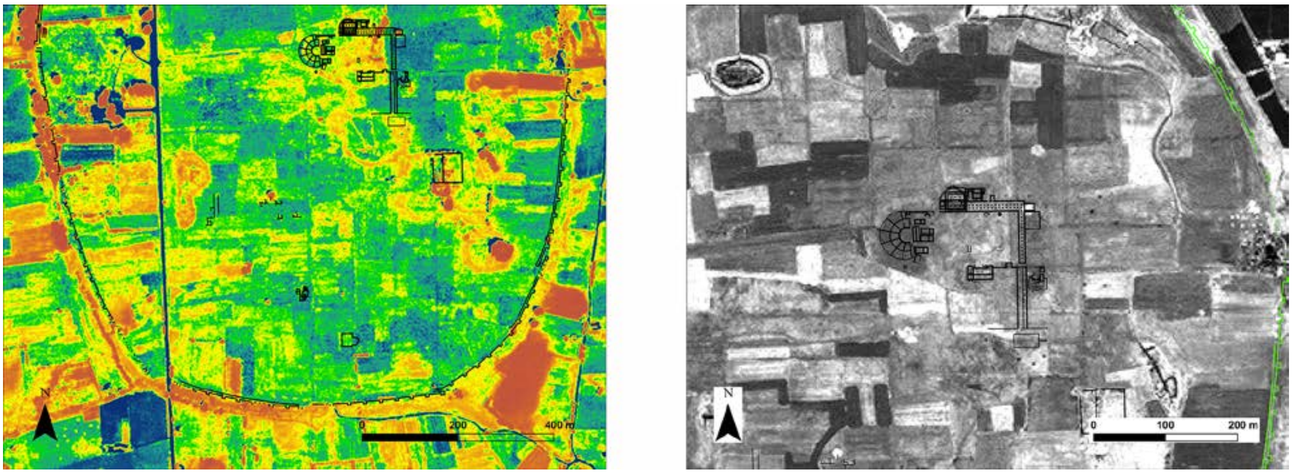

Figure 1. Green NDVI applied to Quickbird 13 September 2003 (left) showing anomalies in the southern region of Mantinea, and MSAVI applied to Quickbird 10 June 2009 (right) showing anomalies in the eastern region.

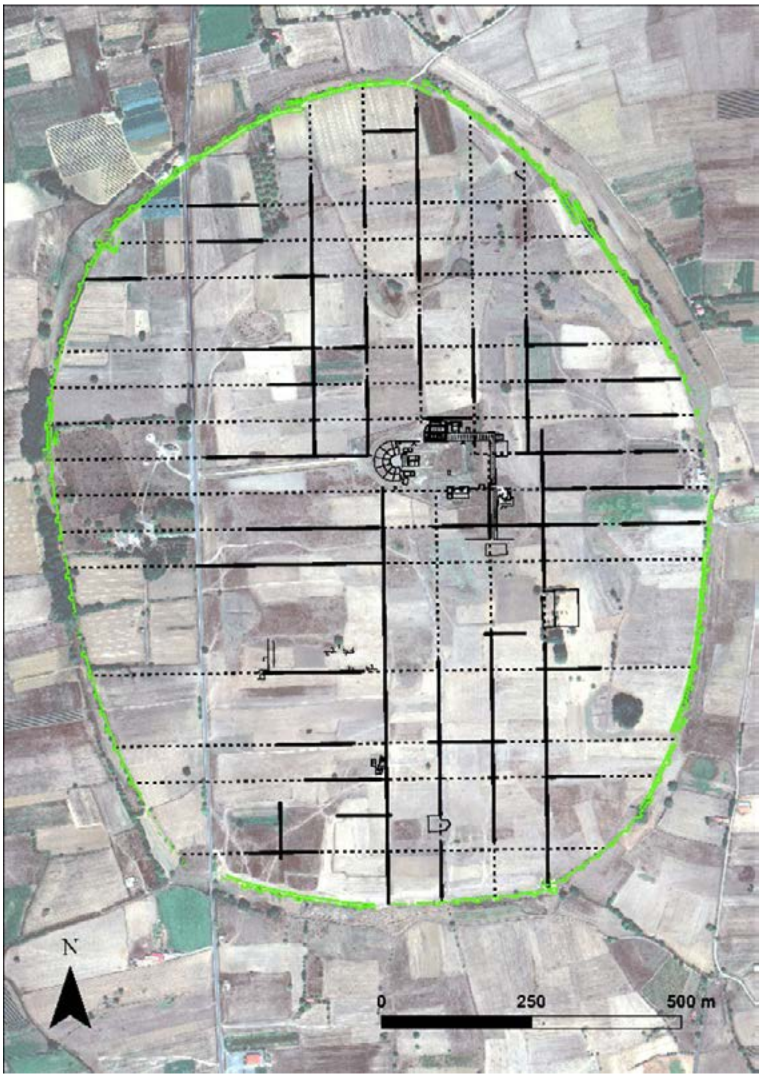

Figure 2. A partial reconstruction of the orthogonal street system at Mantinea. Streets in solid black are confirmed by surface anomalies.

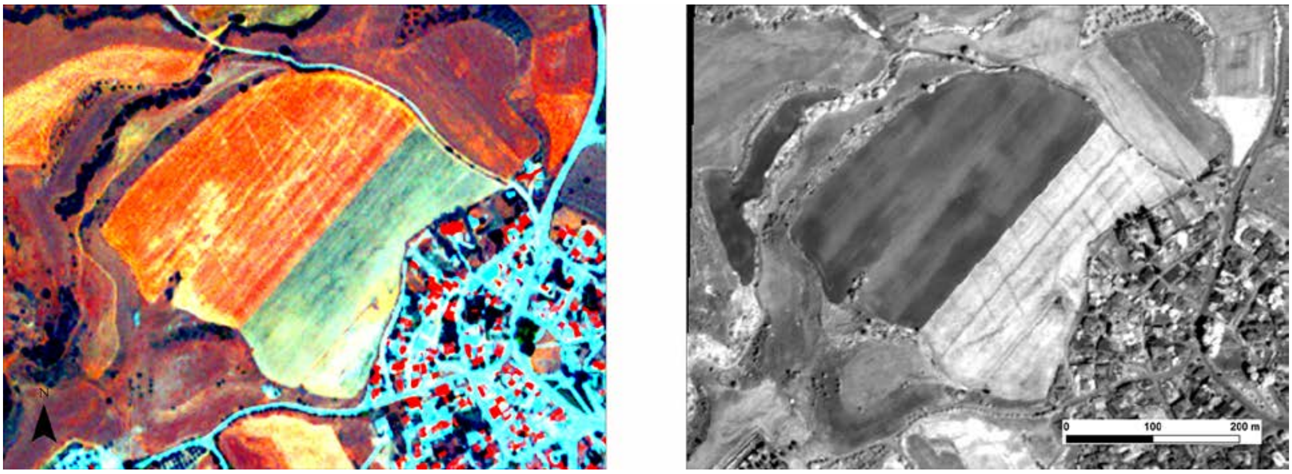

Figure 3. Decorrelation Stretch applied to Quickbird, 15 June 2009 (left) and MSR applied to GeoEye-1, 4 May 2010 (right) showing diagonal subsurface streets at Pherai.

linear anomalies. There are still gaps in the data that present ambiguities in the grid plan, and some anomalies likely from streets do not fit into this reconstruction. Therefore, Mantinea probably did not adopt a uniform Hippodamian plan (i.e., a strict grid system of regular streets and city-blocks); rather, there were modifications to a prototype of either single or multiple phases.

5. Pherai

The Thessalian settlement of Pherai was occupied more or less continuously from the Late Neolithic period until the site was abandoned in the Early Roman Imperial period (Béquignon 1937; Dougleri Intzesiloglou 1990; 1994). It was not settled again until the post-Byzantine town, called Velestino, was established in the thirteenth century. Prehistoric remains consist of the Neolithic tell (*Magoula Bakalis*) and Bronze Age graves scattered on the plateau and sloping terrain east of the tell. An Early Iron Age settlement was located on the plateau as well, if the location of contemporary burials, terrace walls, and surface pottery serve as an indication (Morgan 2003, 92-5). By the end of the eighth century BCE, an important cult of En(n)odia and Zeus was established northeast of the plateau, but it was not until the sixth century BCE that a stone temple was constructed (Østby 1992; 1994). The establishment of the cult coincided with an expansion of the settlement, as indicated by the distribution of surface pottery and excavated remains of the same period. Overall, the nature of the Early Iron Age settlement, with dispersed bands of villages eventually coalescing into a core habitation zone, resembles in many ways the better known examples of early Argos and Corinth (Donati 2014a). Throughout the Archaic and Classical periods, Pherai developed into one of the most prominent Thessalian cities. Its apex occurred during the fourth century BCE, when the city was ruled by a tyranny, most notably Jason of Pherai (Sprawski 1999). At this time, fortification walls were built to protect the acropolis and regions of the city to the south and east. The best preserved wall sections are the towers and gate found on the Agios Athanasios hill (Kakovoyiannis 1977). The urban boundaries of the rest of the city remain uncertain, since the modern town limits the scale of exploratory excavations. Estimates of the size of the classical city range from 80-120 ha (Hansen and Nielsen 2003, p. 705).

A satellite remote sensing campaign was conducted using high-resolution multispectral Quickbird and GeoEye-1 satellite imagery and historical aerial photographs from the 1960s and 1970s. As with Mantinea, spectral filters and band ratios, such as MSR and Decorrelation Stretch, applied to the satellite imagery proved valuable in identifying a network of organized streets, especially on the plateau east of the Neolithic tell (Figure 3). Here, several slanting north-south streets appear as parallel linear anomalies spaced roughly equidistant from one another. To be more specific, remote sensing identified at least 12 north-south streets spaced approximately 30 m from one another. There is a distinct convergence of the central cluster of streets toward a common location to the north. It is plausible that a gate once existed in the now destroyed northern fortification walls and the roads therefore provided access. An east-west section of the buried fortification wall appears just to the east as a linear anomaly. At least one east-west street was detected in the satellite imagery at the southern edge of the plateau; however, an extension of the north-south roads further south remains unknown. Perhaps the sloping terrain limited the extension of an urban street system here. Anomalies in the fields below the plateau may tentatively be interpreted as a continuation of the same diagonal street system. It is noteworthy that the anomalies on the plateau east of the Neolithic tell are not organized in a strict orthogonal manner in the classical and Hellenistic traditions, but, instead, they have a diagonal arrangement analogous to planned street systems of an earlier period, most notably to Megara Hyblaia in Sicily (De Angelis 2003; Gras, Tréziny, and Broise 2004). The implication is that this region of Pherai may have been planned with a regular arrangement of streets at an early period in the city's history. Of course, only future fieldwork and ground truthing could confirm or reject an initial theory on the chronology.

6. Elis

Elis is located within a fertile valley of the northwestern Peloponnese. According to ancient tradition (e.g. Homer *Od*. 21.347; Polybius 4.73.5-10), the Eleans resided in a number of small agricultural communities until a synoicism in 471/0 BCE led to the creation of Elis (Roy 1997; 2002). However, the archaeological evidence demonstrates that a settlement existed on the site before this time. A modest collection of Bronze Age and geometric graves, bronze objects, and pottery attests to an earlier phase in the city's history, as do some archaic painted architectural terracottas and an early sixth century BCE bronze judicial inscription (Eder and Mitsopoulos-Leon 1999; Eder 2001). The Austrian Archaeological Institute at Athens initiated fieldwork at Elis from 1910-1914 (Walter 1913; 1915; Tritsch 1932). They found a number of public and religious buildings in the agora and an artificially constructed theater northeast of the agora. Excavations came to an abrupt end with the onset of the First World War. From 1960-1990 the Austrians returned to conduct an architectural and chronological analysis of the buildings within the agora and during this time the Archaeological Society at Athens and the Archaeological Ephorate of Eleias broadened the area of archaeological exploration to include the region of the theater and other sectors of the city. Most significant of these was the excavation of a commercial and residential zone south of the agora with three streets arranged in an orthogonal manner (*Archaiologikon Deltion* 56-59, pp. 479-496). In their present state the roads and buildings date to the Roman Imperial period, but probings beneath the streets confirm that they were first surfaced as early as the fifth century BCE. A geophysical survey using magnetics and electrical resistivity was conducted in 2003 by the Aristotle University of Thessaloniki and the Institute for Mediterranean Studies (FORTH) (Tsokas *et al.* 2012). The survey succeeded in identifying orthogonal streets extending westward from the agora. Together with the streets south of the agora in the commercial and residential quarter, the geophysical data provided reasonable verification that Elis was a planned Peloponnesian settlement. The remainder of the urban environment remains vaguely understood.

Vegetation indices such as NDVI and SAVI have identified over 50 linear surface anomalies at Elis (Figure 4). The anomalies are divided among those whose alignments closely follow the cardinal points and those whose alignments do not. Anomalies concentrate predominantly in regions south and southwest of the agora. Only a limited number were found in the northern and eastern regions, probably because of erosion activity from the nearby Peneios River. Likewise, the eastern terrain has low hills with orchards which could affect the detection of subsurface features in satellite remote sensing. Many of the anomalies at Elis designate a system of organized streets in the southern and southwestern regions of the city. The arrangement and metrology of these anomalies, together with their relationship to streets identified in the 2003 geophysical survey and through excavations, are

Figure 4. SAVI feature enhancement applied to GeoEye-1 20 July 2009 showing anomalies (indicated by yellow arrow) that relate to buried orthogonal streets at Elis.

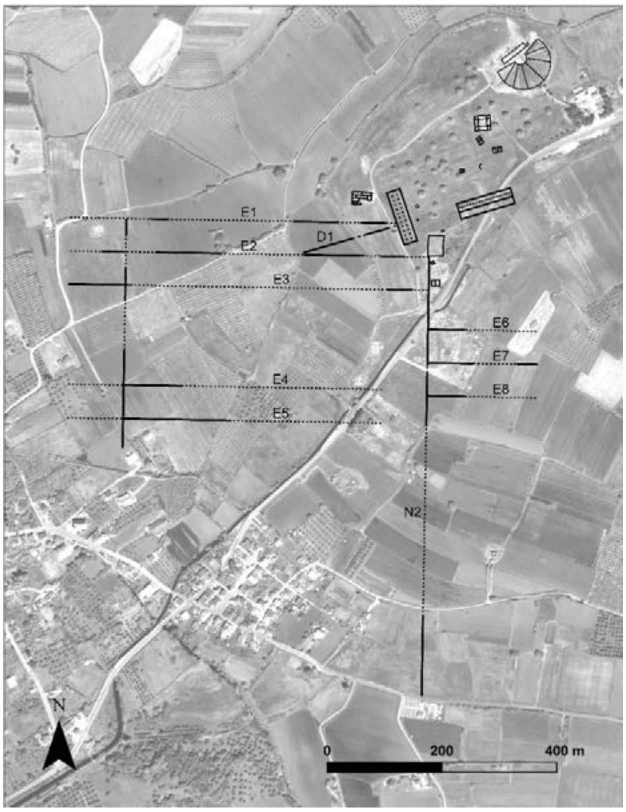

Figure 5. A partial reconstruction of the orthogonal street system at Elis. Streets in solid black are confirmed by surface anomalies.

good evidence. A recurring pattern at Elis is a system of east-west anomalies spaced between 57-59 m (Figure 5). The streets identified in the 2003 geophysical survey fall within this range, and, in every instance, additional evidence for their projected courses comes from satellite remote sensing. The location of anomalies marking an orthogonal network of streets is particularly useful in estimating the urban extent of Elis, which unlike Mantinea and even Pherai is meagerly documented. Streets in the southwestern region are at a minimum distance of 500 m from the agora. Their orthogonal arrangement is very much indicative of an organized network of streets inside the city. The southern parameters of the city are more opaque. One road extends 600 m beyond the agora, but, as an isolated feature, it would be premature to speculate whether its whole course falls within the city.

7. Conclusion

Anomalies identified with satellite remote sensing methods at Mantinea, Pherai, and Elis unmistakably relate to a subsurface system of orthogonal streets at these cities. The evidence demonstrates rather lucidly that these settlements were planned according to Greek urban trends during the second half of the first millennium BCE. If the results effectively underline the rewards of satellite remote sensing in Archaeology, it is equally important to reflect on the inherent unpredictability and limitations of its application. Buried road networks and especially organized urban systems can be fairly easy to recognize in feature enhancement indices. Mantinea must be singled out as an exceptional case where satellite remote sensing methods can be used as a primary archaeological tool for reconstructing a large part of the urban street system. However, near-surface architectural features at this site and others were not evident in the satellite imagery, either on account of modest building materials or the size of features. At all three sites a subsequent geophysical survey from 2014-2015 by the GeoSat ReSeArch Lab found extensive evidence for buildings, both large and small. Elsewhere, my application of satellite remote sensing was not effective in finding buried roads. At the Hellenistic settlement of Demetrias in Thessaly, two different satellite images identified only a handful of surface anomalies that could plausibly be associated with the ancient city. Yet a geophysical survey found numerous near-surface orthogonal roads and buildings. The ground conditions at Demetrias mostly consist of flat fields with low vegetation, not unlike the surroundings at Elis or Pherai. Other factors, such as climatic and soil conditions or the depth of features, may have played a role. Moreover, it is possible that satellite imagery from a different year and season would produce better results. At the Greek and Roman city of Gortyn on Crete, I also failed to locate many anomalies connected to the ancient settlement. In this case, however, the site is heavily covered by olive tree orchards, which makes it challenging to identify surface anomalies using vegetation indices. It is also worth mentioning that remote sensing methodologies, geophysics included, cannot establish the chronology of buried buildings and street systems at ancient cities. Hypotheses can be proposed based on the structure of certain architectural features, but a firm dating must come from ground truthing and artifact analysis.

Overall, the benefits of satellite remote sensing should be obvious in this brief presentation. Remote sensing was able to extract valuable information about buried features of archaeological interest on a vast scale. Traditional fieldwork and geophysical prospection using conventional equipment would require many months, if not many years, to obtain similar results with much higher operational costs. The evidence for town planning at Mantinea, Pherai, and Elis should only be the starting point for unravelling the urban dynamics at these cities. Geophysical prospection and targeted excavations can and should be employed to confirm the results with greater resolution and to fill in the gaps, most notably in the detection of architectural features like residential houses and to better establish the chronology of the town plans. Although satellite remote sensing can be implemented quite effectively as a stand-alone method for exploring past landscapes, it is used to even greater effect in conjunction with other methodologies.

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More Than Line of Sight and Least Cost Path. An Application of GIS to the Study of the Circular Tombs of South-Central Crete

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Abstract: This paper falls within the scope of GIS-based studies of past landscapes. Visibility and movement analyses are implemented in order to explore two specific questions and, in this way, shed light on some of the criteria that influenced the location of circular tombs in the Prepalatial landscape of south-central Crete (3100/3000-1900 BC). First, viewshed analyses are performed to test the hypothesis that circular tombs were located so as to offer a commanding view over their surroundings. To do so, a comparison is made between the extent of the area visible from the tombs and nearby random points. In a second phase, the recently developed focal mobility network procedure is used to address the issue of spatial connectivity in south-central Crete and assess whether circular tombs were preferably built along natural corridors of movement.

Keywords: GIS, landscape, movement, visibility, Bronze Age, Crete, tombs.

1. Introduction

'Landscape' has become a central concept in archaeological research over the past two decades (e.g. Tilley 1994; Ashmore and Knapp 1999; Forbes 2007). Offering a holistic framework to explore human/environment interactions, landscape archaeology deviates from a purely economic perspective to emphasize that places are cultural and social constructs. For its inhabitants, the world is full of significant locations that are encountered, experienced, and engaged with in the course of daily life and social practices. Landscape is inherent to human life: it is both the medium and the outcome of human actions (Tilley 1994: 23). It influences and is influenced by the actions of human agents. Through the arrangement of objects in it, space becomes an artifact that can be studied just like the rest of the material culture. Geographical Information Systems (GIS), which enable the storage, management, display and analysis of large spatial datasets, have been gradually incorporated into the archaeologist's toolbox, notably within the framework of landscape studies. However, the proponents of the phenomenological approach to landscape archaeology are generally rather skeptical as to the value of GIS-based studies. Phenomenologists, who place the emphasis on bodily experience to explore human engagement with the world, have accused GIS of providing a Cartesian, cartographic and dehumanized representation of space. Tilley's and Thomas' quotations are particularly explicit in this respect:

> 'Ancient stones in landscapes […] cannot be known or understood simply from publications, from maps, diagrams, photographs and descriptions, because these are only representations. As representations they necessarily fail in conveying a bodily understanding of prehistoric remains. Statistical analysis, Geographical Information Systems and simulations are, if anything, far worse' (Tilley 2004: 218).

> 'Digital techniques reduce the past to a pattern of pixels, viewed on the screen on modern rationalism. It may be possible to develop a sensuous, experimental archaeology of place and landscape, which is sensitive to the rationality that renders things meaningful, but it is questionable how far this process can be facilitated by a microprocessor' (Thomas 2004: 201).

Yet, GIS practitioners have devoted much effort in developing methodologies that can help archaeologists approach past perception, experience and behavior. This is particularly noticeable in the profusion of recent publications dealing with visibility and movement, which both take a human-centered perspective (e.g. Wheatley and Gillings 2000; Lageras 2002; Chapman 2003; Fairen-Jimenez 2007; Howey 2007; Gillings 2009; Bevan 2010; Wheatley *et al.* 2010; Howey 2011; Llobera *et al.* 2011; Murrieta-Flores 2012). Such papers emphasize that, in spite of their limitations, GIS hold real potential for the study of interactions between human beings and their environment. The greatest contribution of phenomenologists has been to draw attention to the human scale and the role of bodily practice, experience and perception, but their approach is easily disputable as it is fundamentally subjective. GIS, on the other hand, address experience and perception in a quantitative manner, hence giving a chance to compare datasets, underline the existence of recurrences or differences, and, most importantly, assess the intentionality behind the observed pattern. Furthermore, GIS allow increasing the scale of the analysis much beyond the possibilities of phenomenological approaches. But recent papers also stress that, to be fruitful, GIS analyses must be theory-laden (e.g. Hacigüzeller 2012) and driven by research questions (e.g. Gillings 2009). GIS analyses are a means to an end, not an end per se. And GIS do not represent a methodology but a tool to be implemented for well-defined methodological purposes.

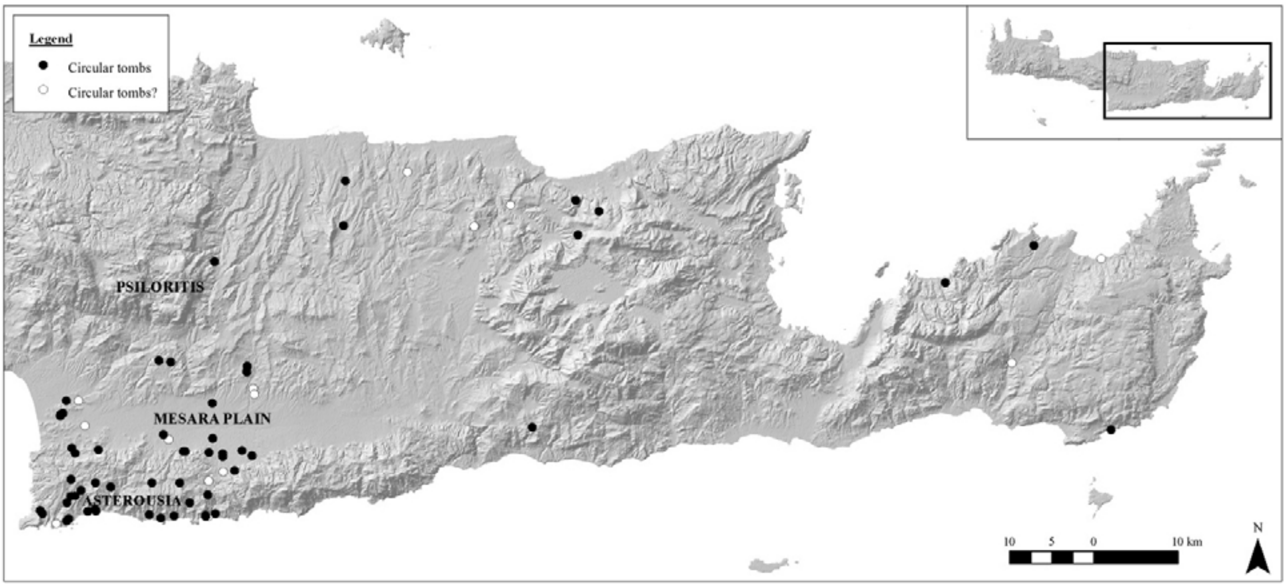

Figure 1. Distribution of circular tombs in central and eastern Crete.

This paper is based on a PhD research that was concerned with the funerary landscapes of Bronze Age Crete (Déderix 2014). A particular attention was paid to the Prepalatial period (ca. 3100/3000-1900 BC). Given the paucity of Prepalatial settlement remains, funerary assemblages are a major source of information on the millennium that preceded the construction of the Minoan Palaces. But unfortunately, Prepalatial mortuary data suffer from major documentation issues (e.g. repeated use of the tombs, looting, incomplete publications), with the consequence that many questions persist regarding, for instance, the duration of use of the tombs, funerary and post-funerary activities, or the nature of the social groups associated with the tombs. In this context of uncertainties, a landscape approach was adopted to explore the available dataset. The objective was to shed light on some of the criteria that influenced the placement of the tombs, so as to gain a better understanding of the roles played by burial places, funerary practices and the dead themselves in the society of the living. Focusing on the particular case of circular tombs, this paper illustrates how GIS-based visibility and movement analyses were conducted to address two specific questions. Were circular tombs positioned to offer a commanding view over their surroundings? And were the communities of south-central Crete spatially well interconnected? The analyses were conducted in ArcGIS 10, using a Digital Elevation Model (DEM) with a resolution of 20 m.

Circular tombs are monumental stone built structures that were used for multiple burials during the Early Bronze Age and the beginning of the Middle Bronze Age. Some remained in use (probably discontinuously) for as long as a millennium. Their inner diameter ranged between 2.7 m and 13.1 m. In several instances, the circular burial chamber was provided with a rectangular vestibule or multiple annex rooms. The identification of a series of circular buildings as Prepalatial tombs is uncertain, and thus the number of circular tombs recorded in the bibliography varies between 76 and 95 – for an updated catalog, see Goodison and Guarita 2005. Circular tombs are known so far in between 56 and 70 cemeteries (Fig. 1), either in isolation, in groups of two or three, or in association with other types of tombs. A few have been recorded in the northern and eastern regions of the island, but the majority is localized in south-central Crete – which includes the Mesara plain, the Asterousia Mountains and the southern foothills of the Psiloritis mountain range.

2. A tomb with a view?

In a pioneering study, Branigan (1998) investigated the location of circular tombs in the natural and man-made landscape of south-central Crete. Building on his deep knowledge and seasoned experience of Early Bronze Age cemeteries, he examined the settings of circular tombs and concluded that they did not occupy dominant topographic positions. This apparent lack of spatial prominence led to the conclusion that circular tombs 'were not consciously related to the natural landscape at all, and were certainly not built to dominate it or to exploit it as an accessory to social domination' (Branigan 1998: 14). Visiting circular tombs, one is tempted to agree with Branigan, given that most of them were built on hillslopes rather than hilltops. Nevertheless, assessing whether a feature is topographically prominent is more complex than simply assessing whether it is located on top of a ridge or in the bottom of a valley. In between these two extremes there is a whole range of topographic settings that afford different degrees of prominence. To use a metaphor, prominence is not 'either black or white'; it is gray-scaled. In addition, topographic prominence is relative and scale dependent – i.e. it is related to a defined neighborhood (Llobera 2001; De Reu *et al.* 2011). A feature that is dominant from close range can quickly become dominated when increasing the comparison radius. And finally, if prominence is to be explored in its totality, the pattern of visibility in the landscape must be taken into account as well (Christopherson 2003). Even though high locations tend to offer commanding views, the relation between topographic prominence and visibility is not as straightforward as it might seem at first glance. It is possible for a feature to be located higher than most of its surrounding area but, because of the local terrain configuration, to remain hidden from much of it. This section focuses on the latter issue. It explores visibility in a quantitative manner with the aim of answering the following question: were circular tombs positioned so as to visually command their surroundings?

Viewshed analyses: potential and limitations

The basic principle of visibility analysis in GIS is to determine whether two points are intervisible or not – see for instance Wheatley and Gillings 2000: 204-209. The computation relies on a DEM and works by projecting a line of sight between a viewpoint and a target cell. These two points are considered to be intervisible when all the intervening cells of the DEM stand below the line of sight. As to the viewshed analysis, it involves drawing multiple lines of sight between the viewpoint and each cell of the DEM. The end product is a binary map with cells marked as in-sight or out of sight. In theory, the area that can be seen from the viewpoint is identical to the area from which the viewpoint can be seen. However, the intervisibility between the two points is no longer necessarily reciprocal once one takes into account the height of the human observer. Whether the observer's height is added to the viewpoint (the archaeological site) or to the target cells (the landscape) modifies the observer's perspective and the question that is being asked through the viewshed analysis – i.e. 'which area is visible from the site?' or 'from which area is the site visible?'

Over the past two decades, the calculation of viewshed has been one of the most popular GIS analyses to be performed in archaeology – for a review, see Wheatley and Gillings 2002: 201-216; Lake and Woodman 2003; Llobera 2007a. Such an interest for visibility in past landscapes has been triggered both by the central role played by vision in human perception of space, and by the unprecedented possibilities offered by computer-based analyses. GIS approaches are of course not exempt from limitations. Beside issues regarding the computational process and the quality of the DEM, the most common objections raised against viewshed analyses are related to the exclusive reliance on modern topography, the absence of concern for the vegetation cover and the effect of weather conditions, the inability of the software to take into consideration parameters that strongly influence the visual impact of the features being studied (such as color, material, and contrast with the background), the difficulty of accounting for the gradual loss of visual clarity with increasing distance, and the incapacity of a static 2D map to render the complex, dynamic experience of human beings (Wheatley and Gillings 2000; Wheatley and Gillings 2002: 209-210; Lake and Woodman 2003: 693-695; Conolly and Lake 2006: 228-233). GIS practitioners, who are perfectly aware of such limitations, keep working on developing solutions to reduce their effects (e.g. Wheatley and Gillings 2000; Lake and Woodman 2003; Ogburn 2006; Llobera 2007a; Llobera 2007b; Llobera *et al.* 2010). In addition, efforts have recently been made towards the fusion of GIS and 3D technologies to explore human visual experience within urban environments in a more realistic manner (Paliou 2011; Paliou, Wheatley and Earl 2011). But when it comes to regional studies, viewshed analyses remain an unequaled means to rapidly quantify visibility on a large-scale, compare the visual characteristics of different locations, and hence gain some insights into the way past people used monuments to structure their landscapes.

The case of the Minoan circular tombs

One of the most frequent applications of viewshed analysis in landscape archaeology consists in comparing ancient sites with locations that did not yield archaeological remains, so as to explore the decision-making process that led to the positioning of the sites. Indeed, if it is of interest to describe the visual structure of past landscapes, it is crucial to evaluate whether it is just a stroke of luck or the outcome of meaningful decisions. Comparing the Neolithic mounds of Salisbury (England) and random points drawn from the same region, Wheatley (1995) was in this way able to prove that the mounds were deliberately erected in areas affording both extended viewsheds and intervisibility with other mounds. Similar examples abound in the literature (e.g. Ruggles and Medyckyj-Scott 1996; Fisher *et al.* 1997; Lake *et al.* 1998; Lake and Woodman 2000; Lageras 2002; Roughley 2004a; Roughley 2004b). Such applications generally proceed in a similar manner: 1. a region characterized by a high density of archaeological sites is delimited, 2. the visual attributes of the sites are defined and compared with those of random points distributed across the region, and 3. a statistical test of significance is conducted to assess whether the results obtained for the sites are different enough from those obtained for the random points to confirm the hypothesis that the location of the sites was not merely the result of chance. A different procedure was implemented to explore the visual structure of the landscape of the dead in Prepalatial Crete. The location of cemeteries is usually strongly influenced by the place of dwelling of the associated communities. Tombs are therefore local features that must be studied accordingly, in comparison with a local neighborhood. Given the contrasted topography of south-central Crete, which includes hills and mountains, coastal zones, valleys and an extended plain, this neighborhood was conventionally chosen to be 500 m in radius, which seems large enough to ensure meaningful comparison while retaining the local character of the burial sites.

52 cemeteries of circular tombs were examined, mostly in south-central Crete but also further to the north and to the

east. Only the sites identified with certainty and located with sufficient accuracy were considered. Each one of them was studied individually and in relation to its 500 m radius neighborhood with the following question in mind: do the cemeteries afford more extended viewsheds than nearby locations? The extent of the area visible from the burial sites was in this way compared to the extent of the area visible from 100 points located within a distance of 500 m from the site. The analyses were limited to the island itself, hence leaving aside the possibility that the tombs offered wide sea vista. A total of 15,756 individual viewsheds were computed and processed in the course of three sets of analyses based on different parameters. In every case, an offset of 1.5 m was added to the observer points, accounting for the position of the observer's eyes. For the first set of analyses, the 100 random points were selected anywhere within a 500 m buffer drawn around the site, and the viewing radius was set up at 50 km. It goes without saying that at a distance of 50 km, only the major topographic features can be outlined by the human eye, and only in case of clear atmospheric conditions (Higuchi 1988: 14). Such a long distance nevertheless accounts for the existence of an open view. The same viewing radius was used for the second set of analyses, but slope was added as an extra constraint when generating the random points. Indeed, even if Bronze Age people had sought to construct circular tombs at important viewpoints, they would still have had to cope with the terrain and restrict their choice to topographic units able to accommodate large buildings. Based on the topographic characteristics of circular tombs, it was decided to set the gradient threshold at 16°. For each burial site, 100 random points were thus automatically generated in land tracts situated within a 500 m radius from the site and characterized by a slope index of maximum 16°. The slope constraint was kept for the third set of analyses, whereas the viewing radius was reduced to 5 km to explore the middle distance view (Higuchi 1988, p. 12, 17).

The calculation of these 15,756 viewsheds led to the creation of one attribute table per cemetery and per set of analyses, each table recording separately the amount of cells in-sight from the cemetery and every one of its associated random points. These tables gave a chance to assess whether individual cemeteries afford a low, medium or high visibility in comparison to their own surroundings. Each table was treated independently. The 100 random points were subdivided in 10 ordered classes defined in such a way that each comprised exactly 10% of the random points – class 1 corresponding to the locations that offer the lowest visibility over the surroundings and class 10 to those that offer the most dominant views. The burial site itself was then assigned to one of these classes according to the breaking values obtained by this means. The graphs describe the relative extent of the area visible from the cemeteries and the random points, for each set of analyses (Fig. 2), whereas the map illustrates the result for the third set (Fig. 3). In all three instances, one observes a strong underrepresentation of circular tombs in the left half of the chart and a corresponding overrepresentation in the right half. Kolmogorov-Smirnov tests confirmed that the difference between the sites and the random points is large enough to be statistically significant at the 0.01 confidence level. In other words, the cemeteries considered in the analyses offer a wider view over their surroundings than they would have if they had been randomly distributed within their 500 m radius neighborhood. This underlines the existence of a clear concern for visibility in the decision-making process that led to the location of circular tombs. The latter indeed offered commanding views over their surroundings, and as emphasized by additional viewshed analyses concerned with the tombs themselves (Déderix 2014), they functioned as landmarks in their local landscapes. This actually comes as no surprise, as one may expect that monumental buildings were meant to be seen. The tombs exerted a strong physical presence on the land, emphasizing their significance for the human groups who invested much effort in their construction. Because of their architectural and locational characteristics, circular tombs became reference points in their local landscape.

3. Modelling movement in south-central Crete

It has been suggested that circular tombs functioned as 'visible expressions of the stability and identity of the community' (Branigan 1998: 19). However, small-sized communities such as those that built and used circular tombs cannot live in isolation; they need to interact with each other for the exchange of goods and people. Several researchers have recently argued that the adoption of circular tombs actually represented a way for local communities to reinforce their membership to a wider, regional group (Relaki 2004; Legarra Herrero 2009: 37-38). In this context, there is much to be learned in exploring interactions in south-central Crete. GIS offer more particularly the opportunity to examine the spatial aspect of interactions. Spatial proximity is neither a necessary nor a sufficient condition for the development of social networks. Nevertheless, people have more chances to meet and interact when they can rapidly and easily reach each other. This section focuses therefore on the issue of movement to explore potential connectivity between circular tombs. Even though the association between cemeteries and settlements in south-central Crete is a controversial matter, it is generally accepted that the living resided in relatively close proximity to the tombs – i.e. usually within a distance of 250 m (Branigan 1998; Déderix 2014). The connections observed between the tombs can thus shed some light on the connections that existed between the associated communities.

Exploring mobility in a digital environment

Through cost surface analysis, GIS offer the opportunity to explore movement at the regional scale. This is of particular interest in the case of cultural contexts that lack material evidence of ancient routes. Relying on a friction map that represents the cost (often expressed in time or energy) of crossing each cell of a raster, cost surface analysis calculates accumulated costs of moving from one

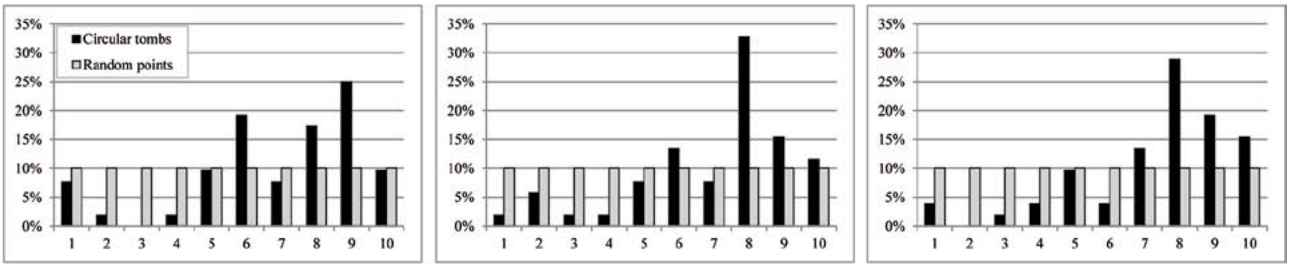

Figure 2. Distribution of circular tombs and random points in the 10 visibility categories (from left to right: set of analyses 1-3).

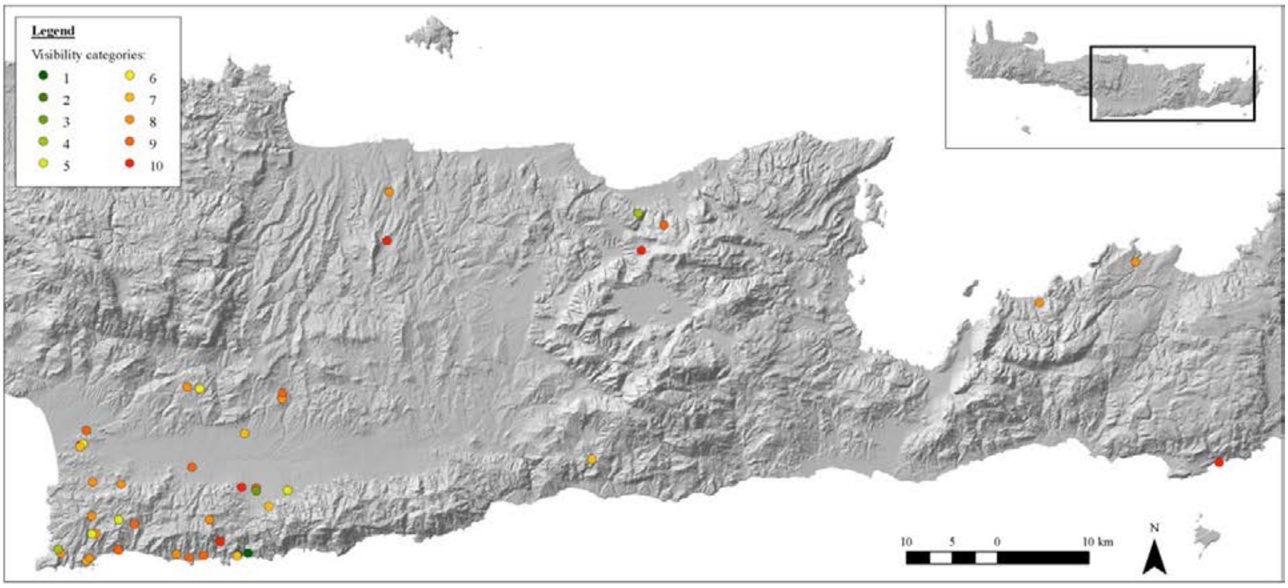

Figure 3. Distribution of circular tombs in the 10 visibility categories.

or multiple origins (Wheatley and Gillings 2002: 151-159; Conolly and Lake 2006: 214-225; Surface-Evans and White 2012). Within the field of archaeology, it is most often used to calculate least cost paths between pairs of sites, or to explore the phenomenon of territoriality on a more humanistic basis than allowed by as-the-crow-flies distances (e.g. Gaffney and Stančič 1991: 36-42; Gaffney *et al.* 1996; Hare 2004; Wheatley *et al.* 2010: 393-397). As far as Bronze Age Crete is concerned, one must refer to Bevan, who implemented cost surface analysis to model palatial territories for the purpose of a research project devoted to the political geography of the Neopalatial period (Bevan 2010; see also Bevan and Wilson 2013). The calculation of accumulated cost surfaces and least cost paths is not without its problems, however. Besides the scarcity of available information regarding paleo-environmental conditions, there are issues about the definition and the quantification of factors impacting on movement, the use of isotropic vs. anisotropic algorithms, as well as the spreading algorithm employed to generate the accumulated cost surface. All these introduce imprecisions or even errors in the model. But least cost path modeling also suffers from more conceptual issues – for a detailed discussion, see Branting 2012. GIS-based analyses of movement indeed assume that travelers are familiar enough with the landscape to know which one is the most efficient path between a starting point and a destination, and that they are willing and able to follow that one path. Yet, this is not always the case. Least cost path modeling also assumes that each pair of sites was connected by means of a direct route, which is, again, far from the case. As such, least cost paths offer limited insights into wider, global patterns of movement.

But more recently, several researchers have approached mobility in a less archaeologically constrained manner, exploring potential patterns of movement instead of tracing discrete paths among known archaeological sites. Addressing the issue of differential accessibility in the landscape, Llobera (2000) created a routine to define the average cost of moving to the destination from all the cells within a defined searching radius. Murrieta-Flores (2012), on the other hand, focused on the impact of natural areas of transit in the location of prehistoric sites in southwestern Iberia. To do so, she used natural entry points to her study area (i.e. passes) as nodes for the calculation of multiple least-cost paths. The density of the routes modeled in this way was then quantified to highlight corridors channeling movement. Similar methodologies have been implemented that consist in calculating the density of paths generated

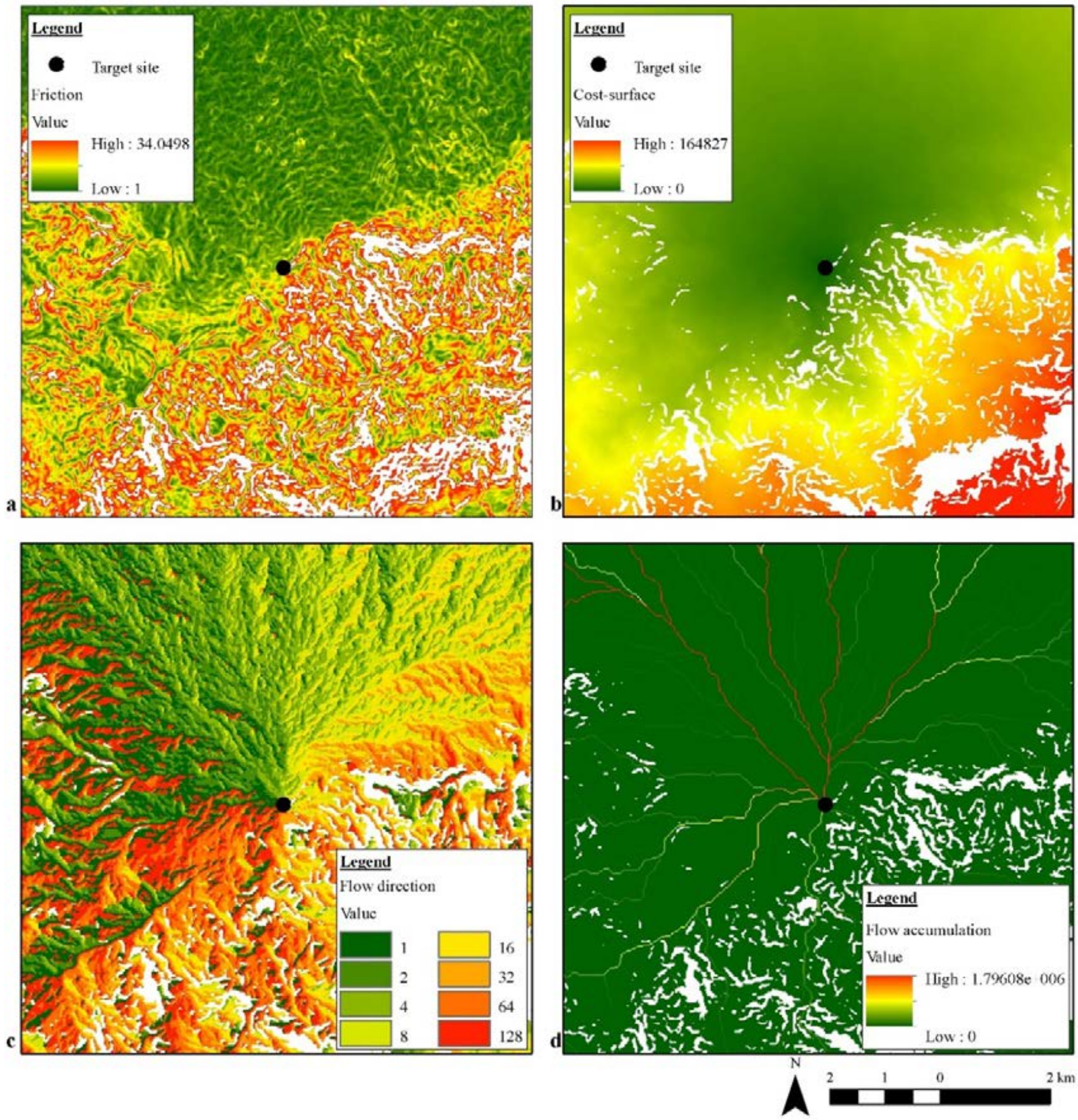

Figure 4. Steps to be undertaken to generate a focal mobility network: a. definition of the friction map, b. calculation of the cost-surface, 3. modeling of the flow direction, and 4. computation of the flow accumulation, i.e. the focal mobility network per se.

from regularly spaced points laid out across the entire study area (Verhagen 2013) or along its border (Whitley and Burns 2008). Such methodologies conceive travel in the landscape as a function of the characteristics of the sole natural environment. If they offer new opportunities to predict the location of archaeological sites or assess whether known sites tend to be found in close proximity to areas of natural accessibility, they also present the risk of falling into the trap of environmental determinism (Fábrega-Álvarez 2006: 7). To examine connectivity between circular tombs, it was decided to use the focal mobility network procedure, which was specifically designed by Fábrega-Álvarez (2006) as a middle-way between analyses that are strictly limited to the calculation of discrete paths between known archaeological sites and those that disregard available cultural data in the course of the computational process – see also Llobera *et al.* 2011.

Focal mobility networks in south-central Crete

Focal mobility network represents an approach to movement without an origin (Llobera *et al.* 2011). The procedure models optimal routes channeling movement towards a given destination from a defined area. Instead of requiring the definition of a specific starting point, it offers the opportunity to shed light on those directions from which access to the target location is the easiest or the fastest. The procedure combines cost-surface analysis and hydrological modeling – for details, see Fábrega-Álvarez 2006; Llobera *et al.* 2011. Just like hydrological modeling calculates the flow of water across the terrain to derive a stream network, focal mobility network produces a system of paths based on an accumulated cost-surface. The process involves a series of steps (Fig. 4), the first of which is the creation of an accumulated cost-surface for

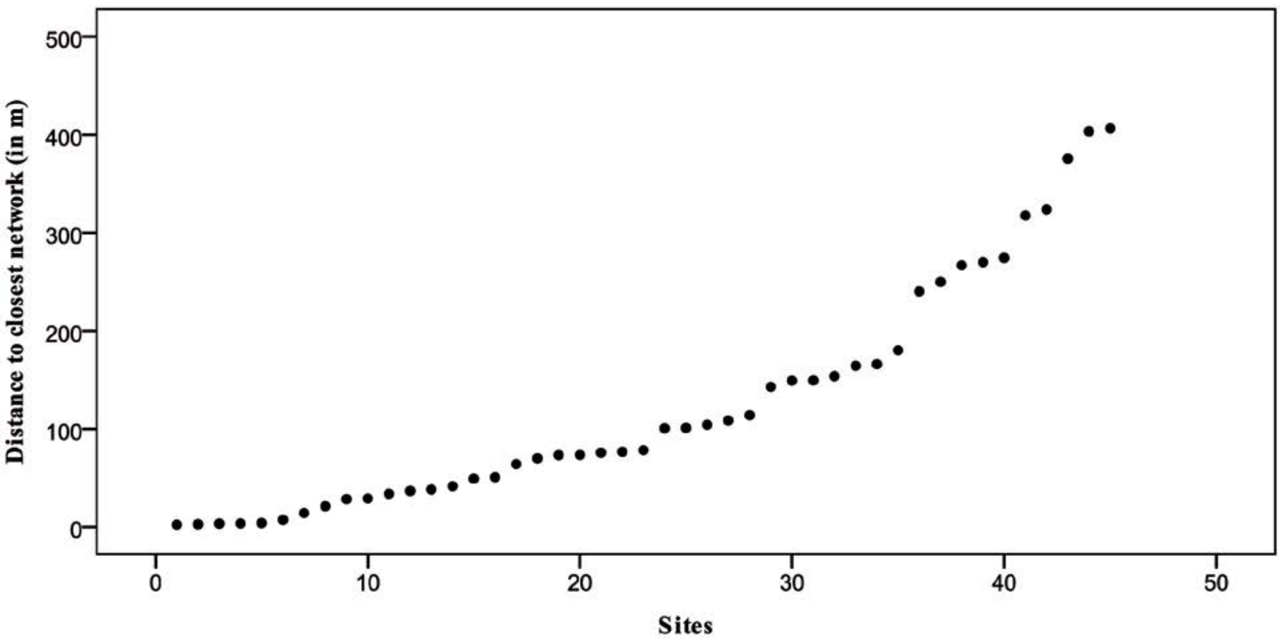

Figure 5. Distance (in meters) between 45 cemeteries of circular tombs and the nearest focal mobility network – n: 45, min: 2 m, max: 406 m, mean: 125.3 m, standard deviation: 115.73 m.

the target site (Fig. 4.b). In the case of south-central Crete, the cost-surface was created on the basis of a friction map produced by means of Bell and Lock's formula (2000: 88-89): C = tan *s*/tan 1, which defines the relative cost (C) of moving up or down the slope as the tangent of the slope (*s*, in degrees) divided by the tangent of 1°. However, relying on the conclusions of physiological experiments (Proffitt *et al.* 1995), it was decided to exclude from the analysis all the cells characterized by a slope steeper than 30°. These cells were reclassified as 'NoData' so that they would function as actual barriers (Fig. 4.a). As a second step, a flow direction model, which is more traditionally used to represent the direction in which water would flow on the terrain, has to be calculated from the cost-surface (Fig. 4.c). And finally, the flow direction map can be used as the input for a flow accumulation analysis, which outputs the focal mobility network (Fig. 4.d). The latter corresponds to a raster outlining the optimal paths leading to the target site. The relative importance of each path depends on the number of cells that 'pour' into it. The larger the number of cells, the greater the importance of the path. Since the model relies on a cost-surface, the accumulation rate of cells increases the closer we get to the target site, which results in this distinctive road system irradiating around the site. Once calculated, the focal mobility network can be reclassified to conceal low values – i.e. minor paths – and stress significant areas of passage. There is no rule as to which threshold value to use to do so, but the lower the value the greater the number of paths to be created.

In order to describe the location of circular tombs with respect to optimal routes of access to each one of them, focal mobility networks were created individually for 45 burial sites identified with certainty and located with sufficient accuracy. No distance limit was specified, allowing the paths to run across south-central Crete. The resulting raster surfaces were then reclassified in such a way that a cell was assigned to a branch of the network in case a minimum of 5000 cells 'poured' into it. Considering the resolution of the DEM and the extent of the study area, 5000 is admittedly quite a low threshold. It presents the advantage of outlining optimal paths well away from the target site but runs the risk of leading to the creation of an extremely dense network closer to this site. Eventually, the raster files were converted to polylines, and the shortest distance between each cemetery and the networks modeled for every one of the remaining cemeteries was calculated. The measurements provide a picture of close proximity (Fig. 5). The values range between 2.4 m and 406.4 m, with a mean of 125.3 m. More specifically, 23 out of the 45 burial sites are located within a distance of maximum 100 m from at least one potential path, and their number reaches 37 at a distance of 250 m. The proximity is visually striking, as at least a dozen of cemeteries are within a distance of 250 m from every one of the focal mobility networks (see for instance Fig. 6).

The above suggests that the communities associated with circular tombs in south-central Crete were easily accessible from one another. One can however wonder: are the distance values significant? That is to say, does the proximity illustrate a real pattern of connectivity, or is it a mere consequence of the density of paths that were created by using the low threshold of 5000 to reclassify the individual focal mobility networks? A test was performed to answer this question. 45 random points were generated in the study area, their distance to the nearest path was measured, and the mean was calculated. The process was repeated 100 times to ensure validity, and in not a single instance did the mean obtained for circular

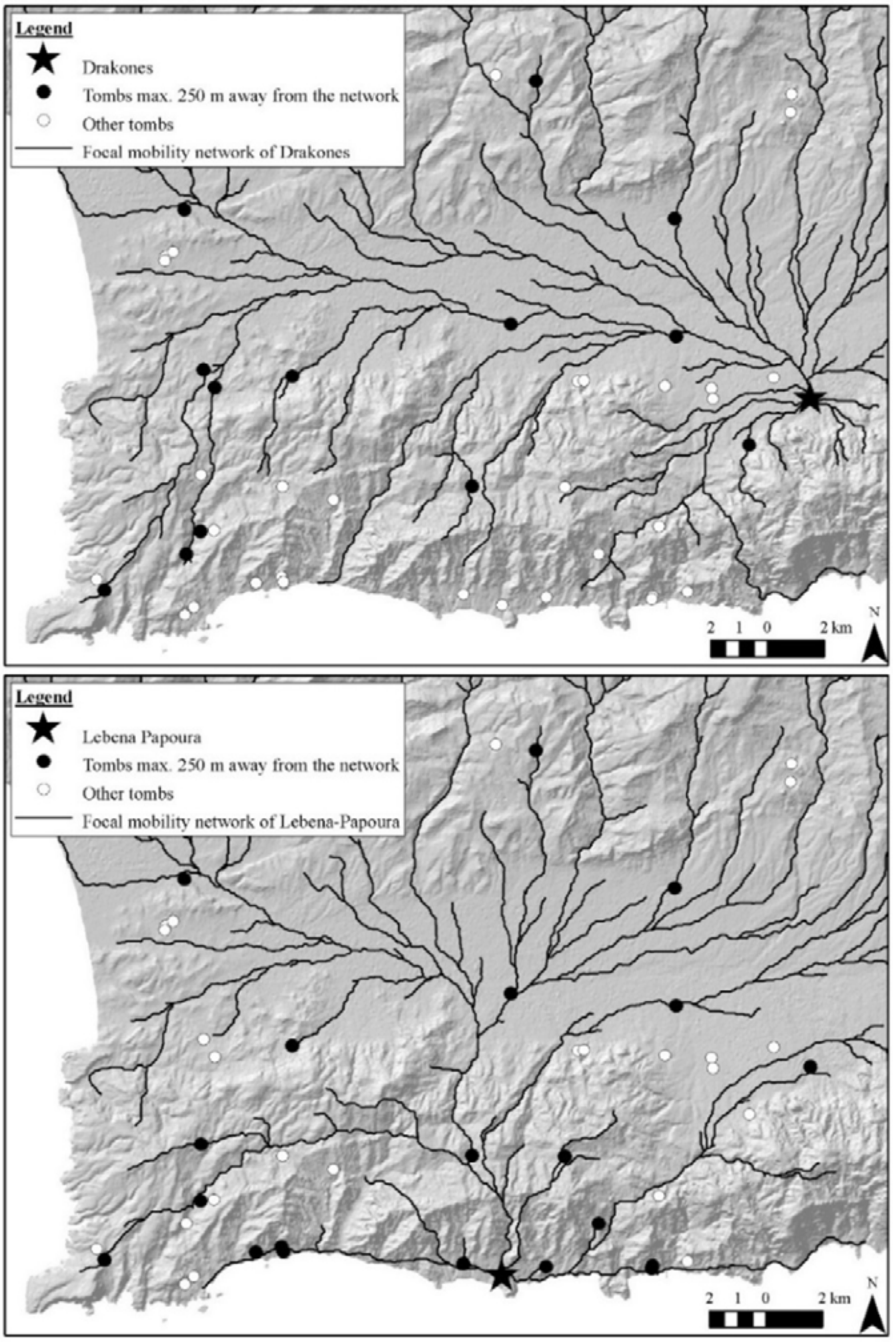

Figure 6. Spatial relation between circular tombs and the focal mobility networks of Drakones (above) and Lebena-Papoura (below).

tombs (i.e. 125.3 m) exceed that obtained for the random points – minimum: 182.37 m, maximum: 521.88 m, mean: 263.66 m, standard deviation: 57.65 m. This indicates that circular tombs are closer to the focal mobility networks than they would if they had been randomly dispersed in the landscape. In order words, it seems that circular tombs were predominantly located along potential routes of access to other tombs, which in turn suggests that the communities of south-central Crete were easily connected. Nevertheless, it must be emphasized that the significance of the result does not apply equally to the whole south-central Crete. In hilly and mountainous regions such as the Asterousia and the foothills of the Psiloritis, movement is strongly constrained by the terrain, with the result that the individual focal mobility networks follow very similar trajectories. Remarkably, there is a strong correlation between the location of the tombs and optimal paths. In contrast, the flat Mesara enables movement so easily that the proximity between the tombs and the paths is just a byproduct of the topographic conditions of the study area.

4. Conclusion

The implementation of GIS has proven valuable in generating new information about life and death in Prepalatial Crete. According to the results of viewshed analyses, circular tombs tend to offer more extended views over their surroundings than nearby random points, which suggests in turn that visibility was one of the criteria to be considered in the course of the decision-making process that led to the location of the tombs. The visual control offered by circular tombs undoubtedly contributed to their symbolic meaning in the eyes of the associated communities. The examination of focal mobility networks, on the other hand, allows concluding that the tombs are preferably found near natural corridors of movement and optimal paths leading to other tombs. The pattern is striking in hilly and mountainous areas. Local communities were apparently able to meet and interact quite easily with each other. Far from a final conclusion, this opens future research avenues for the study of community and interactions in Prepalatial south-central Crete.

Together with many studies published recently, the analyses presented in this paper also emphasize the diversity that is nowadays observed in archaeological GIS. The discipline has long gone beyond the simple use of readily available, push-the button functionalities of the software packages. As a result, its potential for landscape archaeology and the exploration of spatial questions has increased exponentially. There is indeed much more to GIS-based visibility and movement analyses than line of sight and least cost path.

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Mixed Reality Applications, Innovative 3d Reconstruction Techniques & Gis Data Integration for Cultural Heritage

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Abstract: Mixed reality allows us to have more intuitive educational and informative experiences by integrating all the data we have from the archaeological research activities and their results into a more realistic and compelling presentation. There is a lot of information about the archaeological sites, the findings of each period, the life and characteristics of our ancestors that are not presented to a museum or outdoor site visitor at the moment, leaving him with the sense of a mediocre experience. All this information could be presented in a virtual way on top of our real view when visiting an indoor or outdoor area of cultural interest. Imagine being able to visit Phaistos site in Crete and experience through a mobile application how the ancient settlement was at the time it was built, how its residents looked like and acted and also hear their talks and observe the findings of this period. In this chapter we introduce the main technologies and software architecture that should be used as a guide for creating mixed reality applications for cultural heritage. The techniques that could be followed to provide such an experience are analyzed in the following sections, starting from the background and design methodology in this area, the latest and more effective trends in virtual 3D models reconstruction and the effective use of geographical data. Finally, a set of different applications and effective use case scenarios is presented concluding with the benefits of mixed reality for cultural heritage and the future extensions of such applications.

Keywords: mixed reality, 3D reconstruction, augmented reality, cultural heritage, archaeology, education, position and orientation tracking, GIS

Introduction

Mixed reality is the combination of computer-generated reality called virtual reality and the real-world. In mixed reality applications we move actually from the Real Environment (RE) through Augmented Reality (AR), Augmented Virtuality (AV) to a full Virtual Environment (VE), defined as the Reality-Virtuality (RV) Continuum. This means that there are many dimensions we are experiencing between the Virtual and the Real world as depicted in the Figure 1. below (Milgram 1999).

There is a continuous interest nowadays for the promotion of cultural heritage with the use of augmented reality applications that combine real and virtual content, with a focus in archaeological sites, museums, galleries and exhibitions, in order to enhance the visitors' experience. The technologies that could be used in order to develop such applications, as also the tools and devices needed, are described and analyzed further in the sections that follow. At first, we provide an overview of the methodology and the overall architecture design for developing mixed reality applications. We continue by presenting the best methods and latest tools used for creating more realistic virtual content as also the integration of geophysical survey data. Next, we propose a set of effective use cases for promoting and enhancing the cultural heritage education with the use of augmented reality and finally we present the conclusions of our study, the possible future extensions and the overall benefits of mixed reality in this area.

Background and design methodology

There is an increase of interest the last years and huge effort on the research work based on the virtual reality innovative techniques and holographic display devices,

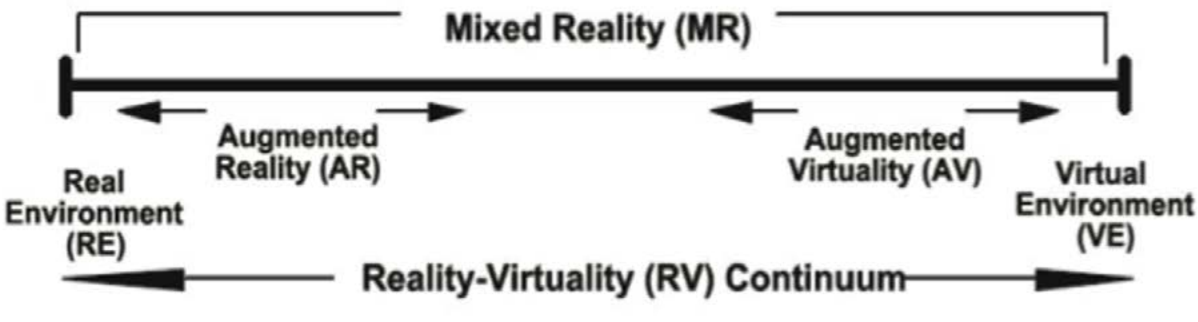

Figure 1: Mixed Reality definition by Milgram 1999

the augmented reality applications and the mixed reality use in the fields of medicine, entertainment, education and cultural heritage. Our study is based on the latest trends and best practices for the development and use of such technology for cultural heritage education. As presented on Archeoguide (Vlahakis *et al.* 2002), augmented reality could be effectively used as a new form for guiding visitors in outdoor archaeological sites with the use of holographic mobile wearable devices (HMDs) and the use of Geographical Information Systems (GIS) data during the creation of the virtual content and the design of the tour. Nowadays, the method of creating such applications has been simplified and improved with the increase on the availability of open source augmented reality Software Development Kits (SDKs), the release of new engines for 3D applications development, the improvement on the results in 3D content creation and reconstruction, the use of 'smarter' mobile devices and more effective devices for scanning and tracking.

First of all, there are more than 50 augmented reality SDK's available nowadays with several tracking and developing capabilities from which we have selected to present two: the Vuforia AR SDK from Qualcomm and the Metaio SDK. Vuforia and Metaio are the most promising and widely used AR SDKS at the moment. Metaio is the leader in 3D tracking, while Vuforia is considered as the best SDK for 2D tracking. Some of their main characteristics are presented in Table 1 below (O'Shaughnessy 2013).

Moreover, Vuforia is free but Metaio is relatively expensive even for its basic license for creating apps without watermark. Metaio though allows you to easily create cross-platform applications in JavaScript along with HTML5 and XML with the use of the AREL (Augmented Reality Experience Language) interpreter. Finally, Vuforia is a vision based SDK while Metaio can be also used for location-based AR applications.

Both of these AR SDKs can be easily integrated with Unity 3D, a game engine that allows the creation of 3D interactive applications with multi-platform support (Android, iOS, Windows). Unity 3D has its own integrated development environment (IDE) providing also an easy way of importing and handling 3D graphics and programming animations. Additionally, the mobile devices available now have increased capabilities in terms of graphics support, processing, memory and integrated sensors for position and orientation tracking (GPS, accelerometer, gyroscope).

For creating the virtual content, there is also a list of 3D graphics authoring tools available such as Blender, 3D Studio Max, Maya and others. In terms of reconstructing the real scene and objects, the latest trend to mobile scanning devices is the Project Tango introduced by Google and the Structure.io which capture dense 3D models and allow us to easily convert the real world to a virtual environment. These technologies promise a more easy and faster way for reconstructing virtual scenes or objects in real-time than applying photogrammetry techniques to create the 3D models. There has been also an extensive use of time-of-flight cameras such as the Microsoft Kinect depth sensor in the 3D reconstruction field that is still really promising and allows the volumetric depth-fusion in real-time (Shahram *et al.* 2011). Kinect has also been used along with drones in the reconstruction of indoor scenes that cannot be easily scanned by hand (Henry *et al.* 2012).

At Fig.2 we present the overall architecture and tools needed at each stage of developing augmented reality applications.

We can use the Unity 3D engine to build such an application by integrating the AR SDK of our preference. As a next step, the AR scene must be created by inserting an AR camera and importing the targets we want to use (image, text, and objects) for triggering the virtual objects. The reconstructed or created 3D content should be then imported in the scene (in FBX format) and connected to each relevant target, creating a relation of father-child. The application should be also programmed to use the mobile sensor data from the GPS, the gyroscope and the accelerometer to change the camera view but also place the virtual objects to the correct positions according to their real location in the scene. Finally the application must be selected to be built for our preferred mobile platform (Android, iOS) and exported in the adequate format.

Virtual content creation

One of the main requirements for creating a mixed reality applications is to create the virtual content. The virtual content could be a whole scene, virtual objects but also virtual characters. The use of more realistic 3D graphical representations enhances the sense of realness and therefore, the sense of presence and immersion which are key factors of the Quality of Experience (QoE) of such applications. Therefore, there is a continuous requirement for improving the quality of 3D graphics used in order to

Table 1: AR SDK comparison

AR SDK	Purpose	Tracking	Platform	GPS	License
Qualcomm Vuforia	2D Images, Markers	NFT, Marker, Text	iOS, Android	No	Free
Metaio SDK	2D Images, GEO, 3D, Anywhere	NFT, GPS, 3D, SLAM	iOS, Android	Yes	0-$10.000

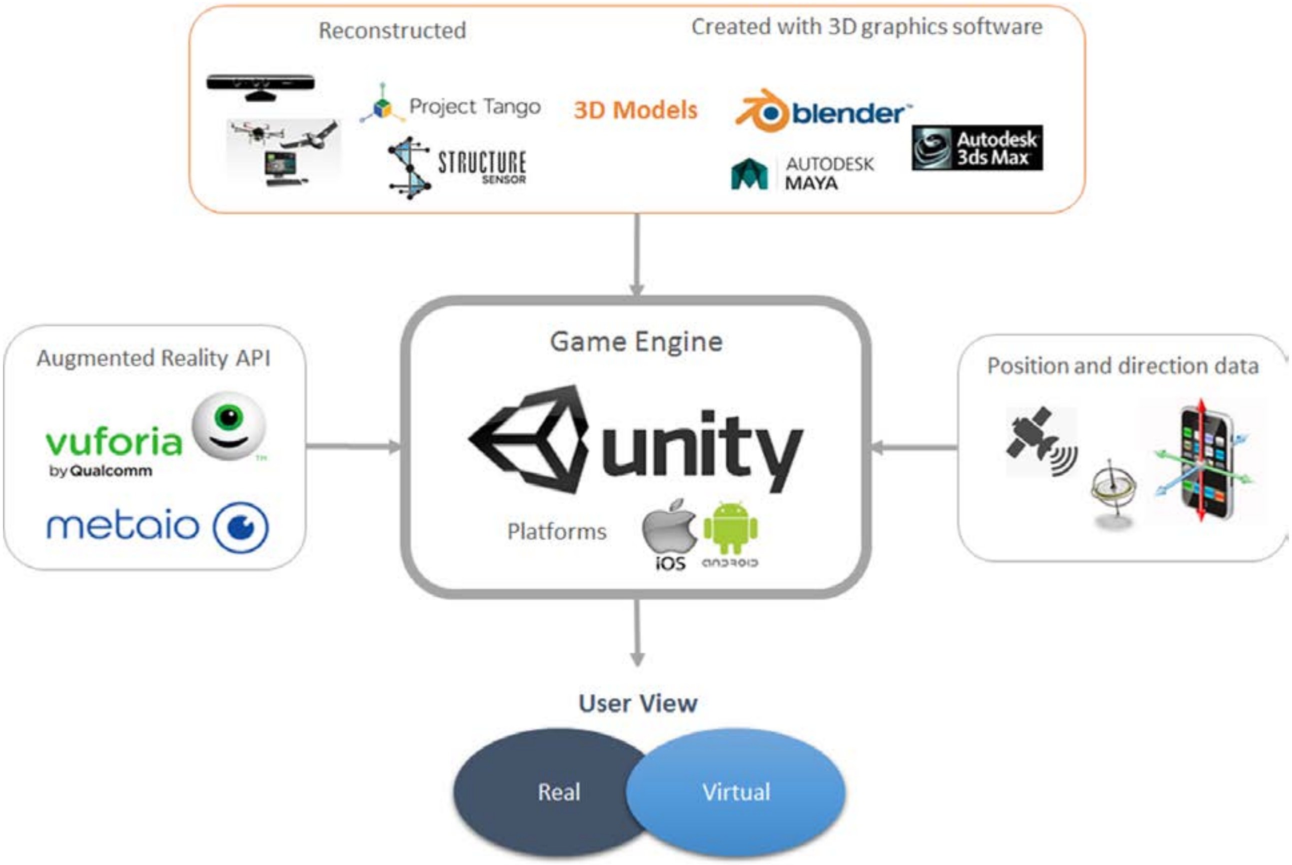

Figure 2: Augmented reality applications proposed development flow.

provide a better experience. One option is to work towards the direction of creating high quality 3D reconstructions of archaeological sites and findings. For this, we propose the use of cameras along with drones for capturing outdoor sites and monuments and process the content with photogrammetric algorithms (point cloud, RGBA-SLAM algorithms) in order to have better and more realistic results. The procedure, based on digital photogrammetry and computer vision (Mundy and Zisserman 1992; Buchanan 1993), consists in the acquisition of a number of overlapping photographs depicting the object to be reconstructed from different angles. Given the assumption that the object point, the camera's projection center and the image point are located on a straight line and the image is formed on an exact plane, as stated in the collinearity equation, the intersection of 2D elements in two or more views may be converted in 3D information. One possible approach for the accomplishment of this operation is known and the acronym SfM, that stands for Structure from Motion. According to this, only corresponding image features occurring in a series of overlapping photographs captured by a camera moving around the scene are needed. In the specific case, a sequence of images has been captured keeping the camera pointed at the different sides of the exteriors of the Venetian Castle at Heraklion, Crete (Greece) (Fig. 3). In order for the final model to be correctly scaled, oriented and positioned in space, a series of ground control points were also collected. These points, measured with a Total Station Theodolite in local coordinate system –then attached to known points of the Greek National Coordinate System EGSA87– were temporarily positioned on the wall surface in the shape of encoded circular targets. Becoming part of the 3D reconstruction, these targets could be easily located on photographs and used as reference points for the model geo-referencing. Despite the elevation of the building, between 11 and 15 meters ca. from the ground, it was sufficient to put targets at variable heights between 0 and 3 meters plus some extra targets at the very top of the walls. To complete and 'close' the model of the castle in a unique solid shape, photographs of the roof were also collected with a remotely piloted aerial system equipped with a compact camera with built-in GPS logging.

In order to minimize the photogrammetric processing, a subset of images representing only part of the entire Castle have been grouped and processed. The availability of ground control points allowed an easy post-processing merge of separate parts in a seamless point-cloud. This set of points has been converted then into a closed surface using the Poisson algorithm. Camera textures have been then projected onto this mesh with adaptive ortho-photo mosaicking technique.

Taking into account now the issue of time and effort needed, there is also the solution of creating 3D models from scratch, close to the real ones, by using 3D graphics authoring tools such as 3D Studio Max or Blender. This solution is also proposed for creating 3D models of

Figure 3: Ground and UAV photogrammetric scanning and reconstruction of the Koules Castle in Heraklion (Cantoro, G. – Politeia research project)

archaeological sites or monuments that don't exist anymore or have been destroyed but we have enough information about their overall architecture and appearance in order to create models close to the real ones. A lot of work has been also done on recreating and animating ancient virtual humans as also virtual archaeological monuments (Magnenat-Thalmann *et al.* 2007; Magnenat-Thalmann and Papagiannakis 2010) based on the appearance of the human statues and the architectural archaeological and historical analysis of the monuments and the findings of each period.

Using Geographical data

Geographical data are considered critical for the development of cultural heritage applications that present accurate information about the position and visualization of the findings of the past. The geophysical analysis and prospection techniques applied to an area allow the extraction of information about what lies beneath us. We can have a clear view of the several modifications of an area through time, the environmental changes and their effects as also the architectural elements in previously inhabited areas. After scanning an area of interest by using laser or radar methods for remote sensing, but also with the use of aerial and satellite photography, we collect enough data that we can analyze with the use of GIS tools such as the ArcGIS or QGIS for the preservation assessment of ancient structures. These tools allow us to represent our data in different layers applied on geographical maps and draw the points of interest that depict the interpretation results of the archeological or environmental analysis.

All this data can be integrated to a 3D graphics tool, such as the 3D Studio Max, in order to create a virtual terrain containing all the key georeferenced points of the archaeological site and design a model that would represent the artifacts of the past with the help of archaeologists and historians that have done research also on the same historical period. We can export then the model in a compatible format for Unity 3D, such as in FBX format in order to develop the main virtual scene with the virtual elements placed on their real position. Working now in Unity 3D towards the development of an augmented reality application, we should check first that the geo-characterized points of interest should be in WGS84 in order to proceed or not with the required transformations in the scene. The reason for doing this is to be compatible with the data received from the mobile device sensors (GPS, gyroscope, accelerometer, compass) that will be used to trigger and place the virtual elements on the user's view of the real scene at the correct position. To reach a better sense of realness in mobile mixed reality applications, the projection of the virtual objects is set according to the position data received from the GPS and the camera view is changed according to the orientation data received from the gyroscope. In this way the application is projecting the 3D models on their 'real' position while also translating the virtual camera's position according to the device's camera position.

Such a virtual reality application has been developed for the Neolithic village of Szeghalom in Hungary (Niekamp and Sarris 2014). There was first a geophysical survey

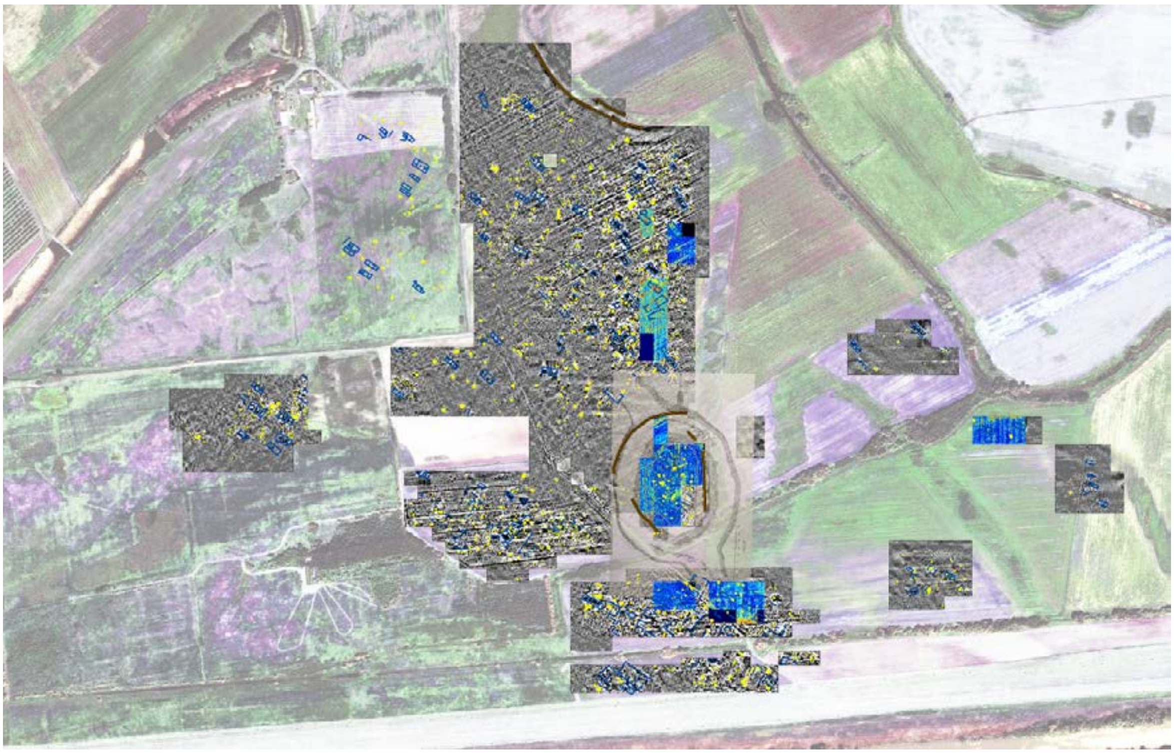

Figure 4: Geophysical survey results including magnetic and GPR from the Neolithic village of Szeghalom (Niekamp and Sarris 2014).

from which the magnetic and GPR results are depicted on the map in Figure 4.

As a next step, an interpretation of the results was made with the help of archaeologists and the elevation map including the spotted residencies was created as shown in Figure 5.

Finally, the georeferenced map where the dwellings position is depicted was integrated in 3ds Max and followed as a basis for the design and reconstruction of the ancient village as depicted in Figure 6.

Mixed reality applications

Outdoor applications with the use of geophysical data

GIS data are really useful for creating accurate virtual terrains enhancing them with spatial information. The information coming from various position and orientation tracking sensors could be combined with the GIS data to provide a view through augmented reality applications of what is underneath us. More specifically, the models created after a geophysical survey of archaeological sites could be shown as visual aspects over the mobiles' screen view while one is moving over the specific area. This could be really useful for the phenomenological analysis by archaeologists during fieldwork (Eve 2012). They could be able to view and examine the 3D models and data analysis of the previous geophysical surveys while navigating on the landscape of interest. While performing the excavation of an area, archaeologists could use augmented reality applications that project virtual element representations of the geophysical assessment in order to be able to examine further and re-design their workflow in real-time. In Fig. 7, we see an interpretation of the soil resistance, GPR and magnetic survey of the ancient city of Sikyon that could be used as a basis of the design of such an augmented reality application (Gourley *et al.* 2008).

Cultural heritage augmented outdoor applications for tourism and education

In most cases, visitors are able to look the excavated archaeological relics of a site. A geophysical survey and more specifically the interpretation of the geophysical anomalies spotted in an area of archaeological interest can lead to more accurate information about the architectural structures of ancient monuments that have been destroyed through time and provide information even for non-excavated parts of a site.

The geophysical results provide the necessary data for the design of the ground floor plan of monuments and therefore their 3D reconstruction, as depicted in Fig. 8. 3D models of these monuments can be used for the development of mixed reality applications enhanced with model representations of the findings and virtual characters of the habitants of that period in order to enhance the experience of the visitors and the level of historical education. As an example, the user of such an application could visit the ancient city of Sikyon in Greece and be immersed to the life of that period by projecting to his device the 3D model of the Bouleutirion (Fig. 9) as he/she navigates on the site.

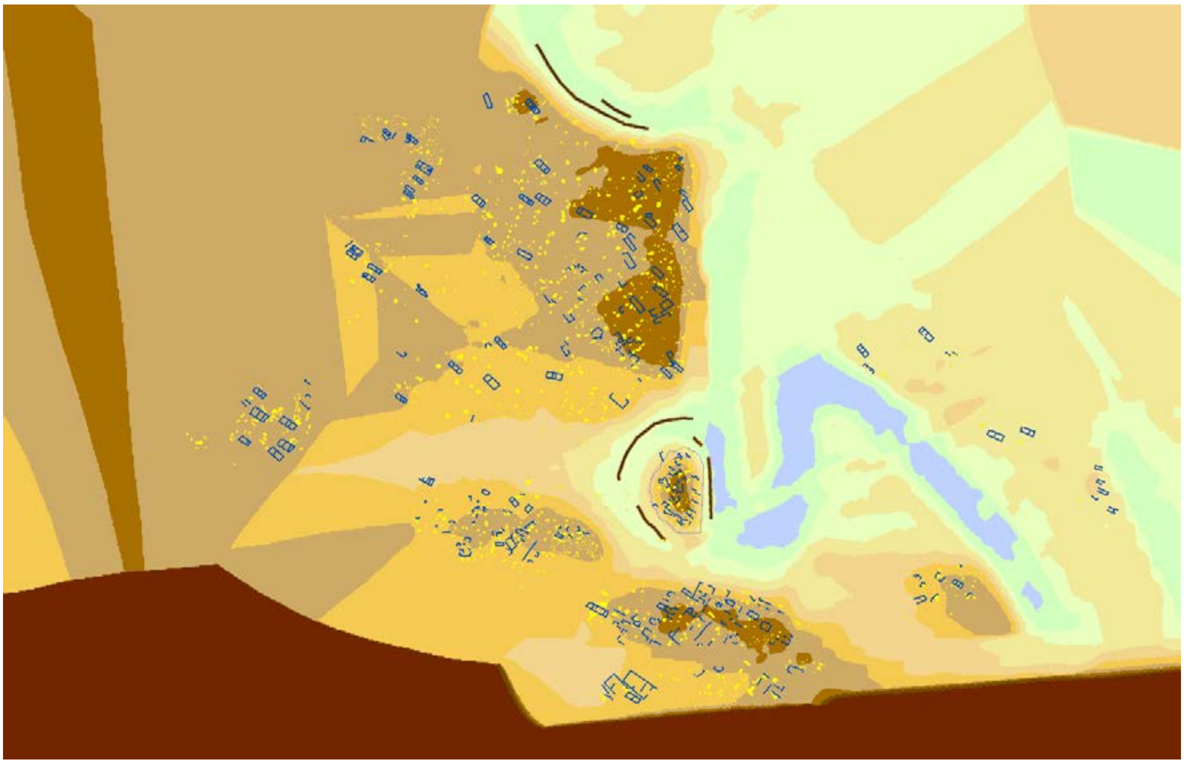

Figure 5: Elevation map and interpretation derived from the geophysical survey of the Neolithic village of Szeghalom, Hungary (Niekamp and Sarris 2014).

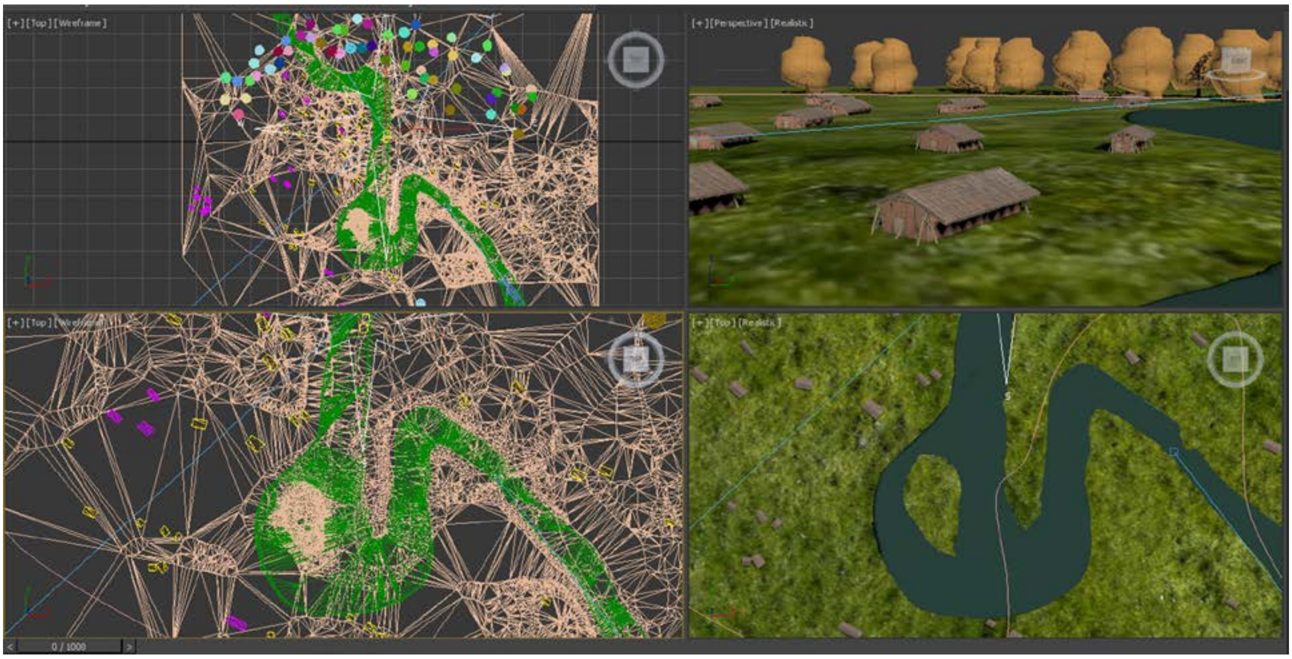

Figure 6: Integration of GIS data to 3ds Max and reconstruction of the Neolithic village of Szeghalom, Hungary (Niekamp and Sarris 2014).

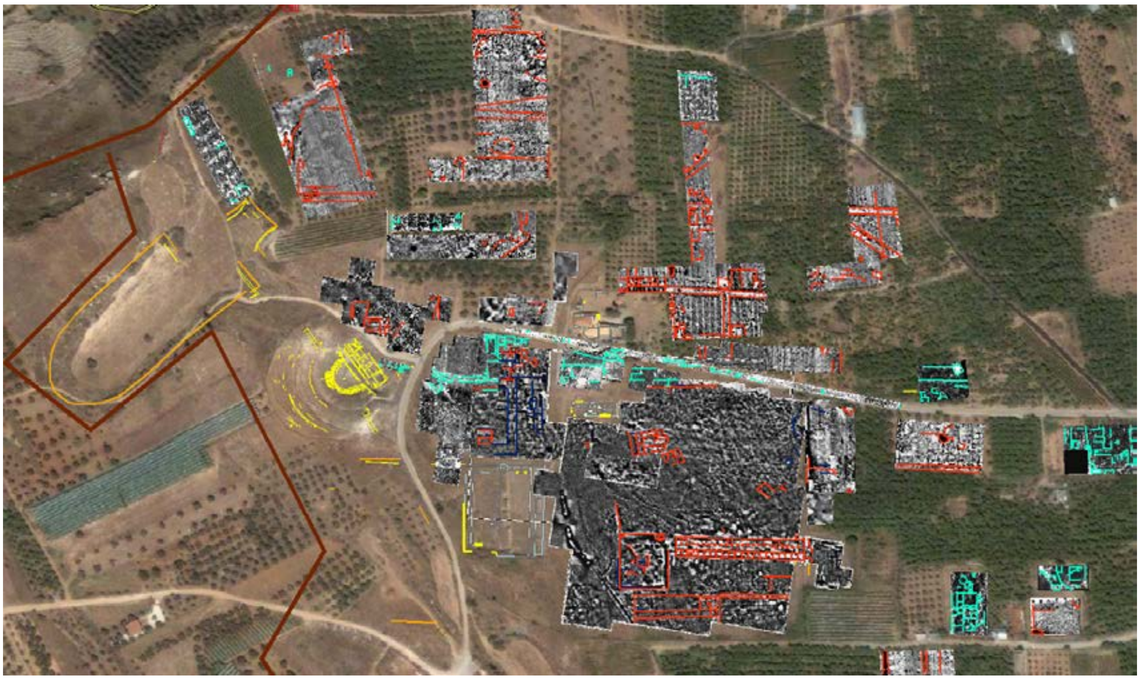

Figure 7: Soil resistance, magnetic and GPR survey data from the area of ancient agora of Sikyon (Gourley *et al.* 2008).

Figure 8: Synthesis of the Bouleutirion and Stoa 3D models in the area of the ancient city of Sikyon (Gourley *et al.* 2008).

Figure 9: 3D reconstruction and modelling using realistic textures based on the findings at the wider region of Sikyon (Gourley *et al.* 2008).

At the same time, he/she could be able to view 3D text of historical information, models of the findings and virtual actors that would be animated representing a daily life scenario. Spatial sound techniques are playing also a key role to the enhancement of such an experience as Unity 3D offers the option of adapting the level of the sound as the user moves closer to the source. In this way, the visitors could listen to dialogues of the virtual characters being in the area of the Bouleutirion or at the Stoa while navigating closer to the place where these monuments used to be.

Storytelling educational applications

Mixed reality applications can be also adapted for creating augmented storytelling experiences for enhancing our visit to museums and exhibitions but also in school. Text, images, but also small objects can be tracked and allow the triggering and presentation of adequate 3D models along with 3D text and voice-over explanations creating an enhanced interactive experience. These kind of applications could be either used indoors for enhancing the educational methods at schools, or outdoor by recognizing text or images depicted on the archeological sites' signs for example (Keil 2013). Once the image, text, or object is tracked, the relevant 3D model is displayed on the devices screen and can be explored from all sides by moving the camera at different angles. This leads to more informative and immersive experience that could easily enhance the level of quality and edutainment in cultural heritage educational trips. Such an application accompanied by a printed map of Crete, enhanced with aerial photos of the most attractive ancient monuments has been created (Fig. 10) in order to inform its users about the history of the island through a 3D non-linear digital storytelling experience. The user uses an Android mobile device and hovers over the images of the monuments on the map. When an image is recognised, the relative 3D model of the monument can be observed along with its 3D text label. The user can then press the relative buttons that appear and listen to the historical information of the specific monument in its preferred language (Greek or English) learning about their story of preservation and their role in the past. The application was introduced to the audience during the European Researchers Night in September 2014 where educators showed a high interest on the potentials of augmented reality in education.

Virtual gallery exhibition applications

Mixed reality applications could also be used for creating virtual gallery exhibitions by projecting 3D virtual artifacts in the form of holographic models. Unity3D game engine provides the capability to set a custom camera projection matrix in order to adjust the camera's field of view in real time. Setting a custom projection matrix could be used for projecting 3D models (archeological findings, artifacts) in a real scene, allowing the visitor to view a projection of three dimensions. This is achieved by changing dynamically the perspective view of the model depending on the visitor's head position and orientation. In order to track the visitor's head position and direction, a Kinect sensor is being used and the appropriate projection matrix parameters are adjusted accordingly (Garstka and Peters 2011). Kinect, through its infrared (IR) sensor, has the ability to track humans in detail and follow their movement. By using the Kinect's SDK, information about the joints of a tracked human body can be extracted. By combining the capability of tracking the head of a human body in world

Figure 10: Android Augmented Reality application for the monuments of Crete

space coordinates with the option to change the projection matrix in Unity, the development of applications that give the user the holographic effect illusion by observing a 3D model projected in real space is made possible. The users have the opportunity to view every angle of the model just by moving around the area where it is projected. Such applications can be effectively used in museums or galleries in order to exhibit 3D models of archeological findings or art, simply by placing a projector device in the museum's ceiling, projecting to a flat surface, and a Kinect sensor to an appropriate location in order to be able to track visitors.

Conclusions

There is a huge potential in enhancing the level of interest to cultural heritage by increasing the attraction of visitors to archaeological sites, galleries, museums with the development and use of mixed reality applications. Through mixed reality, the overall experience in becoming more immersive, more interactive and more interesting. By using also realistic visual aspects, the edutainment factor is increased, leading to a higher level of quality of experience for the users. These applications are also useful in the area of education as they provide a more interactive and interesting way of learning about history and art.

New tools and methods for creating and experiencing such applications are being developed day by day leading closer to more realistic immersive experiences but also making their development easier and faster. The capabilities offered by the AR SDK's are increasing over time in terms of tracking accuracy and stability in performance. Smart devices are becoming 'smarter' increasing their sensors efficiency, their camera resolution and their processing capabilities. New wearable devices (such as the holographic projection devices and virtual reality glasses) for experiencing such applications are being developed. Moreover, the integration of results of the work coming from the research and analysis in several areas such as in archaeology, geophysics, art and computer science, could lead to the creation of more effective and realistic experiences that allow a better sense of 'being there'. Mixed reality can, and therefore will, revolutionize the way we learn about art and history and will change significantly the way we experience and interact with the past.

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Interpreting the Past through Agent-Based Modeling and GIS

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Abstract: The past decade has seen archaeology taking an increasingly high interest in agent-based modeling (ABM). ABM's emerging popularity is due to its ability to model individuals and societies, readily incorporate any geospatial data available, and encompass uncertainty inherent in archaeological theories or findings. Indeed, the unpredictability of interaction patterns within a simulated agent society, along with the strong possibility of emergent behavior, can help researchers gain new insights into existing theories; or even come up with completely novel explanations and paradigms regarding the ancient societies being studied. Agent-based modeling is thus a potentially powerful tool, which can be used to assess the plausibility of alternative hypotheses regarding ancient civilizations, their social organization, and social and environmental processes which might have existed. The purpose of this chapter is to provide an overview on ABM and corresponding methodologies, and present examples of recent work that has applied geospatial agent-based models in archaeology.

Keywords: agent-based modeling, multi-agent systems, archaeological simulation, geographical information systems, social archaeology, computational archaeology

Introduction

The study of social and environmental change is key to improving our current understanding of human behavior and history. Nowadays, computer science and modern information systems provide us with the opportunity to build virtual laboratories in which we can address various questions and hypotheses about such transitions. At the same time, knowledge of historic events that have actually occurred provides the possibility of interpreting the results and evaluating the accuracy of specific computational models or simulations. As such, *computational archaeology* has emerged as the discipline that focuses on the study of ancient societies via the use of computer models and simulations. Archaeology is a data oriented discipline, with a strong focus on the collection of material information for the study of past human societies; and computational archaeology builds on this information in order to enhance our understanding of the long-term human behavior and behavioral evolution, via modeling and simulating the socio-environmental processes at play. Computational archaeology uses mathematics, logic, or even cognition as the means for converting observations and knowledge about nature into quantitative research; and scientific inquiry is used in order to produce, test, and confirm quantitative data and theories.

The concept of agent-based modeling (ABM[1]) has become very popular within computational archaeology over the last two decades (Lake 2014). ABMs incorporate ideas from *artificial intelligence* (Russell & Norvig 2002) and *multiagent systems* (Wooldridge 2002), and define a social system as a collection of *agents*, which represent individual entities within a wider population. These entities are assumed to be acting *autonomously,* and may be able to learn and adapt in their environment. Agent actions occur in time and space, affecting the wider environment while individuals cooperate and/or compete with each other. ABMs can model systems that are either highly diverse or heterogeneous in terms of both agent abilities and underlying environment, and allow the study of interactions and (potentially emerging) behaviors that would be difficult to examine by using simple aggregate styles of representation (Batty *et al.* 2012).

ABM is particularly appealing as it promotes a style of modeling that reflects the characteristics of our real world, in a way that appears to fit well with existing explanations of how spatial structures such as settlements, cities, states, our global system and all its natural components evolve. This results in an increased descriptive power that facilitates interdisciplinary research, as it allows the incorporation of concepts used in various disciplines (regardless of the discipline-specific 'language' they were originally stated in). The emerging popularity of ABM in computational archaeology, in particular, is largely due to its ability to represent individuals and societies, and to encompass the uncertainties inherent in archaeological theories or findings.

The purpose of this chapter is to provide a general introduction to the ABM approach in archaeology. The next section provides some background on important concepts and techniques for accommodating the use of ABM in archaeology, integrating ideas and methods

[1] We will be using the acronym ABM to refer to both 'agent-based modeling' and 'agent-based model'.

already applied in other research domains. Following that, the corresponding architecture, methodology, and libraries to for assisting ABM, as well as the model design framework that needs to be followed are discussed further. Finally, several relative recent examples of the ABM approach in archaeology are presented, along with some concluding remarks.

Background

Archaeologists attempt to interpret human (pre) history and explain their theories about the interactions between societies and their natural environment (as described by biologists, ecologists, geologists, and others). This is accomplished via the use of formalisms, and via the constant re-definition of objectives to be attained, questions to be asked, and methods and techniques for answering them. However, archaeological theories are generally incomplete in the sense that they are based on data that is *static*: it might reflect the results of the dynamic interactions among people, materials, monuments, landscapes, and the inhabited environment in general, but *not these dynamics themselves*. The discipline therefore has difficulty linking cause and effect in the past (van der Leeuw 2004). Thus, computational modeling and simulation can assist archaeologists to express phenomena, relationships and ideas, allowing them to explore and test theories against observed data and experiment with different scenarios to explain particular sequences of cause and effect. Conducting plausibility (or improbability) tests; experimenting with different sets of initial conditions and scenarios; as well as calibration, verification, and validation of models are all essential components of computational modeling work. Agent-based modeling, in particular, is quite effective in representing the interactions among acting entities (representing individuals, social groups, households, or societies and even nations).

ABM is a field research methodology originally developed as part of computational modeling, but widely used by other disciplines, from life and physical sciences (biology, genetics, physics, chemistry) to environmental and social sciences (ecology, geosciences, demography, economics, sociology, archaeology). ABMs incorporate computational models which can be run to test whether agents are behaving as their originators intended. It must be understood, however, that this has little or nothing to do with how well they might reproduce observable data (Batty *et al.* 2012). This is not necessarily a drawback: ABM models are not usually built for prediction per se, but (to a large extent) to feed structured debate and dialogue, and to provide a tool for apprehending and explaining certain underlying properties (cause and effect) of the world (Eipstein 2008). Thus, a key ABM objective is enriching our understanding of fundamental processes that appear in a variety of archaeological applications. There are many formal systems competing or combining to provide the theoretical foundations for ABM. Their relative value is determined by the questions that need to be answered in each particular situation (North 2014). In the remainder of this section, we briefly describe the most important such formal systems.

Apart from natural language, an alternative way to reason about historical and past actions and events from observed data, is to transform theoretical questions and hypotheses into computational terms; the aim is to find the means to explore possible answers. One of the pillars of computational modeling, essential for any simulation process, is of course mathematics, based on variables and their relationships. *Equation-based modeling* is about defining a recurrence relation of given variables, once one or more initial values are given (difference/partial difference equations), or about relating some process or function with its derivative—i.e., its rate of change (differential equations). For example, logistic or *exponential growth equations* describe population dynamics, while *predator-prey equation models* describe the dynamics in which two populations interact, one as a predator and the other as prey. Moreover, *reaction-diffusion equations* describe the spread of populations in space, when two populations compete for a common food source ('competition'), or benefit from each other ('symbiosis'). Such computational realization of conceptual processes assists researchers in multiple domains to model and simulate real world phenomena. Furthermore, an equation-based modeling system is in general able to report the same results as an equivalent ABM approach, whose enhanced descriptive power alone does not significantly alter the understanding of the phenomenon under study (Castiglione 2006). Why then not use solely equation-based models rather than integrate them into ABMs?

The major difference between these approaches is that the accuracy assessment of (real) observational data can be much better determined by an ABM, as it can adequately represent situations where small fluctuations in the input data can drive a system to a completely different state. By contrast, equation-based systems would usually smooth out such effects, not allowing such out-of-the-norm situations to emerge. Moreover, while equation-based modeling variables allows saving and reusing data while the model runs, ABM can incorporate complex 'agent-variables' which include both data and functionality at the same time.

In most cases in archaeological *field* research, on the other hand, scholars explore past processes that occurred in a *geographical* landscape. An effective means for modelling is the coupling or integration of *Geographical Information Systems* (GIS) with ABMs when spatial and temporal design and analysis is required (Crooks and Castle 2012). When one or more agent actions involves movement, when agent's location within the environment influences its decision making, or when spatial arrangement of features on the landscape can be altered by the agents, then a *geospatial* ABM can better support the research requirements of the modeler. Moreover, in geospatial ABMs the importance of the spatial resolution is equally as important as the *temporal* resolution, where duration and frequency descriptive characteristics of events and phenomena are essential for temporal and spatial (pattern) analysis. Thus, when geographic context constitutes an important aspect of the *conceptual* model, the translated computational ABM needs to be coupled or linked with a GIS computational library, e.g. GeoTools (a Java GIS software library), Java Topology Suite (JTS), OpenMap, ESRI ArcObjects SDK, and others. Thereby, several important functions of the ABM can be assisted, such as data acquisition, pre-processing or transformation, as well as determining and assessing various inputs and outputs when needed through spatial analysis tools provided (density map, cost distance, least cost path, etc.).

The ABMs spatial and computational models can also be enhanced via the use of *cellular automata* (CA) to model complex systems. von Neumann and Ulam (Neumann 1966) introduced the concept of cellular automata in the 1940s. CA is an insightful approach for building a system of many objects (or, more generally, agents) that have varying states over time. However, now agents are *cell* objects existing on a *grid* (a tessellation of n-dimensional Euclidean space), where each cell has a number of *states* and a *neighborhood* which is a list of adjacent cells. Cell states evolve over a series of computational time steps: a cells new state is a function of all the states in the cells neighborhood at the previous time step, along with a set of simple rules for the cell to follow. Depending on the complexity, patterns may present simple specific rules, or the rules themselves can be classified as ones that evolve quickly into a stable state, into oscillating structures, in a pseudo-random or chaotic manner or into structures that interact in complex ways (Ilachinski 2001). Using CA use within an ABM allows the conceptualization of a variety of real-world systems, with complex behavioral patterns and intelligence emerging out of the interactions among simple agents. One significant recent work on CA is that of Wolfram (2002), which discusses how CA are not simply 'neat tricks', but are relevant to the study of biology, chemistry, physics, and all branches of science.

On a parallel direction, von Neumann and Morgenstern (1944) invented the mathematical theory of games. Since 1970s, *game theory* (GT) became the main instrument for the analysis of the *strategic interactions* among *rational agents* – that is, entities that encompass *preferences* or *goals* and act upon them (Myerson 1991). Agents can be described by means of an abstract concept called *utility*, referring to some ranking of the *subjective welfare* an agent derives from other objects, events, or interactions with others – and the aim of the rational agent is to maximize its utility. Subjective welfare can be evaluated by reference to the modeler's own implicit or explicit judgements of it, depending on the conceptual ABM. The concept of a *game* refers to all situations in which at least one agent can act to maximize his utility through anticipating (either consciously, or just implicitly in its behavior) the responses to its actions by one or more other agents. Interestingly, agent interactions in a game might produce outcomes that have been intended by none of the agents (Don 2014). GT aims to provide an explanatory account of strategic reasoning based on 'rational' actions of agents—and thus to prescribe 'optimal' strategic behavior for use by agents in games. In situations where this is not the case, i.e. when actions are not necessarily the results of rational deliberations by individual agents, but are rather 'biologically' attached to particular strategies used by entire populations, then *evolutionary game theory* (EGT) can be of use. EGT originated as an application of GT to biological contexts, arising from the realization that frequency-dependent 'fitness' introduces a strategic aspect to evolution. EGT has been applied in evolutionary biology with some success (Maynard Smith 1982), but has also recently attracted the interest of social scientists, as 'evolution' need not be strictly biological, but can be understood as 'cultural evolution' also: beliefs and norms change over time, and EGT can help answer questions about the conditions under which language, concepts of justice, altruism, and other non-designed general social phenomena are likely to arise (Skyrms 1996).

The above theoretical foundations can be fruitfully combined in ABM, depending on the theories and hypotheses that need to be modeled. We next turn our focus on ABM and agent design methodology, which is largely based on concepts derived from *artificial intelligence* (AI) and *multiagent systems* (MAS) (Russell & Norvig 2002, Wooldridge 2002). MAS in particular can offer the state of the art in designing *sophisticated* agents, including complex knowledge structures, reasoning from models, learning from data and experience, as well as applying strategic principles for selecting among agent behaviors (Wellman 2014).[2]

ABM design methodology

ABMs or MAS computational experiments simulate the simultaneous (synchronous or asynchronous) operations and interactions of multiple individual agents, combining theoretical foundations discussed briefly in the previous section, where complex phenomena may emerge even when simple rules are introduced in the model. Thus, a key principle, known as K.I.S.S. ('Keep it simple…and short') is extensively adopted in the modeling community (Axelrod 1997). The entire process of building an ABM begins with a conceptual model, where the main questions or hypotheses of the researcher solidify models elements, i.e. agent entities, with their attribute characteristics, behavioral and interaction rules between themselves, the models environment. In this section, we discuss the design methodology and available architecture for these elements, as well as a way of making model descriptions more understandable and complete. Moreover, for a beginner or non-expert in computer programing, there are several modeling system tools available to assist the development

[2] Niazi and Hussain (2011) try to draw an 'empirical' distinction between ABM and MAS based on keywords found in a literature citations study, and relating them to ecology/social sciences and computer science clusters.

of an ABM. The subsequent section identifies some of the ABM toolkits available.

Modeling toolkits

Until now, any ABM can be implemented with any *object-oriented programing* (OOP) language, since it is developed as a computer program. The concept of 'object' in the computer programing paradigm, is used to describe (perhaps inadequately) data structures that contain data (fields or attributes) and functions (procedures or methods) that can access and modify their own data. Thus, the most suitable way to develop ABMs is if we consider objects as *agents*. Although an experienced modeler in OOP can build an ABM from scratch. However, there are several advantages to utilizing existing modeling tools for ABM development. Such benefits include reduced time for programming non-specific parts, e.g. data import/export, GUI, etc., or the inbuilt implementation of various procedures, routines or methods needed. Although there are many toolkits for developing ABMs, only a few of them are presented below, selected because they have up to date active maintenance and development, and are widely used with a large user community, model libraries, tutorials and documentation, as well as capable of being integrated with GIS extension libraries for geospatial ABM development. However, the modeler must always select software based on their purpose, design objectives and modeling capabilities.

NetLogo[3] is highly recommended for modelers with beginner-level programming skills. It is a multi-agent modeling environment for simulating natural and social phenomena, has been in continuous development since 1999, and is capable of modeling relatively complex systems. NetLogo is simple enough for both students and teachers, yet advanced enough to serve as a powerful tool for researchers in many fields. It has an extensive documentation, many online tutorials, with a large model library of collected pre-written ABM simulations, addressing research areas for almost every discipline, as well as several useful extensions, such as *GIS* and *Networks*. NetLogo is now open source and runs on the *Java* virtual machine, thus it also constitutes a cross-platform modeling toolkit, while its computer programming language is the *Logo* dialect, a programming language designed specifically for ABM.

The *Repast* Suite[4] is a family of advanced, free, and open source ABM and simulation platforms that have collectively been under continuous development for over 14 years. It is perhaps the most actively maintained solution for ABM with a large user community. Repast comes in two editions. The *Repast Symphony* edition can be used if the modelers programming background is limited or if the modeler wants to use rapid prototyping to quickly develop an ABM using the *ReLogo* computer programming language, or the *Java* computer programming language for developing more complex simulation models. If the modeler wants to develop a model of a complex system with a large number of agent interactions and is also familiar with the *C++* computer programming language, the *Repast HPC* (Repast for high-performance computing) version can be used. The Repast suite provides visual and easy to use capabilities for agent design, behavior specification, model execution, and results examination. The modeler may also specify the spatial (e.g., geographic maps or networks) structure of the model and different types of agents with specified behaviors. Moreover, if the modeler is looking for a rich set of development tools, then Repast is one of the best options to get started with ABM.

MASON[5] is a multiagent simulation modeling tool designed to support large numbers of agents relatively efficiently on a single machine; it has no capabilities for distributing models over multiple computers, although an extension for this (D-MASON) is available. MASON has no domain-specific features unlike the previous toolkits and it is highly modular and consistent, allowing the modeler to use and recombine different parts of the system. Moreover, it has a large set of utilities to support model design as well as several valuable extension packages, such as GeoMASON for geospatial support, JUNG for social network systems, and of course ECJ, a high performance evolutionary computation system to discover design solutions for complex ABMs. A working knowledge of the *Java* computer programming language is required in order to use MASON.

Agents, environment and interaction topologies

A typical agent-based model has the following essential features: a set of agents with their attributes and behaviors, a framework for simulating agents in which they interact with their environment in addition to other agents and a set of agent relationships, and methods of interaction in which an underlying topology of connectedness defines how and with whom agents interact (Figure 1).

While ABM originates from computer science as a computational modeling approach, the interdisciplinary nature of ABM may not allow a universally accepted definition of the term *agent*. Nonetheless, one of the most widely accepted definitions of an agent is provided by (Jennings 2000). According to Jennings, an agent is a software-based computer system, situated in some *environment,* and which is capable of *autonomous action* in order to meet its *design objectives*. The main agenthood properties emanating from the above definition are the following:

- *autonomy* - agents are actual problem-solving entities, and have (at least some kind of) control over their choice of actions and behaviors—i.e., they rely on their own percepts and deliberations

[3] http://ccl.northwestern.edu/netlogo
[4] http://repast.sourceforge.net
[5] http://cs.gmu.edu/~eclab/projects/mason

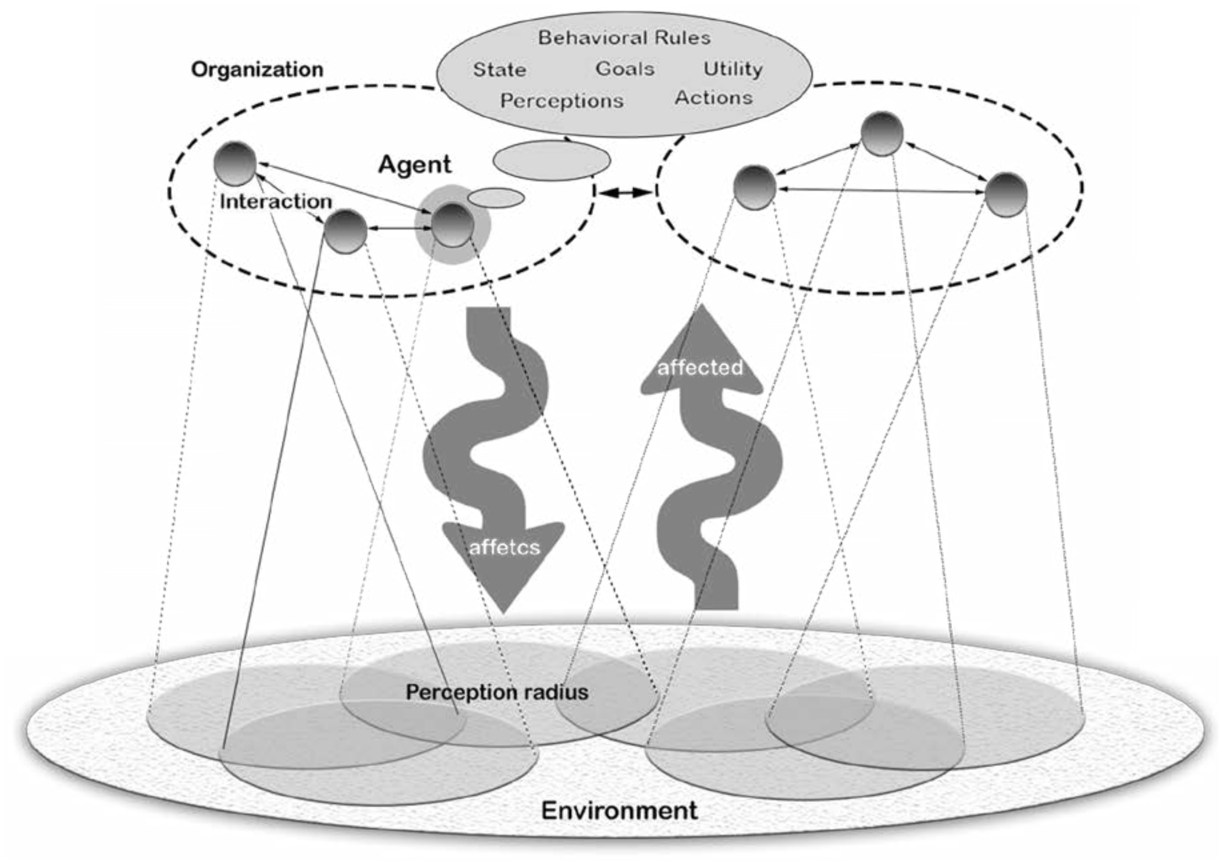

Figure 1. Virtual structural framework of a typical ABM (adapted from Jennings 2000).

for decision making, and are capable of processing (and exchanging) information in order to make independent decisions;

- *heterogeneity* - the development of autonomous individuals is not disallowed;
- *pro-activeness, re-activeness, social ability, and related notions*- agents are able to perceive and respond (act) within their environment in order to satisfy their design objectives. Thus, an agent can be regarded as *pro-active* (exhibiting goal-directed behavior) or *reactive* (responding to percepts in a simple manner); *socially able, interactive* or *communicative* (being able to share/exchange information with others, and/or act within a given social environment); exhibiting *bounded rationality* (i.e., not having unlimited access to information resources, foresight, etc.); can be *mobile* or fixed within its environment; and can be *adaptive*, able to alter its state depending on previous perceptions (memory), or based in *learning*—depending on the situation being modeled.

However, agents can possess other properties and depending on the application, some of their features will be more important than others. Thus, the above list is not exhaustive or exclusive. Along with agent behavioral characteristics, the *structural design* of the agent needs to be described. The appropriate structure of the agent depends on the nature of the environment modeled. An agent can operate in an environment that has various properties that influence its behavior as well as its structural design. Thus, before designing an agent, the first step is to always specify the environment in which it will act as fully as possible. According to Russel and Norvig (2002), agent structures and environments vary along several significant dimensions. Agent environments can be organized according to their properties like *fully* or *partially observable*, i.e. the agent is either able or unable to gather complete information about the environment. When only agent actions, along with the current state of the environment determines its next state, i.e. where there is no environmental uncertainty, then an environment is characterized as *deterministic* or *non-deterministic* if otherwise. Moreover, an environment can be also *static* (when the agent is the only entity that inflicts changes on the environment); or can be *dynamic* (when changes in the environment take place while the agent is performing an action). Moreover, an environment can be *discrete* when possible environmental states are finite or *continuous*, when they are otherwise. Finally, an environment can be obviously *single-agent* or *multiagent*, and the later can be also seen as a *competitive* or *cooperative* one, depending on the situation.

A simple case scenario of an ABM environment would be a fully observable, deterministic, static single agent

Figure 2. Possible agent interaction topologies for a computational ABM (adapted from Macal and North 2009).

environment. Perhaps in such an occasion designing the simplest agent structure could be sufficient, a *reactive* (or *simple reflex*) agent. These agents select actions based on their current perception of the environment, ignoring previous perceptions history. They are based on simple *condition-action* or *if-then-else* rules—i.e., providing immediate (reflexive) responses to perceptions. Although such an agent design has a low demand on computational power, the resulting agents are of very limited sophistication or intelligence. For complex settings, a *deliberative* or *rational* (or *intelligent*) agent needs to be designed. Such an agent is able to store previous *perception history*; use an *internal model*; employ some *goal* information for its decision making; or use a *utility* function to evaluate how close to its goal the agent is, rather than simply perceive whether a goal has been achieved or not—and then choose an action.

Agent perception (within a sphere of visibility and influence) and action capabilities determine their interactions with the environment and other agents. What is more, when agents interact there is typically some underlying *organizational* context, representing the nature of the *relationships* among the agents. Moreover, the possibility of specific agent interaction *topologies* might need to be taken into account prior to model design (Macal and North 2009).

The choice of a topology very much depends on the modeler's needs. In Figure 2a, a grid or lattice interaction topology is shown, where an agent can represent either a grid's cell (cellular automata), or one or more entities situated in that cell. *Von Neumann* or *Moore neighborhoods* are depicted for the former.[6] Likewise, a polygonal (employing polylines as well) tilling scheme can be used when a realistic GIS map needs to be the environmental framework of the model (Figure 2b). The ABM's interaction topology might be represented by a Euclidean 2-D (or even 3-D) continuous space, where agents can move and interact within a simple representation of physical space (Figure 2c). Finally, a network interaction topology can be used, representing (weighted) connections between the agents, where both directed and undirected relationships (links) may exist.

There are several other common structural conventions seen in most ABM implementations (North 2014). A *logging* mechanism is used to record values within an executing model for later analysis. A *scheduler* is responsible for representing the flow of time in a simulation; it can be a 'time stepped' scheduler, where agent actions or events (procedure calls) occur in each time (period) increment, or a 'discrete event' scheduler when several actions or events need to be executed at a specific time (duration). An optional *Graphical User Interface* (GUI) is also frequently included to provide necessary interactivity for the modeler during the implementation, initialization or simulation of the ABM. Except from these features, it is also necessary to provide a formal description of any ABM, independent of their domain, purpose, complexity, and computer implementation, both for assessing the model design and the dissemination of the researcher's work.

Formalizing the ABM design

Building a computational model from an informal theory is not a trivial matter, while formal theories are often too wide ranging to be put into computational terms—and so it is necessary to pare them down to a few limited features which contain the essence of what is being said. Given this need, the *ODD (Overview, Design concepts, Details) protocol* was developed as a standard format for describing ABMs (Grimm and Railsback 2012).

ODD provides only a general structure for formulating ABMs. It describes models using a three-part approach involving *(i)* an overview of the model, *(ii)* important design concepts, and *(iii)* specific details (Table 1). The model overview includes a statement of the model's intent, a description of the main variables, and a discussion of the agent activities. The design concepts include a discussion of the foundations of the model. The details include the initial setup configuration, input value definitions, and descriptions of the ABM.

Model calibration (or sensitivity analysis), verification, and validation can be part of the ABM methodology.

[6] Note that, although rarely used, a triangular, hexagonal, etc. tessellation can be of use instead of a rectangular one.

Table 1. Structure elements of the ODD protocol (adapted from Grimm and Railsback 2012)

ODD	ODD element	Questions to be answered
Overview	Purpose	What is the purpose of the model?
	Entities, state variables, and scales	What kind of entities are in the model? By what state variables, or attributes, are these entities characterized? What are the temporal and spatial resolutions and extents of the model?
	Process overview and scheduling	Which entities do what, in what order? When are state variables updated? How time is modeled (time steps, discrete event, both)?
Design concepts	Design concepts	There are several design concepts (emergence, adaptation, objectives, learning, prediction, sensing, interaction, stochasticity, collectives, and observation).How have these concepts been taken into account in the model's design?
Details	Initialization	What is the initial state or set up of the model?
	Input data	What input does the model use from external sources such as data files or other models to represent processes that change over time?
	Submodels	What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'? What are the model parameters, their dimensions, and reference values?

Indeed, depending on the case study, a modeler may calibrate an ABM to specific historical cases if there is enough supporting data (deductive reasoning), or sweep a range of parameters over several possible scenarios to identify important thresholds or reveal tradeoffs and inherent uncertainties. Moreover, ABM simulations can be reproducible (defining *random seeds* for the incorporated pseudo random number sequence generator); but even if they are not, a modeler needs to run a high number of simulations and examine average values, rather than using one single run of the model. The true power of the ABM approach is that one can rigorously incorporate in the model any recent research findings within any given domain (e.g. biology, physics, geography, archaeology, sociology, etc.) This ability brings out the interdisciplinary nature of ABMs. Finally, it is absolutely essential that ABMs are run to test whether they are behaving as their modelers intended.

Now that most essential parts of the ABM methodology have been described, we proceed to present several ABM examples applied in social sciences, and in particular in archaeological research.

ABM in archaeology: examples

In recent decades, archaeologists have used ABMs to test possible explanations for the rise and fall of simple or complex ancient societies. One example of such a system is the study conducted for the region of the Long House Valley in Arizona, examining the reasons why there have been periods when the Pueblo people lived in compact villages, while at other times they lived in dispersed hamlets (Kohler *et al.* 2000). Simulation results for thirty different (distinctly parameterized) scenarios of a single run each are reported and agents have a simple rather than sophisticated design structure, while they do not interact with each other, but act independently. Nevertheless, the ABM results show the importance of environmental factors related to water availability for these settlement changes. An extension of the model involved the cause of the collapse of the Anasazi civilization/culture, around 1,300 CE in Arizona, USA (Axtell *et al.* 2002). Scholars have argued for both a social and an environmental cause (drought) for the collapse of this society. The authors refute the hypothesis that environmental factors alone account for the collapse, via simulating individual decisions of household agents on a very detailed landscape of the physical conditions of the local environment.

Another ABM that considers agents that are 'utility-based' to some extent, is proposed by Jaansen (2010) for understanding how prehistoric societies adapted to the American southwest landscape of their era. Agents correspond to households, deciding whether to migrate or not. Interactions in the model, like the sharing of resources among the agents, or the exchange of resources among their settlements are to a large extent pre-specified in the system. Moreover, the modeling area is not an actual landscape, but rather a flat 20 x 20 grid, and agents cultivate only cells that they are currently settling, or the ones they are migrating to where renewable resources can be found (after the agents have consumed/exhausted harvests). However, the ABM succeeded in exploring how various assumptions concerning social processes affect the population aggregation and size, and the dispersion of settlements.

Archaeological ABMs can nowadays also make use of available GIS data. Models like the *CybErosion* framework incorporate GIS data and combine them with the modeling of agent actions, to overcome the limitations of existing landform evolution models—which use an ABM to simulate the dynamic interactions of people with their landscape, but have typically failed to include human actions, or have done so only in a static, scenario-based way (Wainwright, 2000). The interactions *CybErosion* simulates relate to a few main processes of food acquisition (hunting, gathering and basic agriculture) in prehistoric communities. Although the ABM's 'goal-based' agents do not interact with each other, they can decide at each time-step what action to select (hunt, forage, collect firewood, other activities) based on their stored energy and the remaining daylight length. Simulations demonstrate the value of this approach in supporting the vulnerability of landform evolution to anthropic pressure, and the limitations of existing models that ignore human and animal agency, and which are likely to produce results that are both quantitatively and qualitatively different.

Graham and Steiner (2006) implemented (in NetLogo) a generic model, *TravellerSim*, that simulates the actions of 'traveler' agents, moving over a road network set out from known archaeological site locations within a given region. The model tries to explore the growth of territories and site hierarchies from the interactions between settlement agents, which are affected by settlement's importance, i.e. the number of hosted traveler agents, and between settlement's distance (if within a day's travel, e.g. around 20km), all competing as destination zones, inspired by an entropy-maximizing method configuration. Although traveler agents in the model are rather simple decision makers, while settlement agents are actually static, representing nodes of a network interaction topology, the results are interpreted through graph theory analysis, e.g. (social) network analysis metrics, denoting settlements importance based on the flow of information (traveler agents), their centrality, degree, and finding isolated sub-networks, characterizing their 'role' in the simulated area. Moreover, three different map areas were examined, assessing the validity of the ABM.

MayaSim (Heckbert 2013) is a very recent example of a simulation model integrating an agent-based, cellular automata, and network model of the ancient Maya social-ecological system. The purpose of the model is to better understand the complex dynamics of social-ecological systems, and to test quantitative indicators of resilience as predictors of system sustainability or decline. The ancient Maya civilization is presented as an example. The model examines the relationship between population growth, agricultural production, pressure on ecosystem services, forest succession, value of trade, and the stability of trade networks. These combine to allow 'utility-based' agents, representing Maya settlements, to develop and expand within a landscape that changes under climate variation and responds to anthropogenic pressure. Agents representing 'settlements' (and hence communities rather than individuals) are operating at a really high resolution environmental grid of 20 x 20 km cells. The temporal extent comprises of a few hundred time steps, each representing roughly two years while population growth rates (constant birth rate at 15%) are set to values that are probably quite high considering the time period. Agents may migrate when population levels decrease below a certain threshold required to maintain subsistence agriculture, while their utility function combines weighted functions for agriculture, ecosystem services, and trade benefit. The latter is affected by agent resource exchanges that occur between settlement agents since they are connected via a network of links that represent trade routes. It is assumed that when an agent reaches (or drops below) a certain size, it will add routes (or allow routes to degrade) to nearby agents within a 'Moore neighborhood' (i.e., *spatial ties* among the agents are created). A larger network produces greater trade benefits, and the more central an agent is within the network (centrality), the greater the trade benefits for that individual agent. The model was able to reproduce spatial patterns and timelines somewhat analogous to that of the ancient Maya, although this proof of concept stage model requires refinement, and additional archaeological data for better calibrations.

Most multiagent-based simulation models used in archaeology simply do not define agents in the way these are defined in AI or MAS research, and do not incorporate truly autonomous, utility-maximizing agents in their models. As observed by Drogoul *et al.* (2003), 'agents nowadays constitute a convenient model for representing autonomous entities, but they are not themselves autonomous in the resulting implementation of these models'. This is a shame because MAS research can provide intuitive understanding for organization and re-organization issues in agent societies, such as how and why agent organizations change, and how can *system re-organization* be achieved *dynamically*, with minimal interference from an external control (the system designer). Such an 'automatic/dynamic' re-organization process is referred to as *'self-organization'* (Di Marzo Serugendo *et al.* 2005). Reorganization may actually be the answer to changes in an (artificial) environment of agent societies, if it leads to increased capacity for survival (vitality) or power to live and grow (utility); the reorganized instance should perform better in some sense than the original situation, not only for the organization but for the agent itself, given the assumption and essential characteristic of agent autonomy in MAS or ABM (Jennings 2000; Wooldridge 2002; Russell and Norvig 2002).

Towards this direction, and in contrast to most existing ABM approaches in archaeology, the authors (Chliaoutakis and Chalkiadakis 2014) developed a model of agents that are completely autonomous, can build and maintain complex social structures, and can incorporate a self-organizing social organization paradigm. Our model employs a utility-based agent design, rather than a simple reactive one. Though inspired by specific case studies, the ABM is generic, can incorporate a number of different

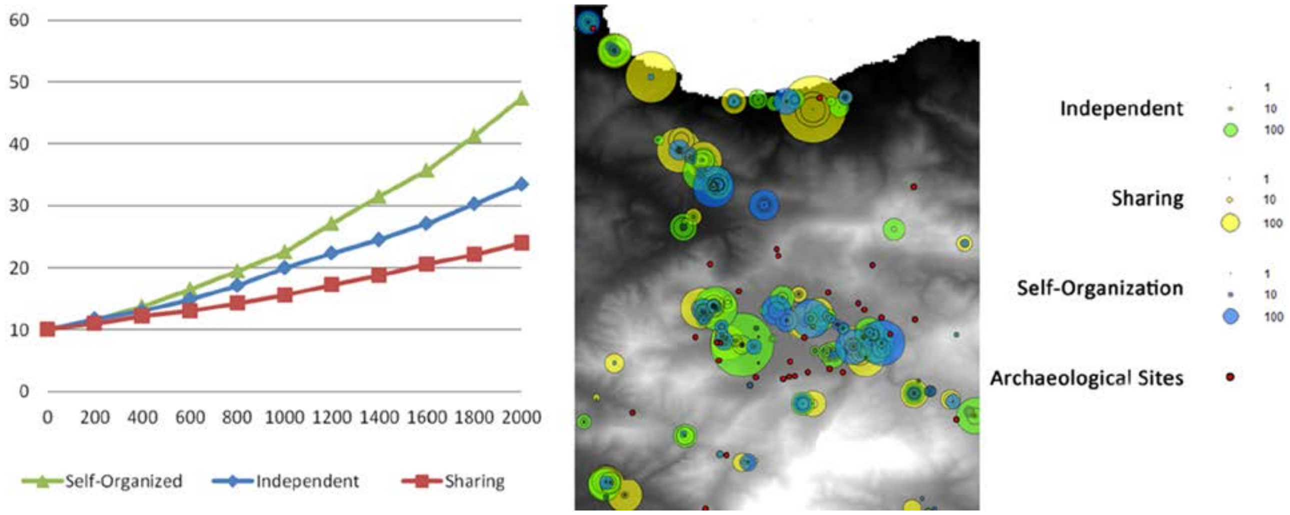

Figure 3. (Left): Agent population size for intensive agriculture over 2000 years with aquifer proximity considered. (Right): Settlement location buffers when extensive agriculture is used with no aquifer proximity considered (Chliaoutakis and Chalkiadakis 2014).

social organization paradigms and various technologies (e.g., agricultural), and does not aim to prove or disprove a specific theory.

The prototype ABM was developed to study land use, settlement and social organization patterns at a sub region of the island of Crete during the Bronze Age. Considering farming to be the main activity for sustaining the early Minoan civilization, the ABM evaluates the impact of different social organization models and agricultural strategies on population viability and the spatial distribution of settlement locations over a 2000 year period. The artificial ancient society of agents evolves in a two dimensional grid. The extent is 20 x 25 km area with a 100 x 100 m cell size resolution for the grid space. Various aspects of the model landscape contribute indirectly to an agent's decision-making process, like where to settle and/or cultivate. The input spatial data are derived from modern data and concern the topography, which is the modern day Digital Elevation Model (DEM), its slope and known aquifer locations (rivers and springs). Modeled agents correspond to households, which are considered to be the main social unit of production for the period, each containing a specific number of individuals (household inhabitants). Each household agent resides in a cell within the environmental grid, with the cell potentially shared by a number of agents. Adjacent cells occupied by agents make up a settlement — and there is at least one occupied cell in a settlement. Each agent cultivates a number of cells located next to the settlement. At every yearly time step, household agents first harvest resources located in nearby cells (corresponding to the fields they are cultivating). They then check whether their harvest (added to any stored resource quantities) satisfies their minimum perceived needs. If not, they might ask others for help (depending on the social organization behavior in effect), or they might even eventually consider moving to another location or settlement.

The ABM allows us to explore the use of various technologies that could potentially be used by the agent society, and thus test their impact on population size and dispersion (e.g., on the civilization's viability). In the model's current implementation, it allows the use of two agricultural technologies: intensive farming ('garden' cultivation with hand tillage, manuring, weeding, and watering) and extensive cultivation (large-scale tillage by ox-drawn ards). Additionally, the ABM attempts to assess the influence of *different social organization paradigms* on population growth and settlement distribution. Importantly, the model allows us to evaluate the social paradigm of agents *self-organizing* into an implicit stratified social structure, and continuously re-adapting the emergent structure, if required. When the self-organization social paradigm is in use, agents within a settlement continuously re-assess their relations with others, and this affects the way resources are ultimately distributed among the community members, leading to 'social mobility' in their relationships. Such a social paradigm promotes the targeted redistribution of wealth, and is inspired by a recent MAS framework for *self-organizing* agent organizations (Kota 2000).

The model parameters are based on archaeological studies, but are not biased towards any specific assumption. The results of (Chliaoutakis and Chalkiadakis 2014) over a number of different simulation scenarios demonstrate an impressive sustainability for settlements adopting a socio-economic organization model based on self-organization; while the emerging 'stratified' populations (corresponding to 'heterarchies' (Schoep and Knappett 2004)), are more populous than their egalitarian counterparts (Figure 3). The ABM results provide support for theories proposing the existence of different social strata in Early Bronze Age Crete, considering them a pre-requisite for the emergence of the complex social structure evident in later periods.

Indeed, using ABMs that are built on knowledge derived from archaeological research, but do not attempt to fit their results to a specific material culture, allows for the emergence of dynamics for different types of societies in different types of landscapes, and can help us derive knowledge of socio-economic and socio-ecological systems that are applicable beyond a specific case study. Although several other remarkable ABM simulation examples could have been reported, an up-to-date history of ABM simulation approaches in archaeology is thoroughly provided by Lake (2014), who notes that while most examples represent certain strands of evolutionary archaeology, explicitly 'sociological' ABMs remain a challenge.

Conclusions

ABM has become well known in archaeology over the last fifteen years, because it has the ability to reflect the properties of the real world, along with their evolution. At the same time, several mechanisms have been observed in nature and biology and subsequently successfully applied in MAS research, e.g. cellular automata, evolutionary game theory, self-organization, genetic algorithms and neural networks. Equipping ABMs with such mechanisms lets us address problems that concern the emergence of system dynamics, describing how the individual components interact with and respond to each other and their environment. The ABM approach in archaeology is a promising tool for exploring the dynamics operating within past societies. As Axelrod (1997) notes, ABM simulation can be seen as a 'third way of doing science': while induction can be used to find patterns in data, and deduction can be used to find consequences of assumptions, agent-based simulation modeling can be used as an instrumental aid to intuition.

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Geomorphometry, Multi-Criteria Decision Analysis and Archaeological Risk Assessment

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Abstract: Geomorphometric data derivatives that can be extracted from Digital Elevation Models (DEMs) can provide information relevant for identifying zones of neotectonic deformation and seismic hazard or potential flooding. Processing of the extracted information based on Multi-Criteria Decision Analysis (MCDA) provides a low-cost approach to risk assessment. The ranking of the derived information relative to specific criteria of weights can highlight interrelationships and assemblages associated with zones of seismic hazard or potential flooding. The outcomes of the methodological framework presented here provide an assessment approach for the spatial distribution of neotectonic deformation and seismic hazard, as well as flood susceptibility, which can highlight at-risk archaeological heritage sites.

Keywords: Multi-Criteria Decision Analysis, DEM, GIS, geomorphometry, neotectonic deformation, hazard mapping (seismic, floods), risk model, heritage sites.

Introduction

Damages caused by earthquakes and floods are considered to be as the most costly natural hazards on the planet (Gil & Kellerman, 1993). It is inevitable that such natural hazards need to be assessed in advance to help decision-makers determine the extent of disaster impact. This aspect becomes of high priority especially for regions exposed to: i) intense earthquake activity with the nature of the tectonic processes taking place not being well understood and ii) intense flooding events with lack of quantitative data from stream-gauging records and other hydrologic data not establishing an effective flood hazard assessment (Cockayne *et al.* 1998, Martinez *et al.* 1998; Ishikawa *et al.* 2014). There are various approaches in literature that can evaluate the seismic hazard, with usage of GPS network or InSAR satellite images being some of the common ones to ground deformation assessment (Martinez *et al.* 1998, Smith *et al.* 1998, Stramondo *et al.* 1999, Feigl *et al.* 2002, Stramondo *et al.* 2005, Shaw *et al.* 2008). Despite those approaches being able to provide surface deformation monitoring, both are costly techniques. Data gathering of many years and extensive processing/interpretation of the data is needed on GPS measurements and InSAR interferometry to assess seismic hazard mapping. Similarly, assessments of flooding hazard based on remote sensing data can be an alternative when there is lack of quantitative data such as stream-gauging records. In that case there is no need of using direct measurements as the basis for flood hazard assessment. Such an alternative can highlight mapped information to define flood-prone areas with an increased probability of inundation (Riggs 1985).

It is quite obvious that a practical and cost-effective way to identify vulnerable regions in natural hazards is essential. The potential impact of flooding and seismic impacts on the cultural and historic heritage sites is assessed within this study, from a geospatial perspective based on cost effective Digital Elevation Models (DEMs). Such DEMs can be the free SRTM (90m resolution), ASTER G-DEM (30m resolution) or the low-cost WorldDEM (12m resolution). The DEMs can reveal information regarding the geomorphological features of an area, which can be particularly helpful for determining surface characteristics that indicate whether an area is prone to natural hazards. Multi Criteria Decision Analysis (MCDA) was applied in this study to highlight areas which are most susceptible to flooding or seismic hazards (Boroushaki & Malczewski 2008).

Research regarding determination of seismic hazard for heritage sites is still limited (Bani-Hani & Barakat 2006, Hemeda & Pitilakis 2010). The geospatial analysis of areas exposed to potential earthquake impacts can provide useful information for decision-makers to protect heritage sites (Berilgen 2007, Hadjimitsis *et al.* 2011). This study uses Digital Elevation Models (DEMs) for extracting geomorphometric, morphotectonic and geological information, which can be used to determine the geospatial variation in neotectonic deformation across a region and indicate zones of severe seismic hazard. Such information can be extracted by spatial datasets such as slope gradient, amplitude relief, stream length gradient, topographic wetness, drainage density, stream frequency, elevation relief ratio, lineament density and lineament frequency.

A few recent studies have attempted to provide a spatial distribution representation of neotectonic activity (e.g. El-Hamdouni *et al.* 2008, Dehbozorgi *et al.* 2010, Alipoor *et al.* 2011, Selim *et al.* 2013). The focus of those studies was to classify neotectonic activity within regional-scale drainage basins, rather than the analysis of intra-basinal variations in neotectonic deformation that this study uses.

Another natural hazard assessed here is flooding and its impact on archaeological heritage sites. Since the first settlements have been concentrated in the vicinity of permanent water courses, with abundant archaeological sites along river margins (Turnbaugh 1978). Such sites are of particular interest for archaeologists to evaluate whether their demise was a result of flood events. Determining the areas exposed to flooding, using GIS-based maps important information for decision-makers can be gathered so as to protect heritage sites (Solsten & Aitken 2006, Nikolova *et al.* 2012, Ronco *et al.* 2014). The use of DEMs is also useful for extracting geomorphometric information relevant to water system behaviour, to characterize zones of fluvial erosion and subsidence. The aforementioned indices (drainage density, stream frequency, amplitude relief, terrain wetness index) can isolate information useful to flood risk determination and, in conjunction with supplementary information gained from rainfall data, soil types and land-cover types, offers a low-cost approach for assessing flood hazard.

In this study a Geographical Information Systems (GIS) - based MCDA approach is used with geomorphometric, morphotectonic and geological data to depict the spatial distribution of neotectonic deformation across a tectonically active area, as well as the flood susceptibility of that area. Such an approach can provide a useful way to assess seismic hazards and flood hazards, assisting disaster risk reduction efforts, including assessments of the likely impacts that those hazards on historic heritage sites.

Methodology

This study focuses on implementing a GIS-based MCDA approach to provide a neotectonic deformation map, a seismic hazard map and a flooding susceptibility map in order to identify cultural heritage sites exposed to such hazards. These maps convey the degree of risk that historical heritage sites are exposed to from natural hazards, in this case earthquakes and floods. A GIS and MCDA based approach is adapted here in for the combination of criterion maps according to appropriate attribute values. The MCDA in this study uses a package of criteria with assigned attribute values, coupled with GIS for spatial analysis and mapping (Boroushaki & Malczewski, 2008). The MCDA approach is dependent on the order weights selection. The Analytical Hierarchy Process (AHP) is used to provide an evaluation of the order weights on which the MCDA depends (Saaty 1977, Saaty & Vargas 1991). Various spatially analysed datasets are classified, based on a set of decision rules, to isolate particular information associated with seismic hazard and flooding. The order weights for each factor are determined for the extraction of a neotectonic deformation map, a seismic hazard map and a flood susceptibility map. The Weighted Linear Combination (WLC) approach is then used for the construction of an overall priority rating. In that way a single final score of evaluation is acquired for mapping flood susceptibility or seismic hazard zones.

The extracted final information can be useful for analysis during the decision-making processes for the preservation, conservation and restoration of heritage sites (Bani-Hani & Barakat 2006).

Data preparation and criteria for assessment of neotectonic activity

There are several studies focusing on the use of morphotectonic, geological and geomorphological analyses in order to determine tectonic activity (Silva *et al.* 2003, Mesa 2006, Della Seta *et al.* 2008, García-Tortosa 2008, Ozdemir & Bird 2008, Perez-Pena 2008, Sreedevi 2009, Alipoor *et al.* 2011, Selim *et al.* 2013). Only few of these studies use spatially analysed datasets. The integration of spatial datasets extracted from DEMs offers valuable information, with their interpretation and interrelationships highlighting neotectonic deformation zones. The datasets used in this study consisted of ten classified thematic maps, extracted using ASTER GDEM data and GIS processing. The indices providing morphotectonic information were: i) amplitude relief; ii) stream length-gradient (see Table 1). Those highlighting geomorphological information were: i) slope gradient; ii) drainage density; iii) stream frequency; iv) elevation relief ratio and; v) terrain wetness index (see Table 1). Finally, geological information was extracted via: i) lineament density; ii) lineament frequency and; iii) lithological information from published geological maps (Table 2).

By evaluating the information provided by each extracted DEM derivative, it is possible to isolate geospatial information and specify the neotectonic deformation across a region. The indices of amplitude relief and stream length gradient can highlight morphotectonic characteristics. The amplitude relief highlights areas undergoing uplift or subsidence (Currado & Fredi 2000, Troiani & Della Seta 2008). The stream length gradient index identifies abrupt changes along the drainage network due to tectonically active faults. The relationships between tectonic activity, rock resistance and channel slope can be investigated with the SL index (Keller 1986). The slope gradient - in conjunction with drainage density and stream frequency information - can highlight tectonically controlled regions (Kouli *et al.* 2007). The indices of elevation relief ratio and terrain wetness index help to determine regions with major ridges, steep slopes and V-shaped valleys (Conoscenti *et al.* 2008, Migon *et al.* 2013). Analysing these extracted geomorphological information the inter-relationships can be used for the examination of neotectonic deformation. Geological information is provided by the maps of lineament density and lineament frequency, as they

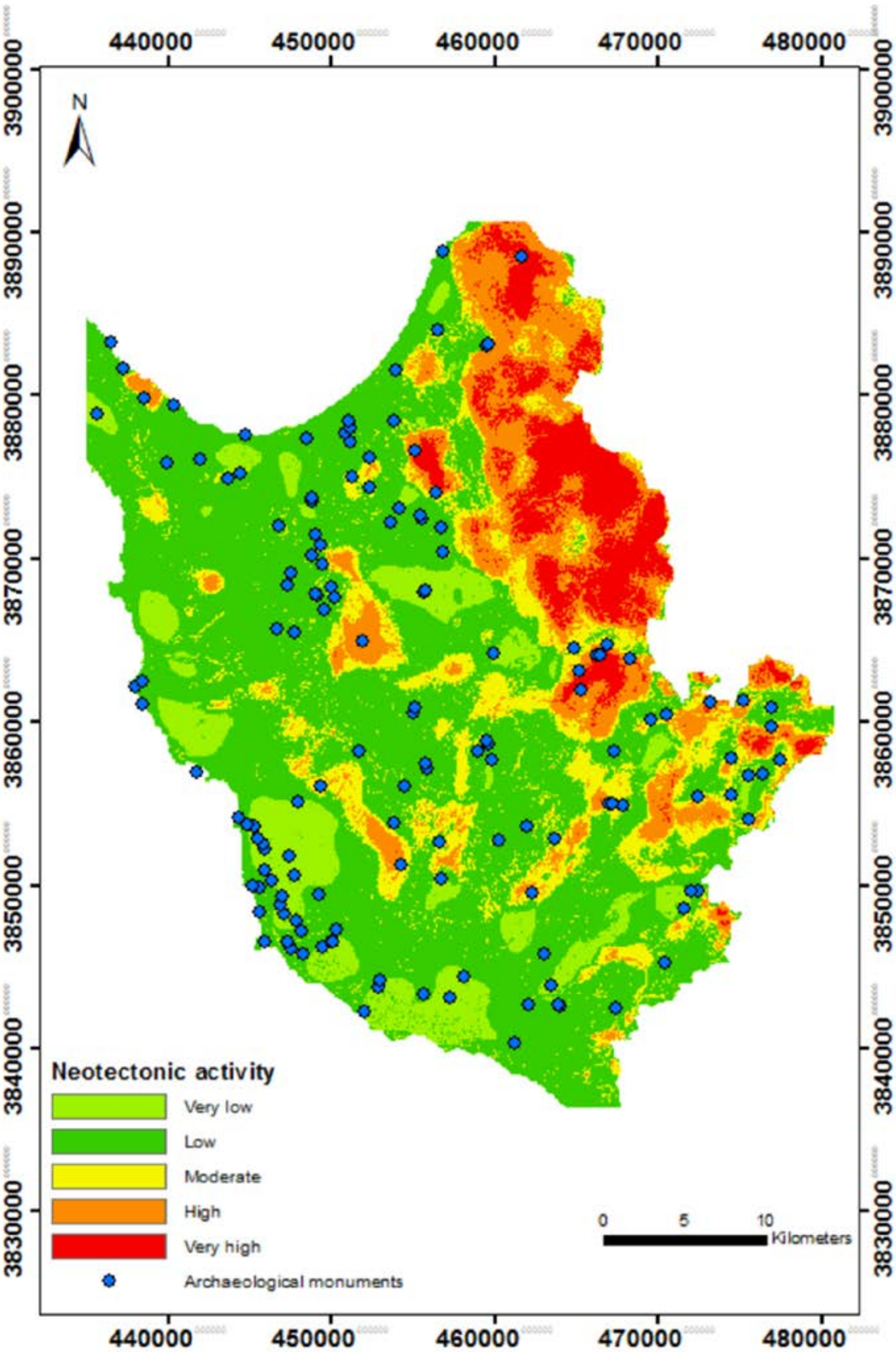

Figure 1: Assessment of neotectonic deformation map, using AHP procedure and WLC procedure.

highlight highly-fractured zones. Such geological information, combined with lithological information and aforementioned geomorphological information, can be used to identify areas at risk from earthquake damage (Fig. 1).

The integration of the datasets was based on the amount of information contributed by each factor to neotectonics determination, using weighting factors for each raster layer through an MCDA model. The historic heritage sites in areas of integrated information extracted from the aforementioned datasets can indicate the degree of damage from earthquakes that those heritage sites are exposed to. Paphos prefecture in Cyprus is selected here as a test area, with the historic monument sites of that region shown in Fig. 1.

Data preparation and criteria for assessment of flooding susceptibility

There are also several studies focusing on the use of land-cover and geomorphological analyses to determine water system behaviour and flood susceptibility (Harrower 2010, Yahaya *et al.* 2010, Nikolova *et al.* 2012, Ronco *et al.* 2014). Obviously the main factors for floods phenomena are the heavy rainfall and the resultant large concentration of run-off, which exceeds the bank-full capacity of rivers, causing floods (Petry 2002). In addition, this study utilizes supplementary factors that can enhance the causes of flood events, such as zones of fluvial erosion, soil types and land cover types. Spatial distribution maps of various factors are utilised during the analysis: i) rainfall data; ii) drainage density; iii) stream frequency; iv) flow accumulation; v) slope gradient; vi) terrain wetness index; vii) multi-resolution index of valley bottom flatness; viii) soil type; ix) permeability and; x) land cover type (Table 2).

The determination of flood susceptibility consists mainly of two stages. The first stage is to determine the causative factors of flooding and examine their impact in the landscape. The extraction of the DEM derivatives (such as slope gradient, terrain wetness index, flow accumulation and multi-resolution index of valley bottom flatness) are considered here, to determine characteristic information that highlights zones high flood risk. Geomorphic responses to fluvial erosion, subsidence and slope processes can be assessed through the extracted information provided by the calculation of DEM derivatives, such as the amplitude relief, the drainage density, the stream frequency. The outcomes will provide valuable information regarding the subsidence and the erosional and deposition processes which are the major categories of flood effects.

The second stage is to apply the MCDA technique, using the extracted information from the flood-related factors, to identify flood-susceptible areas. Supplementary information, such as the rainfall, the permeability, the soil and land-cover types, are also considered at this stage, as they represent potential causative factors, influencing water run-off. This is an element which needs to be examined in determining flood susceptible areas. This methodological framework offers a detailed analysis for decision-makers assessing the flood hazard for historic heritage sites (Fig. 2 & 3). Thessaly region in central Greece is selected as an area of interest for flood susceptibility, with the interaction with heritage sites in that region presented in Fig. 2 & 3.

Multi-Criteria Decision Analysis (MCDA)

The MCDA approach consists of two stages: i) Analytical Hierarchy Process (AHP) and; ii) Weighted Linear Combination (WLC) (Table 2). In AHP methodology the selected causing factors for each investigated natural hazard are initially used as the criteria of the pair-wise comparison method. The criterion pair-wise comparison matrix considers as inputs the pair-wise comparisons in order to determine their relative weights. The AHP provides a mathematical method of translating this matrix into a vector of relative weights for the criteria. These relative weights have to be reasonable so their degree of consistency achieved in the ratings is tested by calculating the Consistency Ratio (CR). This ratio implies the probability of the matrix ratings being randomly produced and when CR is less than 0.1 that meets the criteria of an acceptable reciprocal matrix (Saaty 2008).

The criteria with their raw data are typically non commensurate. To make the various criterion maps comparable, a standardization of the raw data is usually required (Eastman *et al.* 1993, Line *et al.* 1997, Malczewski 1999). In WLC approach a standardization procedure is considered for transforming the input data into commensurate scale. Then the weighted sum approach takes place to achieve the flooding susceptible map by multiplying the standardized criteria with their corresponding criterion weights and take their summed products (Table 2).

The MCDA process typically defines objectives, chooses the criteria to measure the objectives, specifies alternatives, transforms the criterion scales into commensurable units, assigns weights to the criteria that reflect their relative importance, selects and applies a mathematical algorithm for ranking alternatives and chooses an alternative (Howard 1991, Keeney 1992, Hajkowicz & Prato 1998).

Discussion

The use of geoinformatic techniques and spatial datasets extracted from an ASTER GDEM were used in this study to summarize geomorphological, geological and morphotectonic features. These features can be combined, with their interpretation and interrelationships providing a package of information to neotectonic deformation and seismic hazard, as well as flood susceptibility. This methodology can thus be a useful risk assessment tool for the protection of historical heritage sites exposed to such hazards. The MCDA was adapted in this study to reduce a complex decision problem into a set simpler decision problems that decision-makers can analyse more easily.

A region exposed to active tectonics, with the active faults obscured or lacking outcrops can benefit from this methodological framework. Neotectonic deformation and seismic hazard, as well as flood susceptibility, can be determined by various geomorphic indices. Such indices can be integrated within an MCDA model to highlight their interrelationships. Decision-makers may have a useful tool for the predicting areas of seismic and flooding hazard. Consequently, disaster risk reduction in seismically active regions and flood-prone areas can be assisted, for instance by the targeting of structures requiring strengthening in potentially impacted historical heritage sites.

Conclusions

A GIS-based MCDA approach was presented here to assess neotectonic deformation, seismic hazard zones and flood susceptibility, from a spatially distribution perspective, focusing on the likely impacts of those hazards on historical, cultural and heritage sites. The outcomes were based on spatial datasets extracted from ASTER GDEMs,

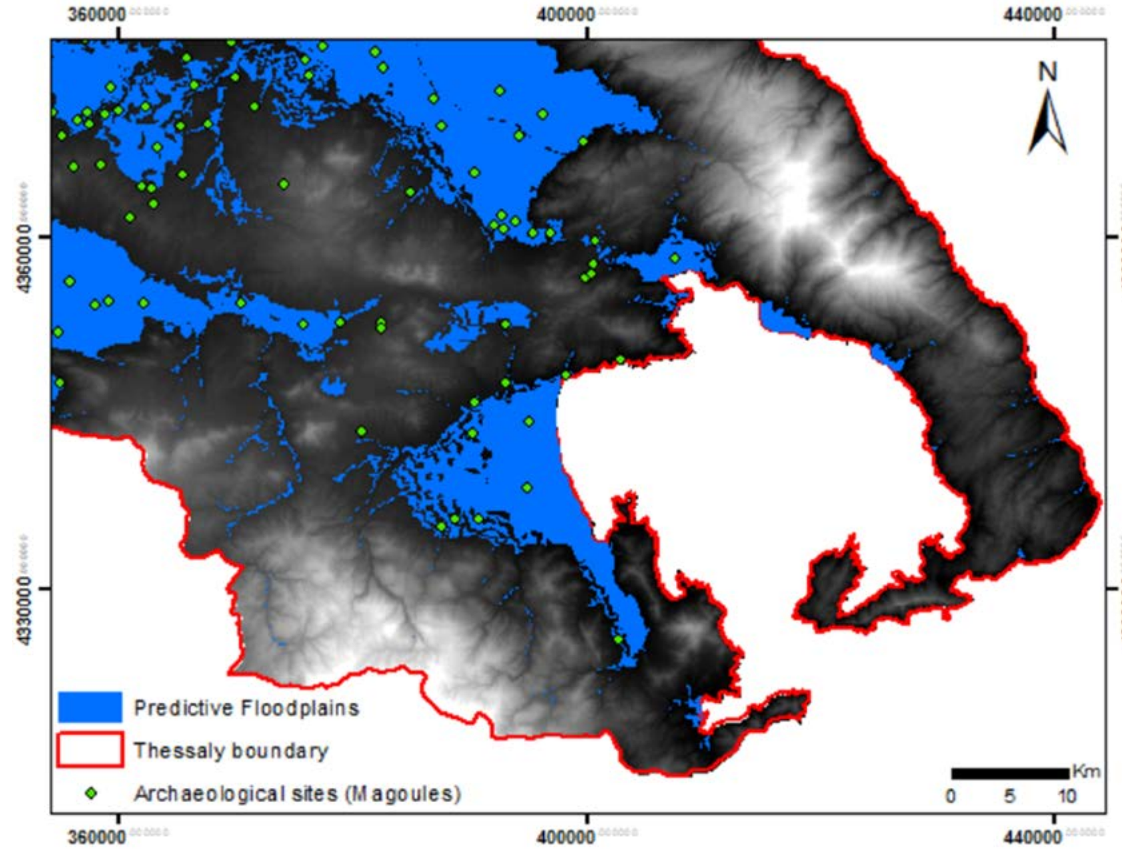

FIGURE 2: FLOODPLAINS IN THESSALY REGION AND ARCHAEOLOGICAL SITES.

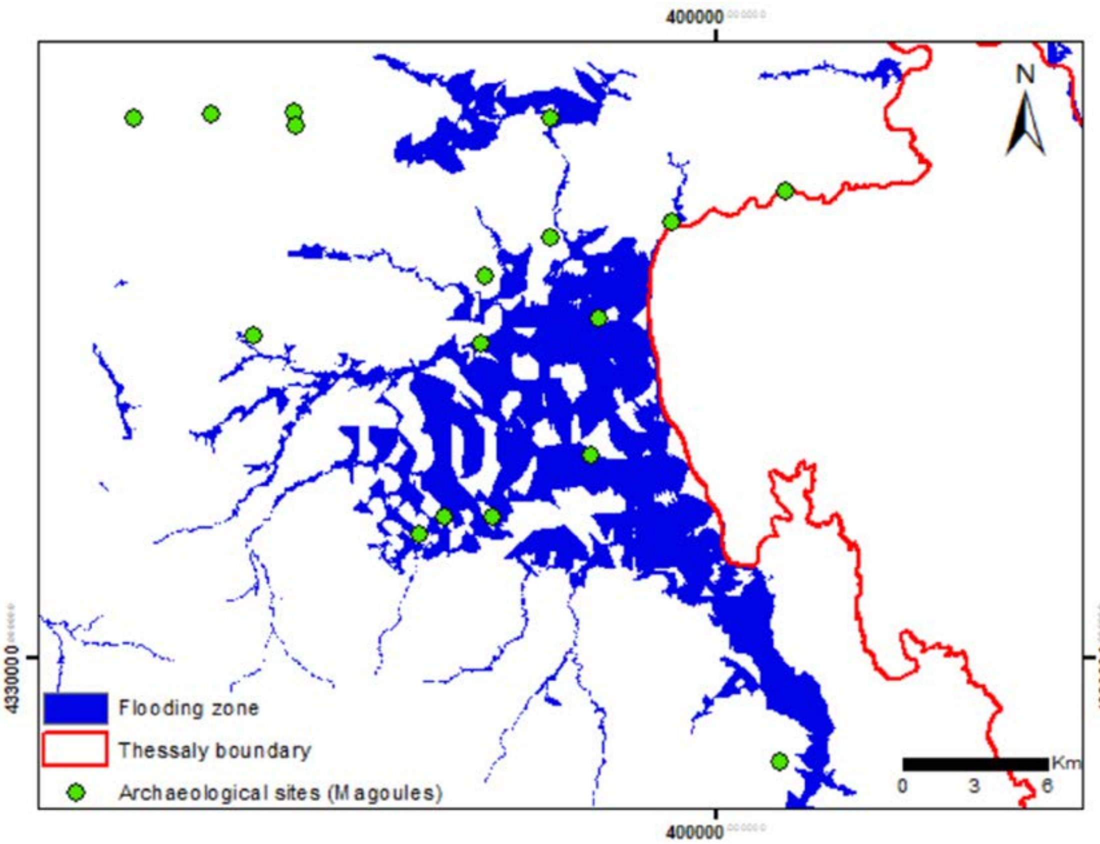

FIGURE 3: FLOODING ZONE OF AN AREA, IN THESSALY REGION, WITH THE KNOWN ARCHAEOLOGICAL SITES.

Table 1: Few derivatives of Digital Elevation Models (DEMs) used in the Multi-criteria Decision Analysis (MCDA).

Indices	Formula	Description	Applications	Category
Amplitude relief (Ar)		The spatial distribution of the maximum difference in elevation within unit areas of 1 km^2. A parameter that can be used for the statistically orographic configuration of the study area in order to determine fluvial erosion. Provides information associated with recent vertical displacements of uplifted or subsidence blocks.	Active tectonics Erosion	-Tectonics/seismicity -Flooding
Stream length gradient (Sl)	**Sl** = (ΔH / ΔL)* L, where ΔH is the height increase, ΔL the horizontal distance corresponding in each case to ΔH, and *L* the accumulated length from the starting point to the middle point of the interval.	The ratio of the change in elevation of the reach to the length of the reach multiplied with the total length of the channel from the point of interest where the index is being calculated. Abrupt changes in the gradient of river can be associated with active tectonics.	Active tectonics Hydrology Landslide	-Tectonics/seismicity -Landslide
Drainage density (Dd)	**Dd= ΣL/A,** where ΣL is the total length of all the ordered streams and *A* is the area of the basin.	The ratio of the total stream length to the area of the basin. The drainage density reveals information regarding surface runoff potential, ground surface steepness, the degree of landscape dissection, rock permeability and resistance to erosion.	Active tectonics Erosion Landslide	-Tectonics/seismicity -Flooding -Landslide
Stream frequency (Fu)	**Fu= N/A** where *N* is the total number of stream segments and *A* is the area of the basin.	The ratio of the total number of the stream segments to the area of the basin. The values of stream frequency indicate the degree of slope steepness, rock permeability and surface runoff.	Active tectonics Erosion Landslide	-Tectonics/seismicity -Flooding -Landslide
Slope gradient (Sg)	$\text{Slope} = \sqrt{(G^2 + H^2)}$ where *G* is the east-to-west gradient and *H* is the north-to-south gradient	Slope gradient algorithm shows maximum slope steepness, indicating the change in elevation between each cell and its neighbors, thus allowing relationships in basin morphometry to be determined.	Geomorphology	-Tectonics/seismicity -Landslide -Vegetation vs archaeology
Elevation relief ratio (Srr)	**SRR = (z(mean) – z(min)) / (z(max) – z(min)),** where *z* is the elevation.	Describes rugosity in a continuous raster surface within a specified window.	Active tectonics Erosion Landslide	-Tectonics/seismicity -Landslide
Terrain Wetness Index (TWI)	**TWI= ln (As/tanb)**, where *As* is the upslope contributing area and *tanb* is the curvature of the slope.	Determines the spatial distribution of soil moisture and surface saturation with regard to the influence of topography, based on digital elevation models (DEMs). Narrow V-shaped valleys can be determined as a characteristic aspect of active tectonics.	Tectonics Erosion Landslide Hydrology	-Tectonics/seismicity -Landslide -Vegetation vs archaeology

with their interrelationships being evaluated through an MCDA model to determine seismic hazard zones and flood hazard zones within the Paphos and Thessaly study regions. This approach has highlighted many heritage sites exposed to neotectonic deformation, seismic and flooding hazards.

The methodology developed in this study, regarding seismic hazard mapping, provides a low-cost and time effective reconnaissance tool in comparison to a costly established GPS network, and can be applied by decision makers via geospatial datasets and GIS analysis. It can also provide a useful alternative to Interferometric Synthetic Aperture Radar (InSAR) data for highlighting zones of neotectonic deformation, particularly where vegetation or snow cover limits the effectiveness of InSAR. Similarly, assessment of flooding hazard by using the methodological framework of this study is cost-effective and significantly beneficial when there is lack of quantitative data such as stream-gauging records. The MCDA approach followed in this study is found to provide reliable preliminary assessment of monuments sites exposed to active tectonics and flood events.

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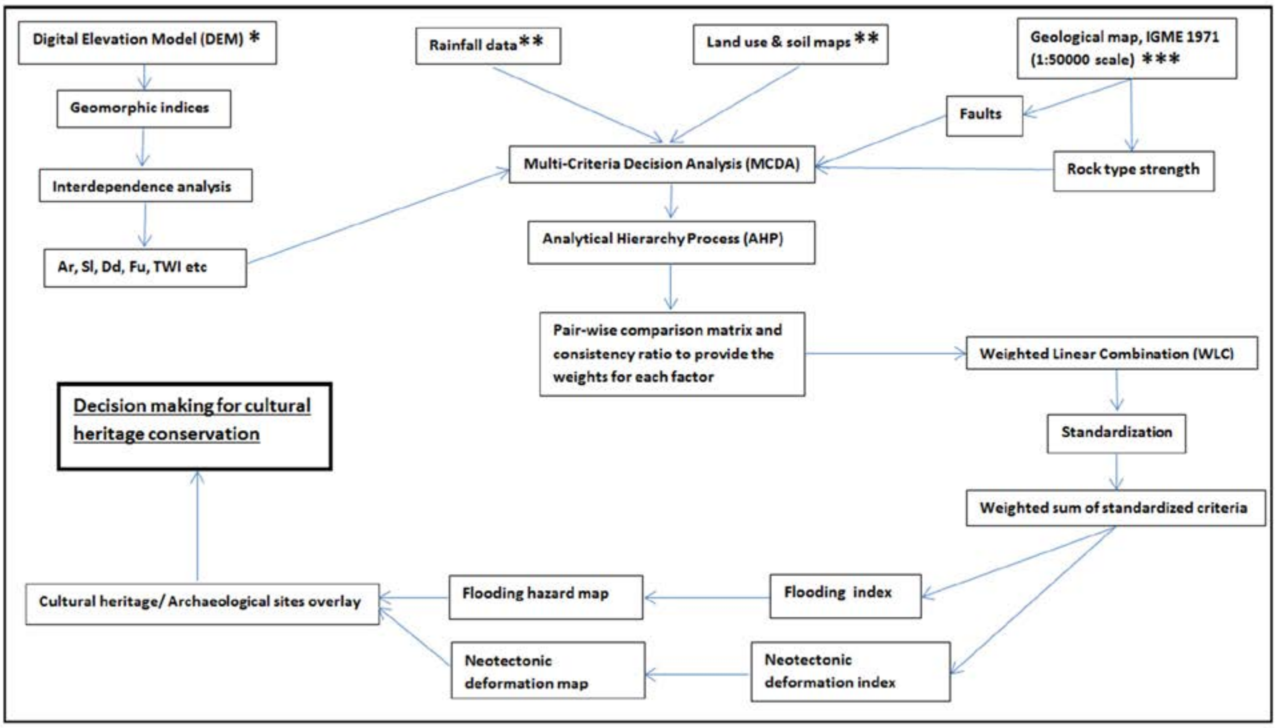
Table 2: Methodological procedure used to assess seismic and flooding hazard mapping..



* : DATASET USED FOR BOTH SEISMIC AND FLOODING HAZARD ASSESSMENT
** : DATASET USED ONLY FOR FLOODING HAZARD ASSESSMENT
***: DATASET USED FOR BOTH SEISMIC HAZARD ASSESSMENT

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Adding a Geographical Component in Cultural Heritage Databases

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Abstract: The paper provides an overview of the different approaches for bringing the geographic component in web based databases/ inventories containing information on archaeological and cultural heritage sites. Geographic information is usually handled by a Geographic Information System (GIS), whereas information on cultural heritage characteristics can be expressed as simple text, characterized with some keywords, or structured in a semantic database following the guidelines established by existing standards of cultural heritage documentation. Several existing systems allow users to query heritage databases using keywords with results are depicted on maps. The emerging trend of defining Spatial Data Infrastructures brings forward the need to define an SDI for cultural heritage sites based on the same principles used for other spatial data themes (road networks, environmental variables etc.), namely the INSPIRE directive. For this reason, a suggested approach for extending the INSPIRE directive is presented. Finally, the Arches Heritage Inventory and Management System, an information system which allows the geographic query of cultural heritage databases semantically structured, is presented.

Keywords: Cultural heritage, geographic location, INSPIRE, CDS, CIDOC, ARCHES, semantic representation, GIS

Introduction

Geographic information primarily refers to the location of a cultural heritage object (and/or where it was found/ developed-constructed etc.). It is important information because the location can be used to identify what other cultural heritage or other objects exist in the surroundings, the topography of the area and other locational information that can be used for analyzing cultural heritage in a systematic way. Including this component in a database allows the geographic query of the database and makes possible the visualization of the data on a map. Several web sites using custom made software have implemented a component for displaying the location of heritage sites. Usually the approach is relatively ad-hoc and there is not any functionality that permits to identify other spatial/ geographic layers.

As a result of the emerging concept of Spatial Data Infrastructure (SDI), that is providing all spatial data in an interoperable and systematic way, there is an increasing research interest in the cultural heritage documentation field to use the same tools and methodologies as those used for defining other geographic information. SDI can be defined as a set of standards, procedures and tools that allows the organization of spatial data in a way that makes it easy to find them, evaluate them with respect to their relevance and use them in any type of application. The use of standards is necessary, since spatial data are created by different organizations, at different accuracies and resolutions and for different themes. In EU the INSPIRE (INfrastructure for SPatial InfoRmation in Europe) directive was adopted in 2007 and is now the standard for the development of all spatial datasets, there is therefore a strong argument to define an SDI for cultural heritage following the INSPIRE paradigm.

In defining an SDI for cultural heritage sites, the existing standards for documenting archaeological, historic etc. sites must be also considered. The most significant of these are the Core Data Standard for Archaeological Sites and Monuments (CDS no date) and the CIDOC Conceptual Reference Model (CIDOC-CRM) (Doerr 2003; Crofts *et al.* 2010). CDS defines the information needed for describing and cataloguing an archaeological monument or site. CIDOC-CRM which has been accepted as an ISO standard since 2006 provides the definitions and the standards for describing the concepts and relationships that can be used for documenting cultural heritage. Through a semantic framework, cultural heritage entities can be described in a way that allows the integration of information in a comprehensive way.

In this chapter, an attempt is made to provide a synthesis of the current thinking on explicitly specifying a geographic component in archaeological and generally cultural heritage inventories. The outline of this chapter is as follows. In the next section different web sites of archaeological and cultural databases with explicit geographical reference are briefly outlined, while in section three, issues related to extending the INSPIRE framework in order to address cultural heritage entities are presented. Finally, in the fourth section there is a discussion about Arches, a recently developed open source information system which is map-based and has implemented the CIDOC-CRM guidelines thus permitting end-users to query databases both geographically and semantically.

Existing implementations

The CDS specifies that location is a key information that has to be available for every archaeological and cultural site. Depending on the cartographic accuracy, the available location can be expressed as the name of a country/nation, a region (geo-political/administrative), locality (city, township), exact street address or exact geographic coordinates. Any one of these on its own, or in combination, can be used to locate an entity in space. Although nowadays through the use of a GPS and other geo-positioning technologies it is possible to define the exact spatial coordinates for every entity, this is not possible with some archaeological monuments/sites discussed in ancient manuscripts in relatively vague terms and which have disappeared since then.

Such a case is the Pleiades database (http://pleiades.stoa.org/). The Pleiades gazetteer is a joint project of the Institute of the Study of the Ancient World (ISAW) and the Ancient World Mapping Center at the University of North Carolina at Chapel Hill. It currently provides information on about 34,000 ancient places relevant to the history of Europe, North Africa and Western and Central Asia. Central themes to the database are the concepts of *Place, Name* and *Location*. A *Name* is an abstract textual entity and together with the *Location* they provide the geographical and historical context of a *Place*. *Places* can be expanded by human experience and may expand, contract and evolve over time. A *Place* may be unnamed, with no known location, falsely attested or even mythical.

A list of publicly available cultural heritage/ archaeological/ historic web sites that can display the location of heritage sites on a map is shown in Table 1, together with a brief note on their functionality. Typical functionality of these sites is the querying of a database using keywords and results displayed as individual records and then over a map. Several web sites include the functionality of searching on the map to find heritage sites nearby. For examples, in Scotland there are two elaborate applications for providing to the public data on listed buildings, archaeological and maritime sites etc. Both use the data of the Royal Commission on Historical Monuments of Scotland (RCHMS), one displaying the location on raster (scanned) map sheets and the other on a map that also includes other geographical data layers of the spatial data infrastructure of the country.

CultureSampo in Finland is probably one of the most ambitious systems for accessing cultural heritage information since it employs extensive concepts of semantic web. It addresses the difficulties of aggregating highly heterogeneous, cross-domain cultural heritage collections and other contents into a semantically rich intelligent system for human and machine users (Hyvönen *et al.* 2009). The basis of the system is the national FinnONTO infrastructure that includes a collaboratively created system of cross-domain ontologies and related ontology services for utilizing them as web services. Four different map views are provided. Users can '*Search for items on the map'* to display location of objects on a Google map and then obtain semantic spatial relationships such as 'place of acquirement', 'place of subject', and 'place of manufacture'; they can find the boundaries of *Historical Areas*', based on a spatiotemporal Finnish place ontology; view *'Historical Maps'* displayed semi-transparently over Google Maps and also view photos from Panoramio; and finally find '*Nearby Objects'* of cultural sites by clicking at any point on the map.

The list of web sites presented in Table 1 is not complete and additional web sites with similar capabilities might exist. The list contains only web sites that are open to the general public, therefore systems such as ARCHIS in Netherlands are not listed -- version 3.0 of the system currently under development will be available to the public--. Several European and national research projects have also examined the issue of adding a geographical component to cultural heritage databases. INDICATE and ATHENA projects looked on the issue of developing a tool that would automatically geocode --that is place geographic coordinates-- on heritage sites (Zakrajšek and Vodeb 2013), PELAGIOS on developing tools and methodologies for enabling linking ancient geodata in open systems, CARARE on developing an eCultureMap (http://carare.eculturelab.eu/) that displays cultural objects from Europeana, Archaeeolandscapes (ArcLand) to address the use of modern surveying and remote sensing techniques in archaeology, ARIADNE on integrating archaeological datasets and others

Inspire directive and cultural heritage datasets

The INSPIRE Directive

The INSPIRE Directive (2007/2/EC) was enacted in May 2007 to establish an Infrastructure for Spatial Information in the European Community for supporting mainly environmental policies. The Directive advocates the integration of National Spatial Data Infrastructures (SDIs) from Member States into a European SDI enabling the interoperability and harmonization of spatial data sets and services. The INSPIRE Directive relies on the following principles: (a) data must be collected only once, (b) data should be organized in a way that permits combining data from different sources across Europe, shared by many users and used in different applications, (c) information collected at one level/scale can be shared at all levels/ scales, (d) information should be readily and transparently available, and (e) it should be easy to find what geographic information is available, how it can be retrieved and how it can be used. The Directive defines 34 different spatial data themes (layers of geographic information) described in three annexes and each theme must be developed according to an INSPIRE data specification and the generic conceptual schema. The significance of the INSPIRE directive is not only the data specification but also on the rules on metadata and network services that define a system architecture that makes spatial data available across the internet, irrespective of where datasets are located.

Table 1. Cultural heritage web sites with a mapping component

Canada	Register of historical places (CRHP) http://www.historicplaces.ca/en/rep-reg/search-recherche.aspx	Query a database of historic places on the basis of keywords (categories) and/or administrative areas. Results displayed on a Google map where they can be clicked for further information.
England	The National Heritage List of England http://www.english-heritage.org.uk/	Search through a database with archaeological sites, listed buildings etc. using keywords. Results displayed as a list and exact location is shown on a map.
Finland	Finnish Culture on the Semantic Web 2.0 http://www.kulttuurisampo.fi	Users can perform semantic searches to identify heritage sites and display their location on maps, find nearby objects and also observe several historical maps. Extensive use of the semantic web with the mapping component provided by Google.
France	Atlas de patrimoines http://atlas.patrimoines.culture.fr/	Provides display on a map of cultural and heritage information (ethnographic, archaeological, architectural, urban, landscape). Can be searched on the basis of communes. Visualization of the location is provided on maps that display also other information (cadaster, etc.).
France	JocondeLab http://jocondelab.iri-research.org/jocondelab	Access to the items of the Joconde Catalogue that contains all the collections of the French National Museums. Users can search through keywords; also they can click on a community on a map and see cultural heritage objects ‘associated’ with that community (museum there, made there etc.).
Greece	Interactive culture map of Greece http://odysseus.culture.gr/	Interactive map (Google Maps) that shows the location of all archaeological, historical sites and museums of Greece.
Ireland	Ask about Ireland http://www.askaboutireland.ie/map/	Users can search a map with predefined keywords to find the location of various heritage sites. By clicking on a location on the map textual information are provided about the specific site.
Netherlands	Archaeology in the Netherlands http://archeologieinnederland.nl/bronnen-en-kaarten	Several web sites for different archaeology themes; users can locate on a map all archaeological monuments of the Netherlands and obtain information by clicking on a point; they can see expected archaeology in floodplains. etc..
Netherlands	Monumentenregister http://monumentenregister.cultureelerfgoed.nl/php/main.php	Users can search for cultural heritage sites using addresses and keywords to obtain further information and view on Google Maps the exact location.
Norway	Kulturminnesøk http://www.kulturminnesok.no/	Publicly accessible part of the ‘Askeladden’ database of the Directorate of Public Affairs, allows map searching and display of the location of various archaeological and historic sites.
Spain	Patrimonio Galego http://patrimoniogalego.net/	Information on cultural heritage of the region of Galicia. Data are crowd sourced and users can retrieve information with queries with respect to the region, municipality, but also by type of cultural heritage and chronology. Mapping display provided by Google Maps.
Scotland	National collection of buildings archaeological sites and Industry http://canmore.rcahms.gov.uk/	Search for buildings, archaeological sites using a specific entity’s name or keywords. Location of results displayed on a map, further info can be obtained.
Scotland	Spatial data infrastructure (SDI) http://scotgovsdi.edina.ac.uk/srv/en/main.home http://pastmap.org.uk/	On maps of the spatial data infrastructure of Scotland display information related to archaeological sites, listed buildings, and protected areas. Data on sites provided by RCAHMS, though an interoperability scheme of linked databases.
Slovenia	Register of immovable cultural heritage http://giskd.situla.org	On a map of Slovenia that also includes other data as well, users can see the location of all heritage sites and by clicking they can obtain textual information.
Wales	SDI Protected sites http://data.gov.uk/publisher/welsh-government-spatial-data-infrastructure	Provides mapping display of the location of protected sites of cultural heritage as part of the spatial data infrastructure of Wales.

INSPIRE themes pertinent to cultural heritage

Cultural sites are defined by UNESCO as 'works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view' (UNESCO 1972, Article 1). Monuments are defined as 'architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science' (UNESCO 1972, Article 1).

In the INSPIRE framework these concepts are represented by the 'Protected Sites' and 'Buildings' themes. The INSPIRE Directive defines a Protected Site as an 'area designated or managed within a framework of international, Community and Member States' legislation to achieve specific conservation objectives' (Directive 2007/2/EC:11) whether nature, cultural or other conservation related. By definition, the emphasis lies on the legal perspective of the data, namely the existence of legislation that defines the type of the protection for a site and of course its spatial characteristics. The theme is oriented towards environmental aspects, however, historic and archaeological sites and other cultural heritage protected areas – inland and marine – can be also considered in the same theme. The 'Protected Sites' theme included in Annex I, is considered as reference data - and thus important in its development, and must be used at all levels of spatial resolution, European, National, Regional and Local.

The INSPIRE Data Specification on Protected Sites presents a Simple Application Schema with limited attributes for the central class 'ProtectedSite', which is a feature type. The mandatory attributes are the *geometry* and *InspireID*, with the former referring to the geographical boundaries of the protected site defined by the administration responsible for its protection and management and the latter to an identifier of the site. Boundaries may be represented as points, lines or polygons (single or aggregated polygons), it is recommended, however, that sites with an area of greater than 1 hectare be defined as polygons rather than points. The other voidable attributes (that is they may not exist in some data sets although it is recommended to be included) of the class are: (INSPIRE Thematic Working Group Protected Sites 2014):

- *legalFoundationDate*: the date that the Protected Site was legally created (it takes values - defined by the ISO/TS 19103:2005 - from the class *DateTime*).
- *legalFoundationDocument*: the URL or text citation referencing the legal act that created the Protected Site (it has *CI_Citation* as value type defined by ISO 19115:2003).
- *siteDesignation*: the type of the Protected Site according to a schema. At least one designation is required but a Site may have more than one designations. It takes values from the class *DesignationType* that has the attributes: (a) *DesignationScheme*, which stands for a schema for cultural sites that may be international or national and, (b) *DesignationValue*, which gives the value within a scheme, and (c) *percentageUnderDesignation*, which gives the percentage of the site that falls under the designation. For the cultural heritage domain, the 'UNESCOWorldHeritage' and 'NationalMonumentsRecord' schemes can be applied and the designation values *natural*, *cultural* and *mixed* and *monument* are considered accordingly for each schema.
- *siteName*: the name of the Protected Site as defined by the INSPIRE Data specification on Geographical Names. *siteProtectionClassification*: the classification of the Protected Site based on the reason for its protection. *Cultural*, *archeological* and *landscape* reasons are used for cultural heritage sites given as values from the *ProtectionClassificationValue* enumerated class.

In previous versions of the Data Specifications on Protected Sites (version 3.1, INSPIRE Thematic Working Group Protected Sites 2010:12) a Full Application Schema was also defined with additional attributes, all of which considered voidable. Since they included references to the data themes 'Habitats and Biotopes' and 'Species Distribution', data specifications on which were published in 2013, they were removed from the latest version in order to be more consistent with the latest data specifications of these two themes. They could be included however at a later revision.

The 'Buildings' theme handles characteristics of buildings. Building data may be available either as 2D, 2.5D or 3D data. As the Thematic Working Group states (2013:27), 'Buildings are enclosed constructions above and/or underground which are intended or used for the shelter of humans, animals, things or the production of economic goods and that refer to any structure permanently constructed or erected on its site'. Three application schemas are proposed: the BuildingsBase application schema that describes the concepts common to all other Buildings application schemas and contains the core normative semantics of the 'Buildings' theme, the Buildings2D application schema that defines the 2D geometric representation of buildings defined in the BuildingsBase application schema, and the Buildings3D application schema that addresses the 3D geometric representation of buildings. There are also three extended schemas for each one of the above to cover additional details.

The 'Building' is the central class and can be an aggregation of 'BuildingParts'. Both of these are sub-classes of the class 'AbstractBuilding' and 'AbstractConstruction'. Several attributes have been assigned to these classes (Figure 1) such as *conditionOfConstruction*, *dateOfConstruction*, *elevation*, *name* etc. Classification of buildings is through the attributes *currentUse* that describes the use (activity

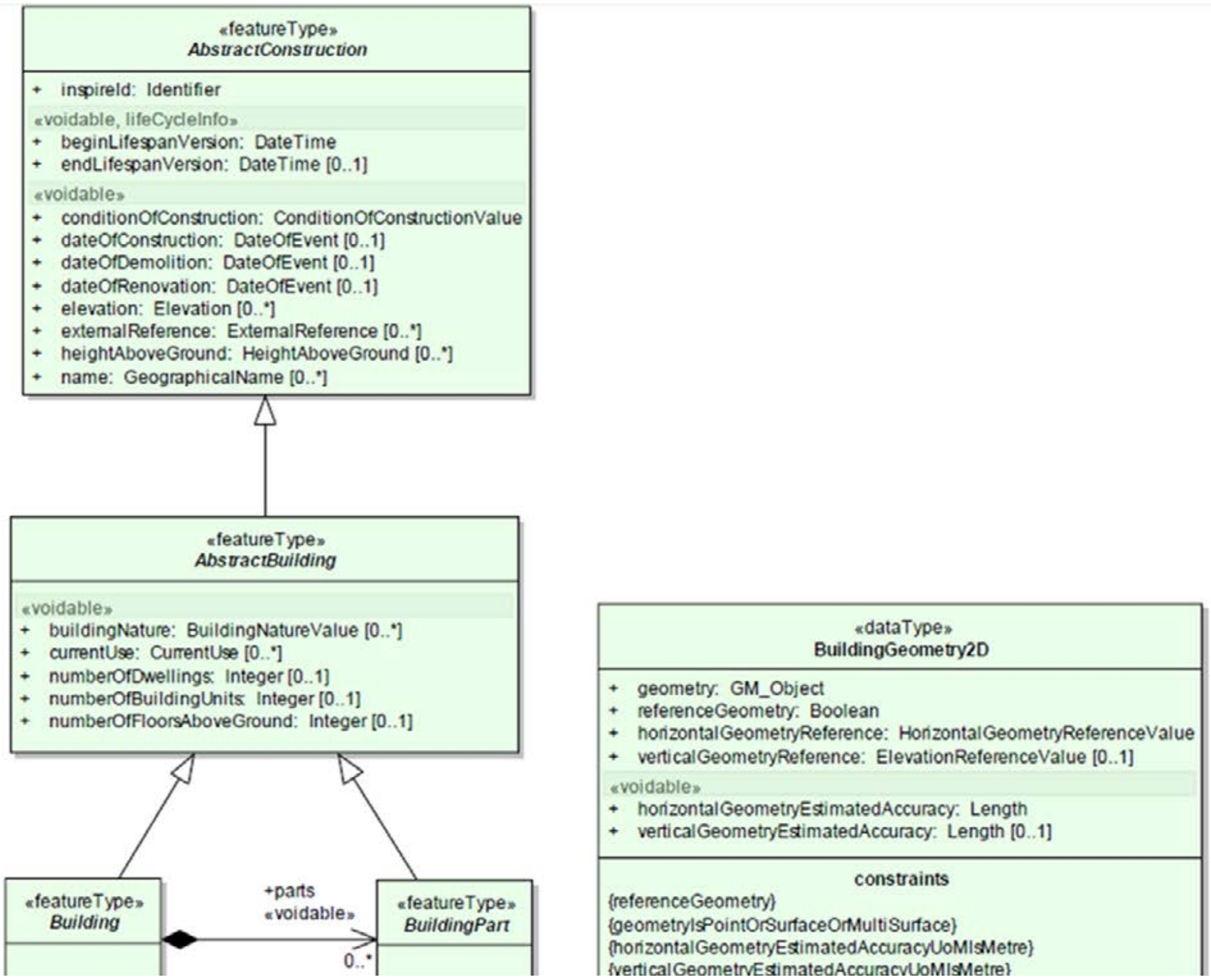

Figure 1. Feature types of the BuildingsBase application schema (INSPIRE Thematic Working Group Build. 2013:36).

taking place in the building, such as residential, agriculture, office, trade etc.) and *buildingNature* that represent the type of a building (such as arch, bunker, castle, church etc.). In the latter attribute, lies the only reference of INSPIRE to *cultural* buildings since values for castle, church, etc. are included. In the *CurrentUse* attribute there is not any value/use that could be associated with cultural heritage buildings.

Extension of the Protected Sites Application Schema for the Cultural Heritage domain

In the INSPIRE framework, cultural sites and buildings are considered spatial objects with emphasis on their legal aspects. Attributes that handle cultural and/or historical aspects of sites and buildings are not included. McKeague *et al.* (2012:38) argue that the 'Directive's relevance to archaeological and built heritage information is unclear' and outline arguments 'for adopting a more expansive interpretation of the Protected Sites theme beyond designated assets' (p. 40). But still, 'INSPIRE and national or regional Spatial Data Infrastructures should be the catalyst to enable those responsible for the documentation and curation of the archaeological and built environment to contribute to and benefit from INSPIRE'S principles' (McKeague *et al.* 2012:41). This is because the INSPIRE methodologies (standards, procedures, metadata and services) can support the need for interoperability among the relevant – usually distributed - databases in the cultural heritage domain.

To address this issue Fernández Freire *et al.* (2014) have proposed an extension of the Protected Sites Application Schema in order to model sufficiently cultural heritage entities. They proposed a Cultural Heritage Application Schema within INSPIRE which extends the Protected Sites Application Schema by adding classes and attributes. This schema is formed in three parts, namely the:

- Legal or administrative part for issues related to the administration of the site and its status of legal protection,
- Cultural part for documenting cultural heritage characteristics,
- Document part that describes various files (text or multimedia) related to the site.

This distinction is based on the concept that real world cultural entities are different from legal artifacts that are products of heritage evaluation (Fernández Freire *et al.* 2014).

For the legal part, the main class of the proposed model is the 'ProtectedHeritagePlace' defined as an area dedicated to the protection of cultural resources and managed through some legal and administrative means; it is a subclass of the 'ProtectedSite', central class of the INSPIRE model. Several new attributes have been added. The new attributes are:

- *ProtectionTargetValue/ BienInteresCultural* that are new schemas in *siteDesignation* with the former defining type of the protected site according to UNESCO while the latter designates a Spanish protection status,
- *siteIdentifier* referring to an identifier for the site, not necessarily unique, using some national or international identification scheme,
- *spatialResolution* of the geometry of the protected site that depends on the way data have been gathered,
- *dataSource* that specifies the name of the organization responsible for providing and maintaining the database,
- *beginLifespanVersion* that is the date and time this version of the spatial object was inserted in the spatial database,
- *placeName* which is taken from a legal foundation document and not from a pre-existing gazetteer as the attribute siteName of INSPIRE,
- *administrativeScope* standing for the scope of the legal definition for the cultural site,
- *type* that provides the reasons for the site's protection; *Archaeological*, *Architectural* and *Ethnographical* are proposed as values but others can be added.

Two relations are also introduced to consider the inclusion of a protected site by another (*contents* relation) and the supplementation among sites under the form of surrounding areas of buffers (*protectionSurrounding* relation). All these new elements along with those from the INSPIRE scheme form the legal part of the heritage place's description.

For the cultural part, the class 'CulturalEntity' is introduced to capture the distinction between protected places and cultural entities. As Fernández Freire *et al.* (2014: 32) points out, a cultural entity might be 'a whole building, an archaeological site or a smaller feature such as a wall or a brick, being the building an aggregation of those smaller features and a cultural entity as well'. That is a cultural entity can be broken down into its parts, which are cultural entities on their own merit or considered as a whole. The 'CulturalEntity' class has three mandatory properties (*entityName*, *chronology*, *entityTag*) and two voidable (*entityDescription* and *geometry*). *EntityName* is the name of the entity, *chronology* is used to document the timeline (significant events/dates) of the entity (i.e. creation, occupation, abandonment, re-occupation, modification, restoration etc.) and is defined on the basis of ISO 19108:2002 and *entityTag* identifies the type of cultural entity on the basis of a some classification standard of heritage objects (Unesco Thesaurus, English Heritage Thesauri etc.). Furthermore, in 'CulturalEntity' the 'MaterialEntity' and 'NonMaterialEntity' sub-classes are introduced to differentiate between tangible/ intangible heritage entities. The 'MaterialEntity' is further categorized according to the typology suggested in CIDOC-CRM: 'HumanMadeObject', 'HumanMadeFeature' and 'NaturalFeature'. The proposed schema also considers the issue of samples taken from a cultural heritage entity for analysis to identify its origin, date, state of preservation etc. (class 'Sample') and the results of the analysis (class 'AnalyticalResults').

For the document part, the proposed extended model includes any resource that contains or provides information for a cultural site. This is described by the attribute *type* of the Dublin Core Metadata Initiative that establishes twelve types of documents such as Text, Image (StillImage, MovingImage), Sound, Dataset, InteractiveResource, Collection of resources, Software, Service, PhysicalObject and Event.

The proposed extended application scheme distinguishes cultural sites (real world entities) from protected sites (legal entities of INSPIRE) resulting to more clear definitions of the various information. It is generic thus permitting different heritage sites information to be included if they have a spatial reference.

Arches

Arches is an open source software system that can be used for organizing and managing information on sites of cultural heritage, first released in early 2013. The system was developed through a collaboration of the Getty Conservation Institute and World Monuments Fund with substantial technical assistance from English Heritage and the Flanders Heritage Agency. It has been designed as a generic platform for addressing the inventory management needs of organizations responsible for cataloguing information on archaeological, historical and heritage sites (Carlisle *et al.* 2014). That is to be a tool that can streamline the development of databases and information systems on cultural heritage sites without extensive in-house software development, and which also follows documentation standards.

A key characteristic of Arches is that it has been developed using the existing standards of cultural heritage documentation world and the latest technologies of geospatial technology. The CDS nomenclature is used for defining all data fields, while CIDOC-CRM provides the semantic framework. Through the use of a semantic framework it is possible to integrate databases from different organizations, while the choices/alternatives for

Table 2. Resources in Arches

Heritage resources	Used for describing the 'heritage type' classification of a site. For each type different information are documented when cataloguing the characteristics of the site.	Archaeological heritage site Archaeological heritage element Architectural heritage Landscape heritage Maritime heritage
Activities	Used for cross referencing activities related to the history of the site, as well as, activities pertinent to the management of a site.	Investigation Management Designation and Protection Historical
Actors	Used to record information about who is associated with the site.	Persons Organizations
Documents	Any file that relates to another Arches resource.	Document Image

the analysis of the information are significantly augmented. The CIDOC furnishes the definitions and the formal structure for describing the implicit and explicit concepts and relationships used in Cultural heritage documentation; it describes the 'who, how, what and when' of the various cultural entities and therefore it is possible to establish relationships, connections between heritage objects which are not immediately evident (Farrallon Geographics Team 2014).

Arches recognizes four major groups of resources, for a total of 13 different themes (Table 2). Entities are defined according to these and for each entity additional information can be documented as needed. For example, for archaeological/architectural elements, classification and dating, materials, measurements etc.

With respect to maps, Arches uses the Google Maps where users can record the exact location of monuments and possibly boundaries of archaeological sites to designate protected areas etc. Users can browse the map to observe the exact location of heritage objects.

A key aspect of Arches is the use of graphs for defining relationships. Each resource type in Arches can be represented by a graph that describes the database schema for that particular resource. This graph represents the relationships, the ontology in more scientific terms, for defining the various entities users want to track. In the existing Arches package the graph nodes identify CIDOC classes, while the edges correspond to the properties of that class. In the upcoming version 3.0 of the software, users can define their own graphs and import them in the system. These graphs can represent standards adopted by other heritage organization and therefore result in versions of Arches suited for cataloguing information based on established standards different than CDS and/or CIDOC.

Conclusions

This paper provided a synthesis of some of the existing and proposed approaches for handling the locational component in databases of archaeological, historic and cultural heritage sites. With the increasing availability of digital mapping technology most of these databases in the near future are expected to have explicit reference to the location of the sites. Whether it is possible to define for cultural sites a data structure consistent with the INSPIRE directive that also incorporates a semantic framework such as the one described in CIDOC-CRM is an open question and this will continue to be an important research question in the future. On the other hand, the intuitive mapping interface and the integration of CIDOC-CRM found in Arches might be arguments that rather than defining new application schemas in the ProtectedSites INSPIRE theme, extend CIDOC by considering more explicitly the location component and if necessary implement a link between INSPIRE-based and CIDOC-based schemas for cultural heritage data organization to permit the latter take advantage of the richness of geographic datasets in the SDI framework.

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Historical Maps on the Semantic Web

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Abstract: This chapter introduces a methodology for the semantic documentation of historical maps to facilitate their accessibility and re-usability on the Web. The key component of the suggested methodology is the development of an ontology for historical maps. The ontology acts as a basis for the semantic profiling of metadata standards currently in use to provide an enhanced vocabulary for historical maps. Furthermore, it can serve as a bridge for linking multiple items of different type (maps, texts, spatial data) together under a common framework. Ultimate goal of the proposed ontology is to: (a) offer a more expressive standard for historical maps, until now absent, since organizations managing cartographic collections mostly use bibliographic metadata; (b) define the concepts and interrelations that describe maps in a standardized way using a language that can be recognized by different applications; and (c) support well-documented publishing and advanced searching of cartographic information on the Semantic Web.

Keywords: Annotation, Application profile, Concept, Historical map, Metadata, Ontology, Semantic Web

1. Introduction

Nowadays, organizations that maintain cartographic collections use bibliographic metadata or cultural content standards for the curation of their collections. Furthermore, the current technological trends towards the development of the Semantic Web enable new techniques for searching and utilizing historical maps that emphasize their semantics. Therefore, the semantic description of historical maps is necessary. This will result in a specialized - conceptual - vocabulary to define the concepts and relations that describe maps. Aligned to this need, this chapter introduces a methodology for the semantic documentation of historical maps that focuses on their special characteristics including their geographic content.

The basic component of the suggested methodology is the development of an ontology for historical maps. Bittner and Smith (2003) were the first who identified the close relationship between maps and ontologies arguing that ‘a map is a specific, simplified and therefore highly efficient representation of the ontology of a certain part of geographical space. It is an ontology because it is an inventory of things that exist in a certain part of the world and of some of the properties and relations between them’ (Bittner *et al.* 2003, p.118). An ontology models the cartographic knowledge in a formal way and publishes it on the Semantic Web. In this way the retrieval of maps via new ‘clever’ queries is feasible. The aim is not to abolish common standards that are already in use but rather to refine them in order to describe historical maps in a more focused and eloquent way, resolving any vagueness in the meaning of their content.

The structure of the chapter is the following: Section 2 outlines current practices regarding the management of historical maps in the Web and highlights their shortcomings. The basic idea of Semantic Web and the research question are also discussed. In Section 3, the methodology for using historical maps in the Semantic Web is described. Section 4 presents a cartographic ontology that has been developed for a series of historical maps, its applicability in the semantic profiles of common standards (such as Dublin Core and CIDOC-CRM), and a paradigm of how it can be used in enriching the annotations in historical maps. Finally, in Section 5 basic conclusions of this research are given.

2. Problem definition

Historical maps on the Web

On the Web, historical maps are accessible either through the digital catalogues of libraries and museums (e.g., Library of Congress) that traditionally preserve them or by digital map libraries (e.g., geoportals). Maps are also a basic component in Cultural Heritage Management Systems that interlink cultural artifacts (e.g., Europeana) as well as the basis in Historical GIS (e.g., Great Britain Historical GIS). Lately, historical maps are also used as a platform in various web applications for tagging historical or other information (e.g., Phila Place digital storytelling or Neatline project).

The first and most important step in the management of historical maps is cataloguing, namely the definition of metadata that describe them. Cataloguing ‘is necessary for the users in order to discover the map they need and for the curators in order to maintain, organize and publish maps on the Web' (Williams 2005, p. 227). The most common metadata standards are the bibliographic ones but standards for documenting cultural artifacts or digital resources are also in place. Worldwide, the following standards are currently in use:

- Bibliographic metadata: MAchine Readable Cataloging (MARC), International Standard Bibliographic Description for Cartographic Materials (ISBD CM), International Standard Archival Description General (ISAD -G), Anglo-American Cataloguing Rules (AACR2), Resource Description and Access (RDA).
- Metadata for cultural artifacts: CIDOC-CRM, Europeana Data Model, Categories for the description of works of Art (CDWA), Visual Resources Association (VRA).
- Metadata for digital resources: Dublin Core, Encoded Archival Description (EAD).

Searching and retrieval of historical maps from library digital catalogues is carried out by using keywords upon their metadata databases (Montaner 2009). Historical maps can also be acquired from portals that harvest metadata from various data providers (Borbinha *et al.* 2009; Simon *et al.* 2010) based on the protocols OAI-PMH or Z39.50 (Borbinha *et al.* 2009).

Historical maps are published on the web as (a) static maps (e.g., jpeg, jp2); (b) interactive maps with the functionality to pan, zoom, turn transparent and print in different scales; and (c) Web Map Services, where users request the map from a map server. In any case, re-usability of historical maps in other systems depends on the level of detail in both their documentation and georeferencing.

Shortcomings and current trends

Evaluating the existing metadata standards, it is evident that there is not a specialized schema for historical maps and their content. Although fields for the description of the map properties (e.g., scale) are defined, these are very limited as the mathematical and geographic characteristics of maps and description of maps content (e.g., spatial coverage, place names, and geographic entities) are missing. These should be considered since, on one hand, they are critical for someone to define whether a map is suitable for an application or not and, on the other hand, can enrich the criteria for a spatial retrieval of maps.

Conversion of library digital catalogues to digital map libraries is presently a common practice and therefore it is necessary to develop bridges between map metadata (bibliographic, geographic and geometric) and the spatial metadata of a geoportal. Also, integration of maps in various web applications requires a technology that supports the interoperability among systems. For this, it is critical to clarify in a common framework the concepts that define historical maps so as to be conceivable from different applications. This can be expressed by the term Semantics, the meaning of expressions in language (Kuhn 2005) which is the basic idea of Semantic Web.

Semantic Web

Semantic Web provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries (W3C 2013). Berners-Lee *et al.* (2001) envisioned it as a highly interconnected network of data that can be easily accessed and understood by any desktop or handheld machine using ontologies as the means to translate information from different databases through common terms and rules. Eventually, Semantic Web provides structure and well defined meaning to the content of the World Wide Web, enabling the use of logic and knowledge sharing.

The basic element of Semantic Web is the resource which is anything that can be described and has a unique identity, the URI (Uniform Resource Identifier). The URI is a string of characters used to identify the name of the resource. Semantic Web uses the descriptive languages RDF(S) and OWL (W3C recommendations) for representing and publishing web content. RDF (Resource Description Framework) is a standard model for data interchange on the Web that extends the linking structure of the Web to use URIs to name the relationship between things as well as the two ends of the link. It allows structured and semi-structured data to be mixed, exposed, and shared across different applications (W3C 2014). RDF model is structured as a collection of statements. A statement describes a resource by a triple consisting of a subject, a predicate, and an object. The subject is an RDF URI reference or a blank node, the predicate is the property of it and is derived from a defined vocabulary and the object is either a resource or an RDF literal that gives the value of the property.

Ontology Web Language (OWL) is designed for use by applications that need to process the content of information instead of just presenting information to humans providing additional vocabulary along with a formal semantics (W3C 2004). OWL is used in order to develop ontologies and publish data on Semantic Web. Ontologies play a key role in the Web since 'they serve as a mean not only for conveying structural aspects and high-level data about information, but also for providing understanding and intelligent manipulation by a computer machine' (Koutsomitropoulos *et al.* 2007, p. 269).

Research question

The question that arises is how map metadata and content must be modeled in terms of Semantic Web. In Semantic Web, a historical map can be handled as a web resource that comes from the collection of a museum and has a unique URI. Its properties are the metadata of the map (e.g., scale). For this, it is necessary to convert map properties to concepts and interrelations in a standardized way to form a specialized vocabulary and in a descriptive language (RDF or OWL). As a result, a complete standard focused on historical maps will be developed so that publishing and accessing of cartographic information in Semantic Web can be supported. It must be mentioned that until now, the only related work includes the development of Semantic Cultural Heritage portals (e.g., CultureSampo and Europeana).

3. Methodology

Ontologies and concepts in historical maps

The basis of the methodology proposed is the development of a cartographic ontology for historical maps. According to Guarino and Giaretta (1995) ontology is a logical theory which provides an explicit, partial account of a conceptualization. Its usefulness relies on its ability to integrate information from heterogeneous knowledge bases in one system using a common framework for the taxonomic classification and definition of entities and their relations (Tomai 2005). There are different kinds of ontologies according to their level of granularity (Guarino 1998): (a) top or upper level ontologies describing very general concepts; (b) domain ontologies and task ontologies presenting the vocabulary related to a generic domain, task or activity; and (c) application ontologies, which discuss concepts depending both on a particular domain and task. For historical maps, an application ontology must be developed carrying out certain tasks.

An ontology consists of the following parts (Maedche and Staab 2001): (a) the lexicon of concepts in physical language, (b) the concepts-entities, (c) the relations between the entities and their properties, and (d) the axioms that rule the entities and their relations or properties. To discover the entities and relations that define a historical map, a syntactical analysis of the definitions associated with the historical map should be conducted. This way, relevant lexico-syntactic patterns are identified and then mapped into relations or properties. Definitions are comprised of the genus (the superordinate term of the defined word) and the differentiae (attributes that distinguish one entity from the other). The patterns applied in the genus part of the definitions extract the 'is-a' relations (hypernymy/hyponymy), while the patterns applied in the differentiae part extract other semantic relations (Kokla 2006). For example, the pattern *the historical map is a topographic map* gives a sub-category (kind) of map, while the pattern *historical map has a scale* gives a basic property of the map or its relation to the concept 'cartographic scale'. The syntactical analysis is conducted taking into account the metadata standards currently in use so as to include all the different elements that experience has shown that are needed.

The concepts identified are then constructed to classes and relations or properties in OWL using an ontology editor (e.g., Protégé) according to a hierarchical classification (taxonomy of concepts). The main classes are defined as disjoint (e.g., the class representing historical map and the class representing its properties) and then sub-classes are inserted as subcategories (e.g. the sub-class 'topographic' and the sub-class 'scale' accordingly). For each class, properties must be applied as well as their between relationships following specific restrictions according to the syntactical analysis (e.g., the relation 'map *has only one* scale'). The relations that explicitly describe a class are inserted as necessary and sufficient conditions and make the class fully *defined* (Fig. 1). Four general categories of concepts are distinguished in historical maps: (a) concepts that describe the map as a cultural artifact, (b) concepts related to the map's design and composition, (c) concepts that refer to the mathematical procedure of the map creation, and (d) concepts related to the map content as well as the concept of time.

Re-using of well-established ontologies in order to describe part of the concepts is a good practice (Keet 2004). In the case of historical maps, the following two ontologies are considered necessary: (a) GeoSPARQL

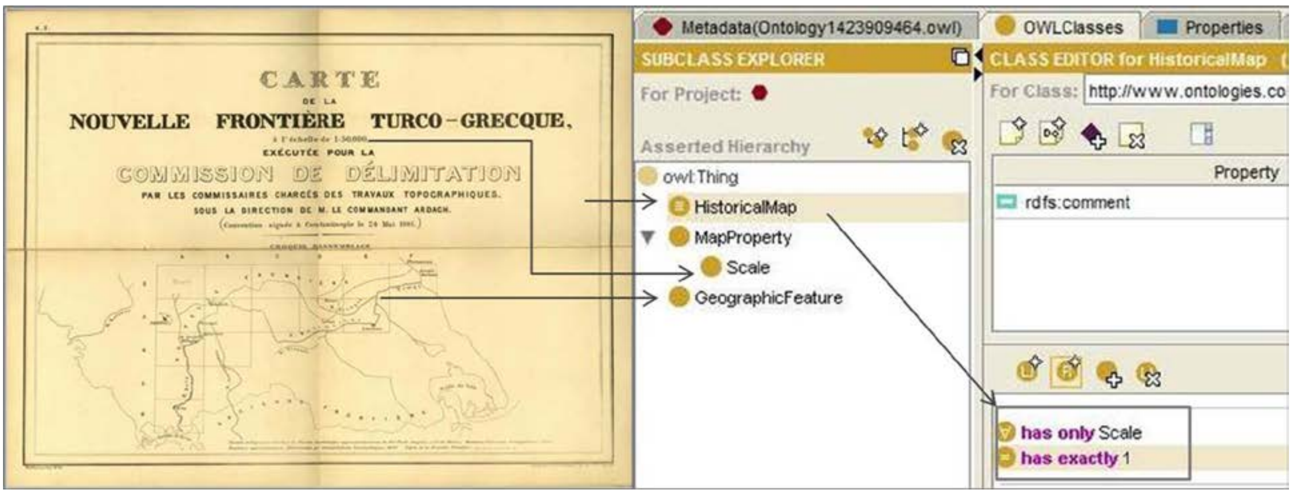

Figure 1. The map 'Carte de la nouvelle frontière Turco-Grecque' and some of its properties constructed as classes in Protégé Ontology Editor. The relation 'map has only one scale' is one of the necessary and sufficient conditions that make the class 'HistoricalMap' defined.

(SPARQL Protocol and RDF Query Language), a W3C recommendation that includes a simple ontology for representing and retrieving geospatial data from the Semantic Web in order to model the geographic information of maps and (b) OWL Time, an ontology of temporal concepts suggested by the W3C Semantic Web Activity. For integrating these two ontologies to the main cartographic ontology, the true integration theoretical guidelines (Kavouras 2005) have been applied. According to it, at first, concepts between the ontologies must be compared (semantic mapping) in order to reveal semantic heterogeneities or similarities. For example, a geographic entity (depicted in maps) is defined - in GeoSPARQL - as an ‘abstraction of real world phenomena’, while in maps, it is a graphical representation of space through specific cartographic symbols. Four cases in semantic mappings are distinguished (Kokla 2006): equivalence (concepts are identical in meaning), difference (concepts have different meanings), subsumption (a concept has broader meaning than the other) and overlap (concepts have similar but not precisely identical meanings). ‘Meaning’ is the sense of a concept and refers to the relationship between concepts, expressions (symbols e.g., words) and real world entities, a triple forming the so-called semantic triangle (Kuhn 2005). There are different methods for executing semantic mappings, either manually or automatically, as presented by Kokla (2006). For the purpose of this research, the combination of mappings based on lexical information and grounding to a top level ontology is suggested. Then, axioms must be inserted in order to develop bridges between these ontologies. This way, a single integrated ontology is created consisting of the resource ontologies which retain their independence, usability and logical consistency.

The last step for the development of the cartographic ontology is subsuming it to a top level ontology. This is a prerequisite since the concepts of the cartographic ontology are inserted as sub-categories in the taxonomy of the top level ontology and thus can be recognizable from different domains.

Semantic application profiles

The proposed ontology can support the refinement of existing metadata standards in order to fulfil the needs of a specialized application for historical maps. The procedure for this is called semantic application profiling. The application profile is the set of elements from one or more metadata schemas used to create a new schema optimum for a particular application (Heery and Patel 2000). Application profiles provide the means to express the principles of modularity and extensibility of systems and constitute a usual method for overcoming problems of vagueness or deficiencies in the description of concepts for a specific domain (Koutsomitropoulos *et al.* 2007).

There are three ways for developing an application profile (Heery and Patel 2000): (a) include selected elements from different schemas (suitable for the particular application) into a single schema; (b) add restrictions to the value ranges of elements either by providing a specific controlled vocabulary as filler to an element or by applying specific formats for values; and (c) refine elements by adding sub-categories in order to narrow or specify the meaning of a concept or introduce some element qualifications. These methods can be also applied to ontologies since these are metadata schemata with precisely defined meaning and richer relations between elements and concepts (Koutsomitropoulos *et al.* 2007). In this case, the term ‘application profile’ turns to ‘semantic application profile’ since it considers the semantic structure of the models used.

In the current research, the third method of the element refinement is chosen. First, a set of elements suitable for describing maps are selected from a schema (model of reference). Secondly, these are refined by new - more specialized - concepts as defined from the cartographic ontology (semantic refinement). The new concepts are introduced strictly as sub-classes in the existing elements of the schema. This means that a new sub-class is introduced only if its meaning clarifies the meaning of the hyper-class (subsumption or overlap of concepts) and in parallel it complies with all the restrictions and relations of the hyper-class. At this point, one of the main concerns is to ensure that the source schema is not affected (Koutsomitropoulos *et al.* 2007). To achieve this, OWL provides an explicit inclusion mechanism through the <owl:imports> statement. The mapping between concepts must precede in order to identify any semantic overlap or absence of concepts.

Information publishing and usability on Semantic Web

The cartographic data either structured as an ontology (OWL) or generated in RDF triples can be published on Semantic Web. This allows users to answer complex queries spanning multiple, heterogeneous data sources from different domains (Janowicz *et al.* 2012). The information is uploaded in repositories or triplestores (e.g., Parliament, Virtuoso, and Sesame) with the ability to apply either SPARQL queries and retrieve results in RDF format or rules of logical inference to produce new knowledge (USGS 2012). To accelerate searching and taxonomy of the data, it is important to create indexes in the RDF triples. In case of spatial data, the GeoSPARQL language and spatial indexing must be supported.

RDF data retrieved from Semantic Web can be integrated to applications that use the same technological approach (Linked Data). Such an example is the use of modeled cartographic information in the annotation of historical maps. Annotations enable scholars to share knowledge and collaborate in the analysis of cultural heritage artifacts. Furthermore, annotations are a valuable addition to traditional metadata and essential for retrieving of objects in cultural heritage collections (Simon *et al.* 2010). Annotations are structured as RDF data. A line or a polygon is drawn on the map to indicate the location or area to be annotated. If the map is already geo-referenced, the system will compute geographical coordinates for the annotated region and develop contextual semantic links to semantic resources in the namespace of a linked data set (Simon *et al.* 2010) such as gazetteers or RDF data from historical maps.

4. The Cartographic ontology and its applications

The cartographic ontology

Based on the methodology introduced above, a cartographic ontology was developed for a series of historical maps of the period 1881-1911 depicting the borderline between Greece and Ottoman Empire (Gkadolou *et al.* 2014). The ontology was built in OWL-DL (using the software package Protégé Ontology Editor) and is available at:

http://www2.unb.ca/~estef/apps/eg/HistoricalMap.owl.

Seven main classes were created in order to describe the four main categories of concepts that define a historical map (class 'HistoricalMap') as shown in Fig. 2. These were further categorized with 98 classes with their definitions and for each class, the domain and range value and the restrictions were set, constituting a semantic lexicon. The class 'Actor' accounts for every person (physical or not) that contributes to the life cycle of a map and is further categorized as 'Surveyor', 'Cartographer', 'Publisher' and 'Collector'. 'Document' describes any document that is related to a 'HistoricalMap' while 'MapCollection' is the collection to which a map belongs. 'MapElement' refers to the characteristics of a map with the subclasses 'MapLayoutElement' for the properties of the map's composition, 'MapMathematicalElement' for the mathematical properties of the map and 'MapObjectElement' for the properties of the physical object of map further categorized with the subclasses that can be seen in Fig. 2. The geographic entities that are represented in a map are documented by the class 'SpatialObject' and its subclasses 'Feature' and 'Geometry' from GeoSPARQL ontology. 'Feature' is the class GFI_ Feature as defined by the ISO 19156:2011. Their relations refer to their topology (Fig. 2) and their geometry.

For the geometry, GeoSPARQL offers the relations 'dimension', 'coordinateDimension', 'spatialDimension', 'isEmpty', 'isSimple' and 'hasSerialization' while serialization is feasible with the common statements 'geo:asWKT' and 'geo:asGML'. For the class 'Feature', 50 sub-classes were created for the entities that were depicted in the series of the historical maps (e.g., village, mountain). The class 'GeographicalName' stands for the placename of the entity. From the ontology Time, the classes 'DateTimeDescription' for the creation and publication date of the map as well as the class 'Instant' (subclass of the 'TemporalEntity') for describing the time instant or span of the occurrence of a geographic entity were used.

The GeoSPARQL and Time ontologies were integrated to the main cartographic ontology, semantic similarities were identified and three axioms that bridge these ontologies were created: (a) 'HistoricalMap' represents *only* 'Feature', (b) 'HistoricalMap' is created in *only*

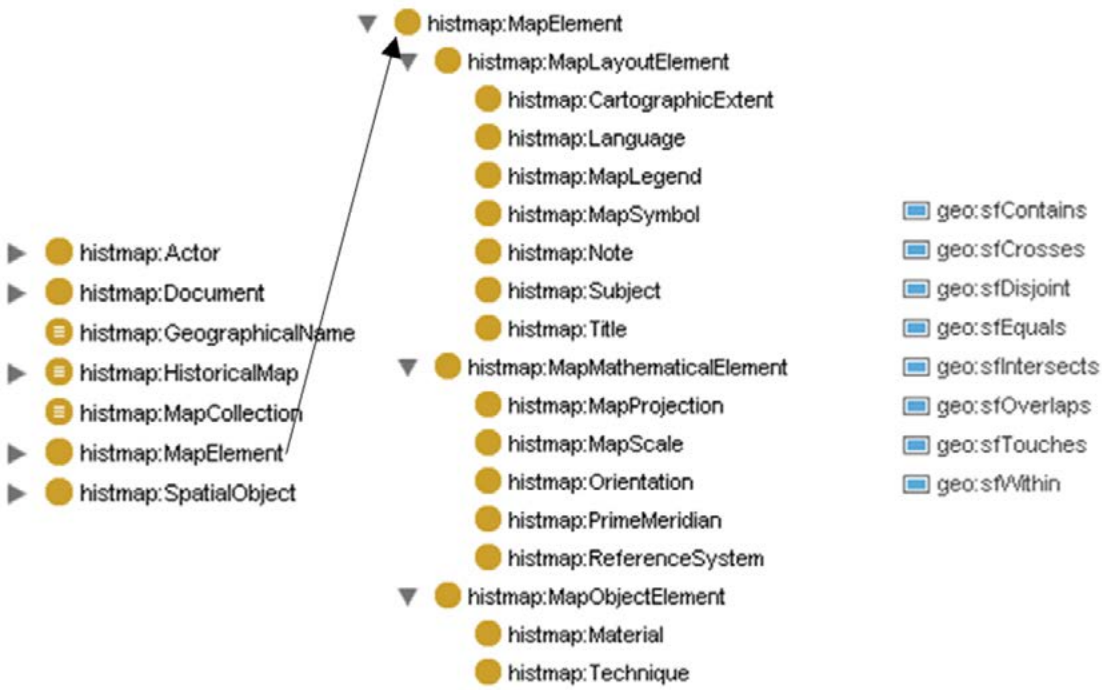

FIGURE 2. THE MAIN CLASSES OF THE CARTOGRAPHIC ONTOLOGY (LEFT) AND THE TOPOLOGICAL RELATIONS OF THE CLASS 'FEATURE' (RIGHT).

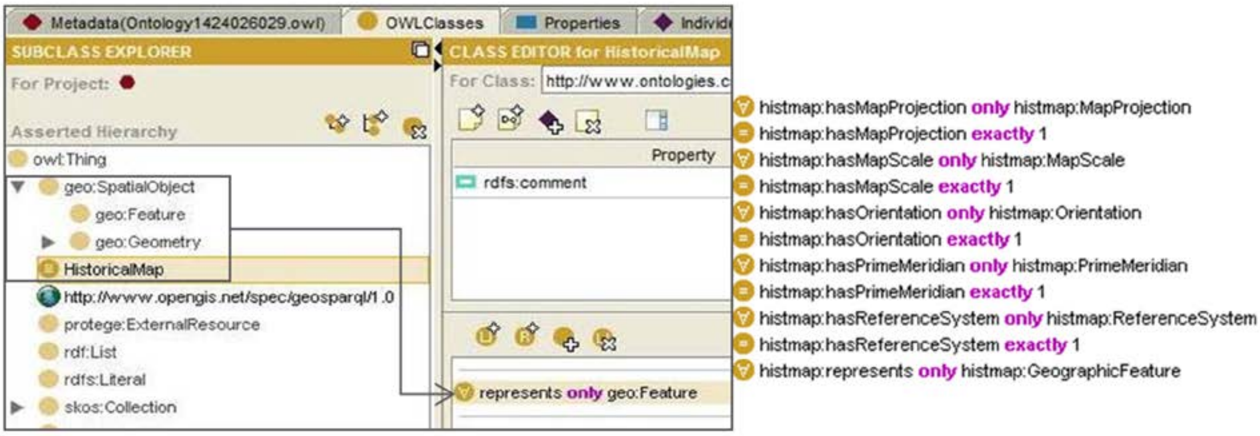

Figure 3. The axiom that connects GeoSPARQL with the cartographic ontology (left) and part of the restrictions for the class 'HistoricalMap' (right).

'DateTimeDescription', and (c) 'Feature' exists in *some* 'Instant' (Fig.3).

Overall, 111 relations with their restrictions that associate map with its characteristics (e.g., map projection) and the entities depicted therein and their relationships (topological or geometric) were created. For example, the relationships ['HistoricalMap' has *exactly* 1 'Scale'] and ['Bridge' crosses *some* 'River']. Part of the restrictions for the class 'HistoricalMap' is shown in Fig. 3.

The last step was to populate the ontology with real data from the series of historical maps and create instances (for several use cases see in Gkadolou 2013). After that, specific queries need to be pre-defined in SPARQL language in order for the users of a semantic web application of historical maps to retrieve information combining spatial, attribute or temporal criteria. Two examples of the queries syntax in SPARQL are given below. The properties 'represents' and 'isPublishedAt' and the classes 'HistoricalMap', 'Area' and 'Territory' come from the proposed cartographic ontology.

Query 1: Select the maps available for the area defined by the coordinates (φ_1,λ_1, φ_2,λ_2).

```
SELECT ?HistoricalMap
WHERE {?HistoricalMap histmap:represents
?Area ?Area geo:hasGeometry ?Polygon
FILTER (geo:sfWithin(?Polygon, 'POLYGON
((λ1 φ1, λ2 φ1, λ2 φ2, λ2 φ1, λ1 φ1))'
^^sf:wktLiteral))   }
```

The class 'Area' has a Polygon geometry and the query is executed using the topological property 'sfWithin' from the GeoSPARQL vocabulary. The polygon is defined as a bounding box by the south west and north east coordinates.

Query 2: Select a map of East Thrace of the period 1911.

```
SELECT ?HistoricalMap
WHERE {
{?HistoricalMap histmap:represents
?Territory}
{?Territory histmap:name ?name
FILTER regex(?name, '^East Thrace')}
{?HistoricalMap
histmap:isPublishedAt<http://www.owl-
ontologies.com/Ontology1284104147.
owl#Date_1911>.}}
```

With this query, at first, all maps that represent territories are retrieved and then using the constraint 'filter' all of which that represent East Thrace. At last, from those, the maps that have been published at 1911 are retrieved as the final result.

Semantic application profiles in Dublin Core and CIDOC-CRM

The cartographic ontology was used to refine the Dublin Core metadata model for a better description of historical maps. Dublin Core (ISO 15836:2009) was selected because it is the most common metadata initiative for describing digital resources as well as for its simplicity and its general applicability. It is a common practice to refine this model's elements in order to fulfil the need of a certain application. Even though the model's properties are constructed as annotation properties these can be converted to object properties without disturbing its consistency. The latest edition of Dublin Core was used (2012) available as a small ontology in RDF 1.1.

Historical map was considered as a resource to which the refined properties were given. The terms of Dublin Core that can be used for the description of maps were selected and then refined. These are: contributor, coverage/spatial, creator, description, extent, date/issued/created, identifier, language, medium, publisher, relation/isPartOf/hasPartOf, requires, subject, tableOfContents, title/alternative, type, Collection.

In Dublin Core, an element refinement is defined by the statement <rdfs:subPropertyOf> from RDF schema. This means that the relationship between two properties is hyponymy, namely an instant of a sub-property is also instant of the hyper property for each resource. What's more, according to the model, an element refinement refines exactly one element, though an element may be refined by multiple element refinements. The element refinements that were created are given in Table 1. An example of a Dublin Core statement is shown in Fig. 4. The term 'tableOfContents' has been refined by the term 'mapSheet', more suitable and specialized for maps.

A semantic application profile in the CIDOC-CRM ontology (ISO 21127:2006) based on the cartographic ontology is also proposed (Gkadolou 2013). In CIDOC, the concept of historical map is added as a refinement of the class 'E84 Information Carrier' that comprises all instances of 'E22 Man-Made Object' that are explicitly designed to act as persistent physical carriers for instances of 'E73 Information Object'. This expresses aptly the basic characteristics of map to carry information (geographical, geometric and thematic) that may exist in several other maps (e.g., copies). The sub-class 'HistoricalMap' inherits all axioms, restrictions and relations of its mother class so the new concept (map) must conform to all of these in order for the model to sustain its logical consistency. Likewise, the rest of the classes of the cartographic ontology are inserted as subclasses to CIDOC. For example, the element map projection refines the class 'E73 Information Object' that comprises identifiable immaterial items (e.g., texts, poems, mathematical formulas etc.) that have objectively recognizable structure and can exist on one or more carriers simultaneously. The semantic profile for historical maps was developed also in CIDOC because the latter is a top level ontology that models all information required for the exchange and integration of heterogeneous scientific documentation of museum collections. Adding sub-classes to this model's generic – whatever the domain - entities gives the advantage that concepts regarding maps are comprehensible from different cultural heritage applications.

Annotation in historical maps and gazetteers

Pelagios platform and Recogito tool (http://pelagios-project.blogspot.co.uk/) have been used in order to experiment with annotations on the series of historical maps. Pelagios is a community-driven initiative with the goal to facilitate better linking between online resources documenting the past, based on the places that they refer to (Simon *et al.* 2014). The key to connectivity in Pelagios is the use of a common vocabulary when referring to places, combined with a set of lightweight conventions on how to publish these place references as Linked Data. The common vocabulary is formed by the Pleiades Gazetteer of the Ancient World (http://pleiades.stoa.org), which provides unique URI identifiers for places in the Greco-Roman world. The Recogito tool in Pelagios supports annotation in maps and connectivity to the gazetteers. A custom gazetteer as modeled in RDF from historical maps (list of toponyms) can also be used. Historical maps, even of a later historical period, contain valuable information that can enrich existing gazetteers and deliver the chronological

Table 1. The element refinements in Dublin Core.

Dublin Core term	**Refinement**
contributor (an entity responsible for making contributions to the resource)	collector
coverage spatial (spatial characteristics of the resource)	cartoArea for the cartographic area of the map, issuedIn for the place of publication of the map
creator (an entity primarily responsible for making the resource)	cartographer
description (an account of the resource)	note (any notations on the map), mapLegend, technique that was used for making the map (e.g., zincography)
requires (a related resource that is required by the described resource to support its function, delivery, or coherence)	mapScale, mapProjection, referenceSystem, primeMeridian, orientation of the map
tableOfContents (a list of sub-units of the resource)	mapSheet

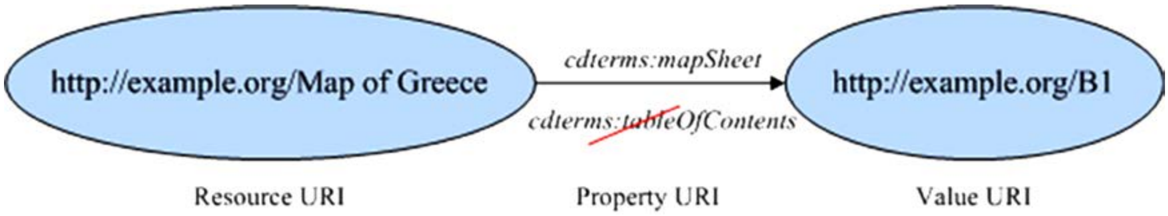

Figure 4. The term 'tableOfContents' of Dublin Core as specialized by the suggested term 'mapSheet'

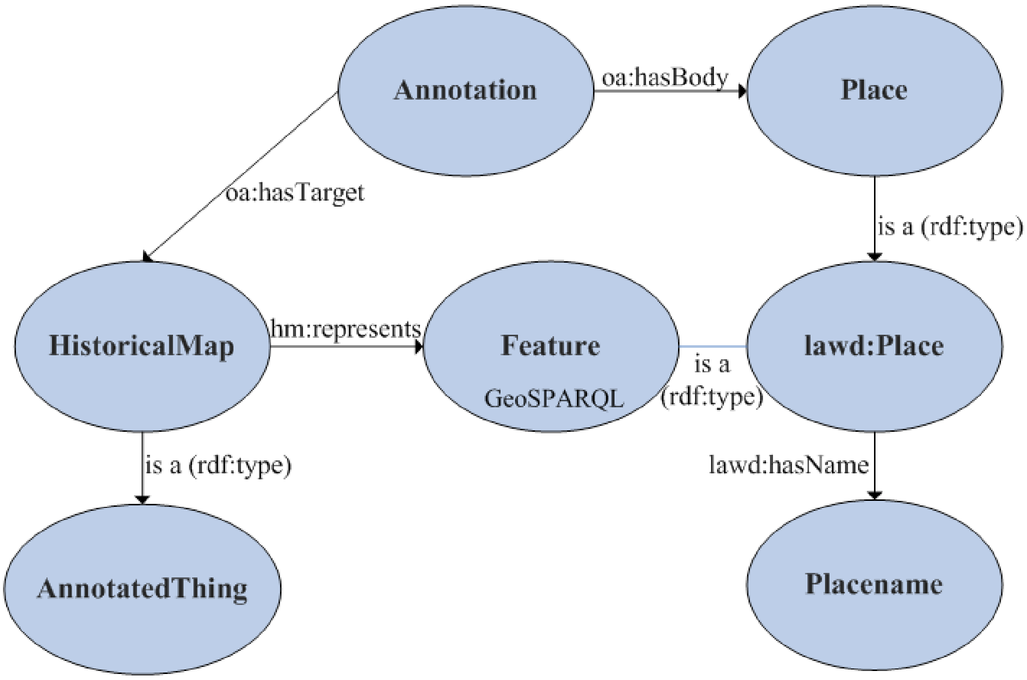

Figure 5. The Annotation model of Pelagios platform extended to include the concepts of historical maps and features.

sequence of changes in place names until today. Such an updated gazetteer can assist archeological research since it connects sites of ancient times to the current ones.

Based on the previous work of Simon *et al.* (2010), an extension in the annotation model that Pelagios is based on, is proposed in order to adapt the concepts of historical map and features (Fig. 5). According to it, places depicted in a historical map can be annotated with place names retrieved from a gazetteer. 'Place' is considered as the primary entity in the model referring not only to the geographical entity but to a more abstract concept. It is also identical to the class 'Place' that comes from the Linked Ancient World Data model and is a 'Feature' for GeoSPARQL ontology. The predicate 'oa' comes from the vocabulary defined by the Open Annotation RDF (a W3C specification) and 'lawd' from the Linked Ancient World Data Initiative. The model covers different scenarios since Open Annotation works across many different document types and formats (e.g., texts, images).

Several maps have been annotated with place names using the Recogito tool (Fig. 6). The next step is geo-resolution, the act of linking place references, i.e. place names in a document to places in Recogito's internal place directory, so that they can be plotted on a map. The place names have been retrieved from Pleiades gazetteer and from a custom gazetteer developed using information from the historical maps that have been uploaded in the platform. Then, places have been placed on the current base map. Conversely, there is also the functionality of downloading the list of the annotated place names with rich information attached (e.g., coordinates, tags etc.).

5. Conclusions

In this paper, a methodology for the semantic documentation of historical maps that focuses on their special characteristics and their geographic content is introduced. Basis of the methodology is the development of a cartographic ontology. Given that historical map is a complex scientific and cultural object, to fully describe it, knowledge from different domains is needed (culture heritage, cartography, history, geography). The ontology offers the umbrella under which this knowledge is integrated, formally modelled and identified from different applications. Concepts and relations that determine historical maps are clarified constituting a specialized semantic vocabulary. Additionally, the ontology - extracted either as OWL or converted to RDF triples - supports the publication of the cartographic data (e.g., place names) on Semantic Web as well as its re-usability in other applications such as gazetteers (RDF triples can be easily linked to others resulting to linked data). Eventually, since information is integrated semantically, it can be retrieved by applying more complex queries in SPARQL language.

The use of the geographic information of the map in enriching its metadata contributes to an overall more correct description of historical map and facilitates the semantic search based on spatial criteria (e.g., through toponyms or geometry). The GeoSPARQL ontology that is integrated connects the artifact (of map) with its content and supports the querying and retrieval of geospatial data on Semantic Web repositories. Geographic information depicted in various historical maps is interlinked and as a result time series of spatial data can be retrieved (e.g.,

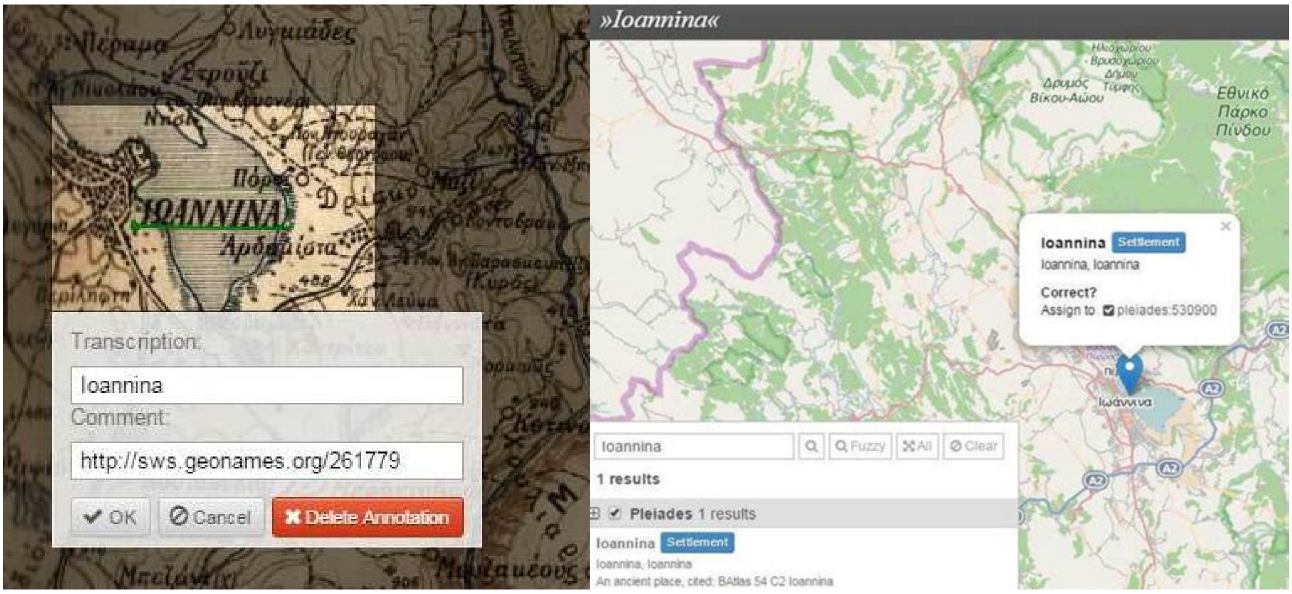

Figure 6. An annotation on historical map (left) and its placement on the current base map (right).

settlements and their name changes through time as documented in a set of maps).

Furthermore, the semantic profiles in Dublin Core and CIDOC - as refined using the cartographic ontology - offer the advantage that these common and widely used standards can support specialized applications for historical maps without starting from scratch.

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Archaeomagnetic Method as a Dating Tool: Application to Greek Archaeological Sites from Prehistoric to Byzantine Periods

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Abstract: The archaeomagnetic method is continuously developing in Greece during the last two decades and important compilations of data on country and regional scale allowed the construction of secular variation curves. Though these are not yet complete, they allow accurate dating for several archaeological periods such as Late Bronze Age, Classical, Hellenistic and Roman. In this paper we will briefly describe the contribution of archaeomagnetic method to sites of the Neolithic and Byzantine periods in Central-Northern Greece and furthermore we will provide new dating for three sites of uncertain age, previously studied archaeomagnetically. The procedure followed has a two-fold approach: dating the structures archaeomagnetically using several reference models and then combining the results with all available information including archaeological and radiometric ones. The outcome brings a better constrained age for three ceramic kilns in Attica, Achaia and Western Crete and we demonstrate the importance of the archaeological input during archaeomagnetic studies.

Keywords: archaeomagnetism, ceramic kilns, secular variation curves, geomagnetic field models.

1. Introduction

Since many decades the Earth is known to be surrounded by a magnetic field. The origin of this field lies in the outer liquid core of the terrestrial globe, and its properties have numerous applications in various disciplines (such as geology, geophysics, astronomy and space physics), apart its potential to protect the Earth from cosmic radiations. Earth Sciences have developed several interactions with the study of this field through *Geomagnetism* and its branch of *Palaeomagnetism,* dealing with the history of the geomagnetic field (GMF) as recorded by geological formations such as volcanics, plutonics and sedimentary ones. *Archaeomagnetism* is a branch of Palaeomagnetism which combines magnetic methods with Archaeology for the determination of the geomagnetic field elements (Inclination, Declination, and Intensity) through historic and prehistoric times. This method is based on two fundamental principles:

A. All archaeological features which are formed by clay contain small quantities of magnetic minerals which can record the direction and the strength of the geomagnetic field under certain circumstances: The material has to be heated up to at least 500-600^{0}C and during the cooling procedure it can record a *thermoremanent magnetization* which is oriented parallel to the ambient Earth's magnetic field at that period and location.
B. *The direction and the strength* of the geomagnetic field are not stable but change continuously in both time and place.

By comparing the archaeomagnetic direction and intensity registered by an archaeological artifact with accurate *Reference Secular Variation Curves* (SVCs) for the same area, it is possible to determine the age of the studied structure. A prerequisite for this dating is the inverse procedure through which well - dated, by independent methods, such as ^{14}C or TL/OSL, artifacts can be used for the construction of the reference curves for an area. Archaeological structures or artifacts that can be used for an archaeomagnetic investigation are mainly kilns, bricks, tiles, ceramics and generally all clay structures that have been heated in the antiquity at high temperatures and were subsequently cooled to ambient temperature.

In the last three decades the discipline of Archaeomagnetism has considerably developed in Europe but also in other continents with a particular opening to the Southern Hemisphere (Hartmann *et al.* 2010). Systematic archaeomagnetic studies in Greece were initiated around the 1980-1990 decade and provided abundant archaeo-intensity and fewer directional data which allowed for the construction of reference secular variation curves for Greece (Evans, 2006; De Marco *et al.* 2008, 2014 and references therein; Spatharas *et al.* 2011; Aidona and Kondopoulou 2012; Tema *et al.* 2012; Fanjat *et al.* 2013). The local SVCs, are built using data from a certain country or geographic area, e.g. Greek, Bulgarian, French etc., and are valid in an area of about 1000 km around the reference point. To enclose larger areas two other categories of Reference Curves exist: the Global and the Regional Reference Curves, using Global or Regional Geomagnetic field models respectively.

Several compilations and models have been published in order to describe the geomagnetic field variations at global scale (Korte and Constable 2005; Genevey *et al.* 2008; Donadini *et al.* 2009). Among these models, Korte *et al.*

(2009) suggest that the ARCH3K.1 (only archaeomagnetic data) global model is the most appropriate for Europe for the last 3000 years. For older times only the CALS7K.2 global model is available (Korte and Constable 2005) that covers the past 7000 years, from 5000 BC to 1950 AD. An intermediate approach between Global Models and local Secular Variation Curves is the calculation of Regional Models. Pavón-Carrasco *et al.* (2009) proposed a regional archaeomagnetic model that calculates the geomagnetic field variations in Europe for the last 3000 years, modelling together the three geomagnetic elements. In order to extend the SCHA.DIF.3K model predictions backwards in time, Pavón-Carrasco *et al.* (2010) have proposed the SCHA.DIF.8K regional model that is based on a selected compilation of both sedimentary and archaeomagnetic data and predicts the geomagnetic field variations from 6000 BC to 1000 BC (Pavón-Carrasco *et al.* 2010).

Tema & Kondopoulou (2011) have monitored the Secular Variation of the Geomagnetic Field in the Southern Balkan Peninsula and provided a more complete pattern for the regional field evolution in the last 8000 years. In spite of the above multiple achievements, building accurate SVCs at a local (country) scale remains an important target. The improvement of the Greek SVCs, especially the ones for directions, depends on the availability of adequate, well-dated archaeological material since its geographic and temporal distribution present important gaps, e.g in Central Greece and the Eastern Aegean Islands, but also in Western Turkey, such data are almost totally missing.

In the present study we cite and discuss examples of archaeomagnetic dating for Greek sites already published in different journals. As a next step we make an attempt to date, on the basis of existing SVCs, three structures which were previously studied by Evans (2006), situated in Central-Southern Greece, with a disputable archaeological age.

2. Methodology

The geomagnetic field can be described as a vector defined at each specific place for a specific time. In order to define the direction of the field (D, I) the studied material has to be *in situ*, a requirement which is not necessary for the calculation of the intensity. Sampling of *in situ* structures includes orientation with a magnetic and sun compass, measuring of the dip with an inclinometer and is followed by samples preparation in the laboratory in order to obtain standard cylinders of 2.5x2.2 cm. Archaeological structures or artifacts that can be used for an archaeomagnetic investigation are mainly kilns, bricks, tiles, ceramics and generally all clay structures that have been heated in the antiquity at high temperatures (at least up to 500-600°C) and subsequently cooled.

A classical archaeomagnetic study consists of several steps. At the beginning the measurement of Natural Remanent Magnetization (NRM) gives the first evidence for the suitability of the material followed by the magnetic stepwise demagnetization either by alternating field or thermally. This procedure aims to the removal of any secondary components which are present in the samples. After the demagnetization process and the statistical analysis the mean direction of a structure is calculated. Additionally, the calculation of palaeointensity is related to a specific procedure, involving numerous heating/cooling cycles possibly inducing mineralogical transformations which might affect the results.

3. Studied areas

In the beginning of the 1990s a great number of archaeological excavations, both systematic and rescue ones, took place in Greece. Significant finds came to light by the important works that took place for the Athenian Metro network. In an extensive sampling which lasted approximately ten years, T. Evans (Univ. of Alberta, Canada) studied a considerable number of kilns with the bulk of this work based in Southern Greece and Crete. The outcome of his studies was published in Evans (2006) and, based on ‘magnetograms’, that is plots of Magnetic Declination and Inclination versus time, the author provided a first effort to monitor the variations of the Earth’s magnetic field direction from the mid-third century BC to the mid third century AD. Among the studied sites in Evans (2006) research, five have been reported as of uncertain or even unknown age (32-36, Table 1) and the author tentatively dated them through his magnetograms. Nevertheless this dating was based on archaeological information provided to him during his sampling, more than ten years before publication. At the same time accumulation of new data and establishment of GMF models (see introduction) gave ground to several possibilities for new and more accurate dating. Two of the above sites (nrs 32 and nrs 35) were re-dated on the basis of new secular variation curves and regional models (De Marco *et al.* 2014) and their accuracy was considerably improved on the basis of updated archaeological information (Kondopoulou *et al.* 2014, in press). In the present contribution we aim to re-date 3 specific kilns (nrs 33, 34, 36) first presented in Evans work (Evans 2006). For such an attempt a thorough update of the archaeological description for these sites is necessary. Therefore we proceed first to this step, respecting an order from North to South.

1.ATHENS C (36). This rescue excavation took place in 1990-91, in the intersection of Vouliagmenis and Alimos Avenues and comprised at least 2 unearthed kilns and a water tank for clay preparation. The orthogonal kiln sampled was built in the north-eastern wall angle of a building dated to the 4th century BC. The combustion chamber with dimensions 1.60x 1.50m was preserved up to a height of 0.70m and hosted several vitrified tiles. The firing channel revealed sparse sherds of the second century BC. It is possible that the workshop was built for tiles mostly, though these could be part of the collapsed dome (S. Michalopoulou, personal communication).The above information constrains the age of the kiln between early-fourth to mid-second BC.

Table 1. Archaeomagnetic results from three kilns. Site = Site of the kiln, coords = coordinates of each kiln, N= number of samples, D = Declination, I = Inclination, F= Intensity a_{95}= semi-angle of cone of confidence.

Site	coords (⁰)	N	D(⁰)	I(⁰)	F(μT)	a_{95}(⁰)	Reference
Athens C	38.0/23.7	11	353.1	58.7	-	2.9	Evans, 2006
Aegeira B	38.1/22.42	9	10.4	65.6	-	5.4	Evans, 2006
Stylos	35.42/24.1	14	3.5	55.1	-	2.3	Evans, 2006
Stylos	35.42/24.1	7	-	52.2	44.5 (±5.9)	4.2	Thomas, 1981

2.AIGEIRA B (34). The ancient city of Aigeira is situated in Achaia (North Peloponnesus), on an extended mountain ridge approximately 416 m above sea-level. Though the settlement's activity extends back to the Late Neolithic period, the peak of its life is dated in the Late Mycenaean period, around the 12th century BC (http://www.oeai.at/).

The excavations conducted by the Austrian Archaeological Institute from 1975 to present brought to light a number of buildings including houses, storage rooms and a pottery kiln. The habitation sequence was well-established within the LHIIIC period. In the remains of a house that is recorded in Phase Ia a pottery kiln was unearthed. It has been considered that the kiln is classified/stratified in Phase Ib. This kiln lined a courtyard, and its combustion chamber and part of the floor were preserved. Together with the surrounding level they were covered by a thick burnt destruction layer. Additional evidence of fire was found in the next Phase II (Alram-Stern 2003) and these destruction layers provided carbonized material for ^{14}C analysis (Alram-Stern 2006). The dates yielded by this study converge well towards an age of 1270-1120 BC at 95% confidence level. The previous archaeomagnetic dating given by Evans (2006) which suggests a period of LHIIIA was probably indicated to him during his sampling. At this point we will try to better define the above chronologies through our new A/M dating.

3.STYLOS (CHANIA-CRETE-33) The excavation at Stylos, a LMIIIB settlement close to Chania city, lasted from 1971 to 1973. A circular kiln with a diameter of 2.30 m and 0.70 m of remaining height was firstly sampled by Thomas (1981) and subsequently re-sampled by Evans in 1992. Davaras (1973) gave a thorough description of the kiln: no pottery or sherds were found inside the structure and its architecture, thin eschara and probable permanent dome indicate firing of small items. Systematic studies on subsequent Minoan excavations confirmed its dating between 1425-1075 BC on the basis of stratigraphy and nearby constructions (Momigliano, 1986). After the excavation period the kiln was soon restored and protected by a shelter. A thermoluminescence dating of this kiln was provided by Liritzis and Thomas (1980) yielding an age of 1878±270 BC. This is clearly contrasting the archaeological age. Thomas (1981) is supporting more the TL dating while Evans (2006) is in favor of a rather younger age, at about 1500 BC. We hope that our new approach will highlight this controversy. The chronological distance between the two sampling seasons exceeds ten years time. As a result samples were taken from different parts of the kiln. Thomas cites 7 samples which were all examined petrographically and reveal important inhomogeneities, not rare in this kind of structures. A matrix of various colors with shades of brown prevails with several inclusions of varied nature. Her results refer to intensity and inclination, while Evans obtained declination and inclination. The overall outcome will be discussed further.

Archaeomagnetic results obtained from the above kilns are listed in Table 1.

4. Archaeomagnetic dating

During the last decade our team has published several datings for burnt structures (both building remains and thermal structures) based either on directions only or on directions and intensities covering a broad time span. Examples of such dating results are presented in Table 2. The archaeomagnetic dating is displayed together with other dating practices such as ^{14}C (BS), archaeological (RS) or TL (Sani). Results will be interpreted in the last paragraph.

New archaeomagnetic dating was performed in the three sites, previously studied by Evans (2006) as already described above. To begin with, local and regional curves (as the Greek and Balkan ones) were used. In addition, possible ages were tested, based on a regional model (SCHA.DIF.8K) using the archaeodating tool by Pavon (Pavon *et al.* 2011). In all cases the directional data (D,I) were used. In the case of Stylos the dating was performed by using one more set of data (intensity and inclination) by Thomas (1981). The possible dating periods were calculated by combining separately the probability functions for declination, inclination and intensity respectively. All the probability density functions were calculated at 95% confidence level (Fig. 1-4).

In the case of Athens C site (Fig. 1), the results are very compatible independently from the curve used for the dating. Balkan curve gives two possible intervals at 498-233 BC and 212-127 BC. The regional model SCHA. DIF.3K indicates ages at 415-154 BC and 76-10BC, while the ARCH3K model provides one interval from

Table 2. Archaeomagnetic dating in Prehistoric and Byzantine kilns from Greece.

Site	Coords	$D(^0)$	$I(^0)$	$a_{95}(^0)$	F (μT)	Archaeomag. dating	Other dating	Reference
Vasili (BS)	$39.3^0/22.3^0$	358.9	43.7	3.5	46.6 ±3.4	5000-4600 BC	4820±150 BC (^{14}C)	Fanjat *et al.* 2013
Thessaloniki (RS)	40.7°/23.1°	358.5	56.9	4.4	-	410-880 AD	4th -13th A.D (ARCHAEOLOGICAL)	Aidona *et al.* 2010
Sani 10	40.07/23.3	358.2	52.8	3.1	61.2 ±1.1	259-439 AD	560± 53 AD (TL)	Kondopoulou *et al.* 2015 (in press)
Sani 6	40.07/23.3	357.8	55.9	3.0	59.5 ±2.5	368-510 AD	509±84AD (TL)	Kondopoulou *et al.* 2015
Sani 8	40.07/23.3	357.2	49.1	5.3	63.06 ±3.4	96-427 AD	360 ±64 AD (TL)	Aidona *et al.* 2010; Kondopoulou *et al.* 2015

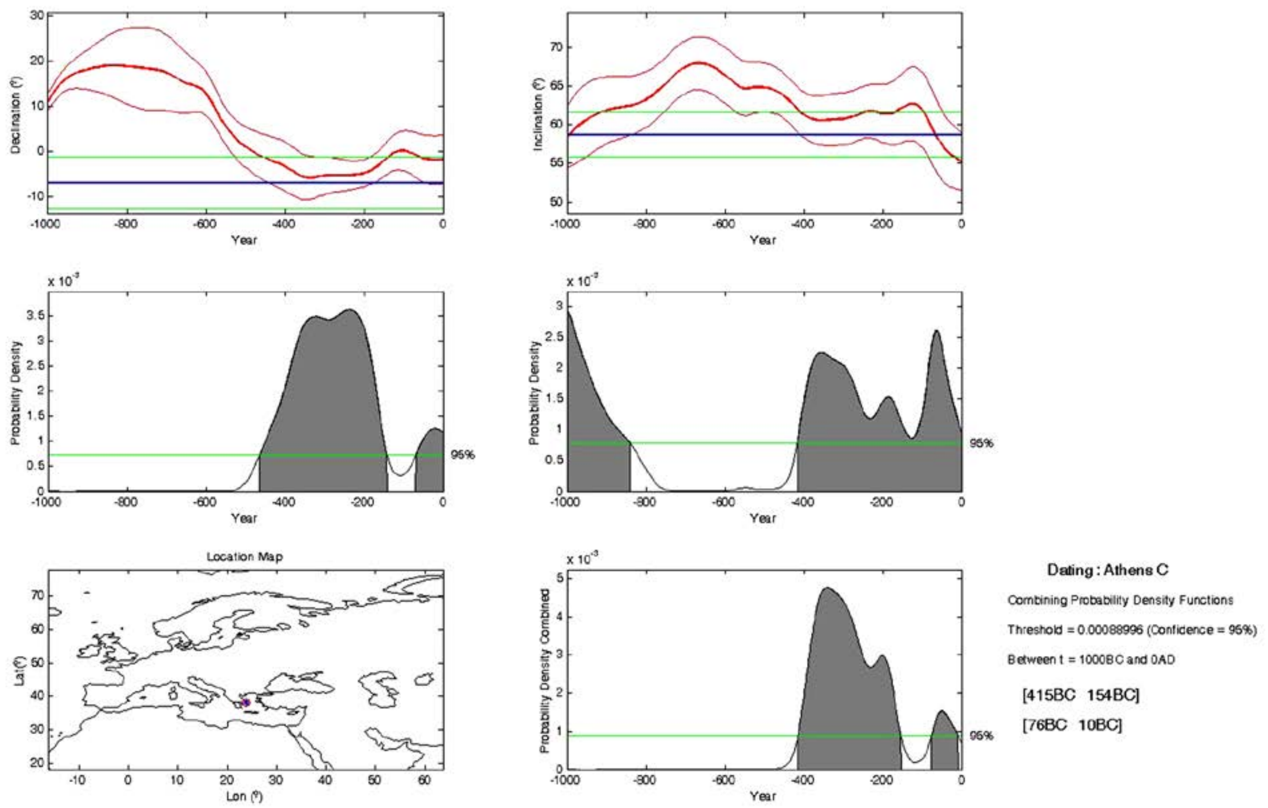

Figure 1. Archaeomagnetic dating for Athens C, using the SCHA.DIF.8K regional model. Top: master curves (red curves with red error bands) of the declination (left), and inclination (right) and the undated archaeomagnetic data (blue line with green error bands). Middle: the individual Probability Densities for the declination (left) and inclination (right). The green lines indicate the different thresholds for each element at the given level of probability chosen. Bottom: Regional map (left) of the data location (red point) and the master PSVC location (blue square); combined Probability Density marked with the green line of probability (centre); and archaeomagnetic dating information (right).

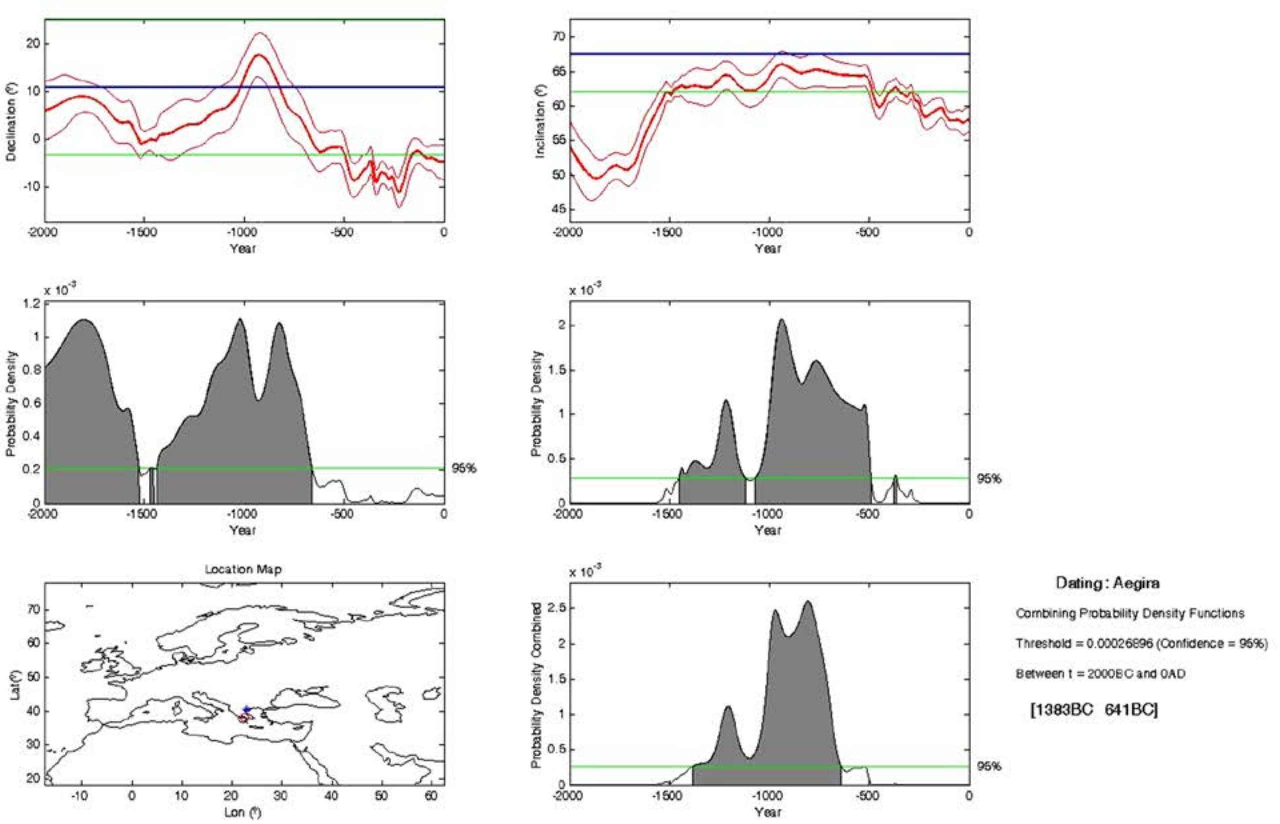

Figure 2. Archaeomagnetic dating for Aegira site using the Balkan curve.

476-18BC. In the case of Aegeira one possible interval is observed using the Balkan curve from 1383-641 BC (Fig. 2). Similar results are obtained when the Greek curve is used (1407-753 BC), while the regional model (SCHA.DIF.8K) seems to be in a very good agreement concerning the lower limit of the dating (1437-1000 BC). The upper limit of the latter cannot be taken into consideration since this curve is available until this time (1000 BC).

Finally the dating for Stylos site using the Balkan curve indicates three possible intervals: 1623-1482 BC, 1430-1258 BC and 1169-1043 BC. Similar results for Stylos can be obtained when using the Greek curve with the possible intervals at 1679-1535 BC and 1190-754 BC (Fig. 3). The second dating was performed using Thomas data (intensity and inclination) and the results are as follow: 2000-1922 BC, 1654-1522 BC, 1501-1487 BC, 1400-1286 BC, 250-0 BC (Fig. 4). Among all these possible ages we need to select the most appropriate ones if all information is compiled.

5. Discussion - conclusions

The archaeomagnetic method provides an important potential for dating structures *in situ* under certain conditions, which are related to the accuracy of obtained results: careful sampling, including thorough examination of the structure to detect eventual structural damages, dense distribution of samples to counterbalance inhomogeneities and laborious experimental work. Once a reliable archaeodirection is obtained then all available information concerning the structure should be compiled. The archaeological information is the basis for each next step. In many cases this includes dating provided either by ^{14}C or thermoluminescence (TL). Both radiometric methods have advantages and disadvantages. In TL we date the same event (last firing) on the same material. But several factors concerning the physical properties of the surrounding soils might affect the results. Dating by ^{14}C is better calibrated but the material used (carbonized organics) has often uncertain connections with the combustion structure we study and might postdate or predate it by several decades or even centuries (Vaschalde *et al.* 2014).Therefore a combination of either TL or ^{14}C with archaeomagnetic dating is the best practice to obtain the optimum result. The above is documented for the examples of published datings we present in Table 2. For instance a very good convergence of ^{14}C and A/M dating methods is shown for site BS, and a net improvement of the unsafe archaeological information is given for site RS, while convergences of variable success are arising from site SANI. More information can be found in the cited references.

Looking carefully to the new dating provided here, some comments arise:

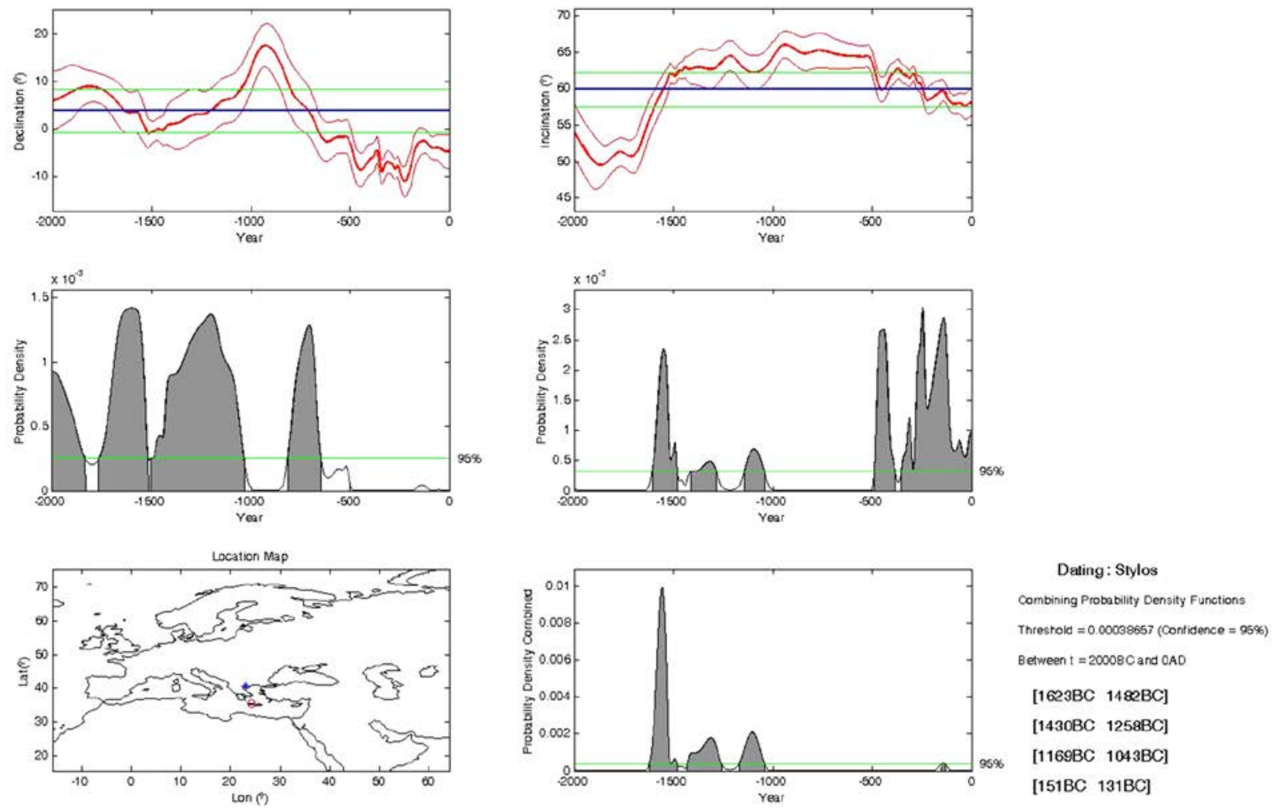

Figure 3. Archaeomagnetic dating for Stylos site using the Balkan curve (data by Evans, 2006).

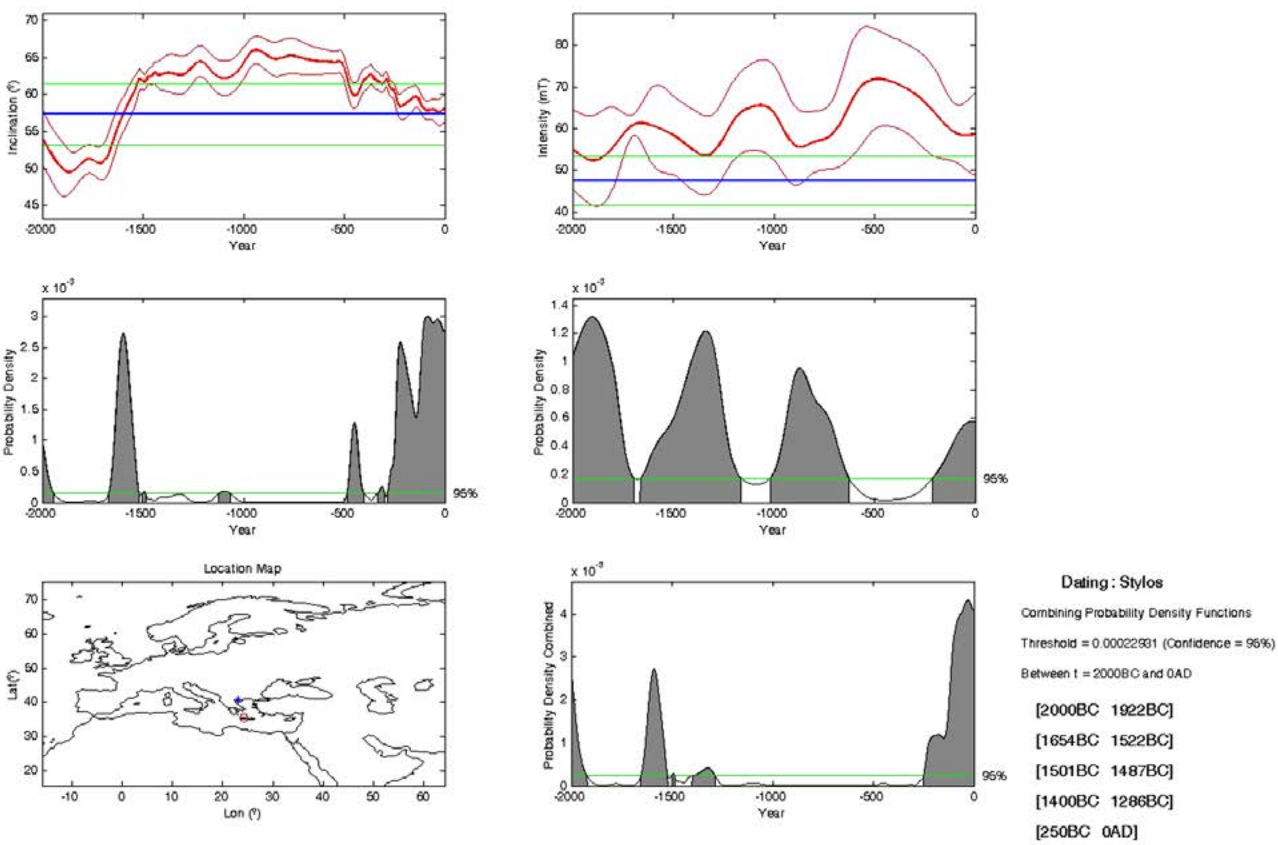

Figure 4. Archaeomagnetic dating for Stylos site with the Balkan curve using Thomas data (1980).

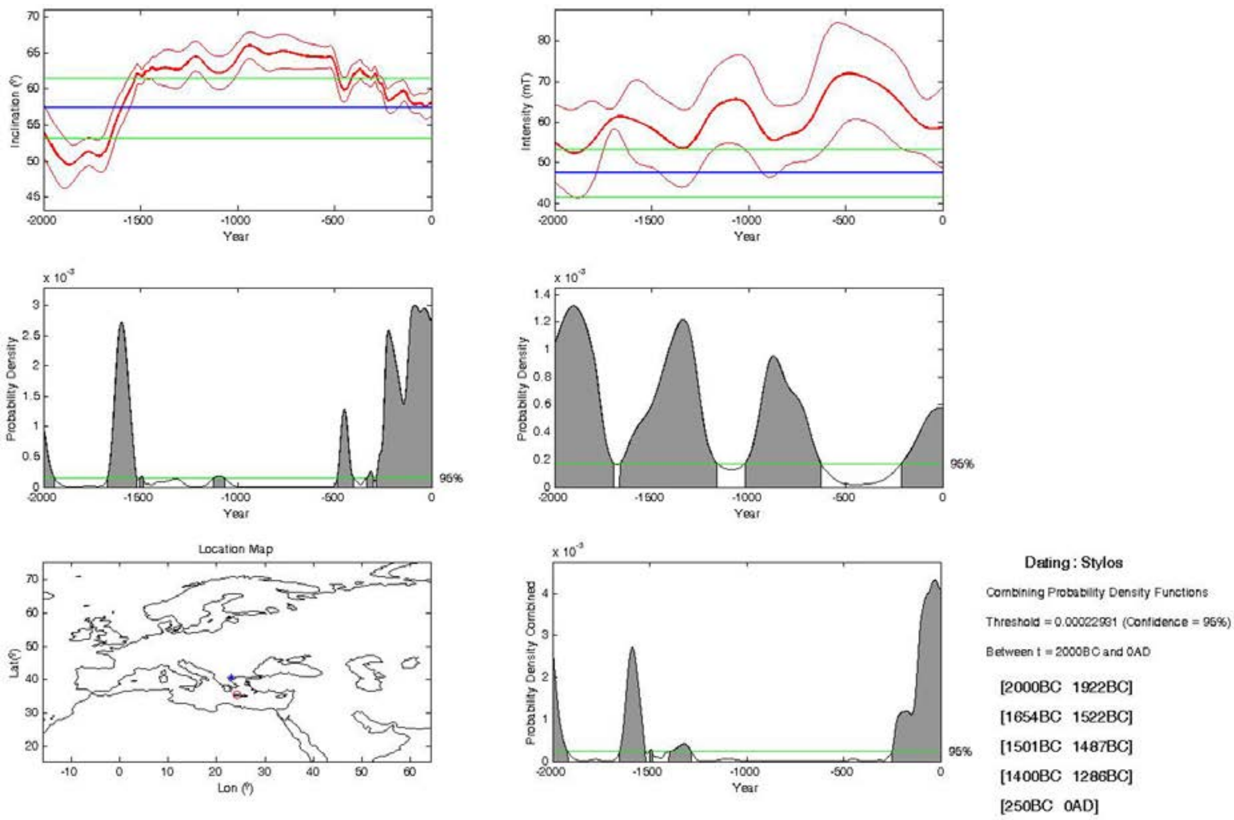

Figure 5. Archaeomagnetic dating for Aegeira site using the Balkan curve at 65% confidence level.

Aigeira. The archaeomagnetic dating is quite large in time when the 95% probability is taken into account. Nevertheless it greatly improves at 65% (Fig. 5) and this result converges perfectly with the ^{14}C one at 95%. This is an example of how the convergence of the two methods balances mutual disadvantages and provides more accurate results.

Athens C. There is a clear indication that the use of the kiln post dates the end of the 5th century BC and stopped before the 2nd century BC. Based on the archaeological information this time span can be narrowed as the upper limit is below the 4th century BC. It is broadly accepted that a kiln's life could not exceed 50-60 years (Hasaki 2002) and therefore the given time span is too broad to date its last use. The choice is difficult since it depends on how long after the construction of the walls the kiln was built and the presence of the sherds does not guarantee that they belonged to the last firing of the kiln. We suggest that this kiln is dated at the second half of the 4rth century BC to late 3rd century BC.

Stylos. The dating provided by the results of Evans (2006) is more reliable than the one provided by Thomas data (1981). Both datasets were examined separately due to the distant, by many years, sampling campaigns. We particularly cite their difference in inclination (I) which is the only commonly measured value and suggest that the shallower I of Thomas could be related to the recent, at that time, solidification of the kiln which probably stabilized later.

The datings provided by Evans (2006) for the three kilns remain valid and close to the new ones which nevertheless improve the precision due to the use of more elaborate models in the present study and are supported by new archaeological evidence and radiometric results. This observation reinforces the importance of high quality A/M measurements for dating.

An important contradiction which became clear during the preparation of this contribution is the following: sampling a kiln in a short time after its unearthing and cleaning is important since it might disappear or be seriously damaged. But the publication of the final results could -and should- be delayed until the archaeological study is completed, even if this might take years. Any hasty archaeomagnetic dating without serious archaeological support includes severe risks.

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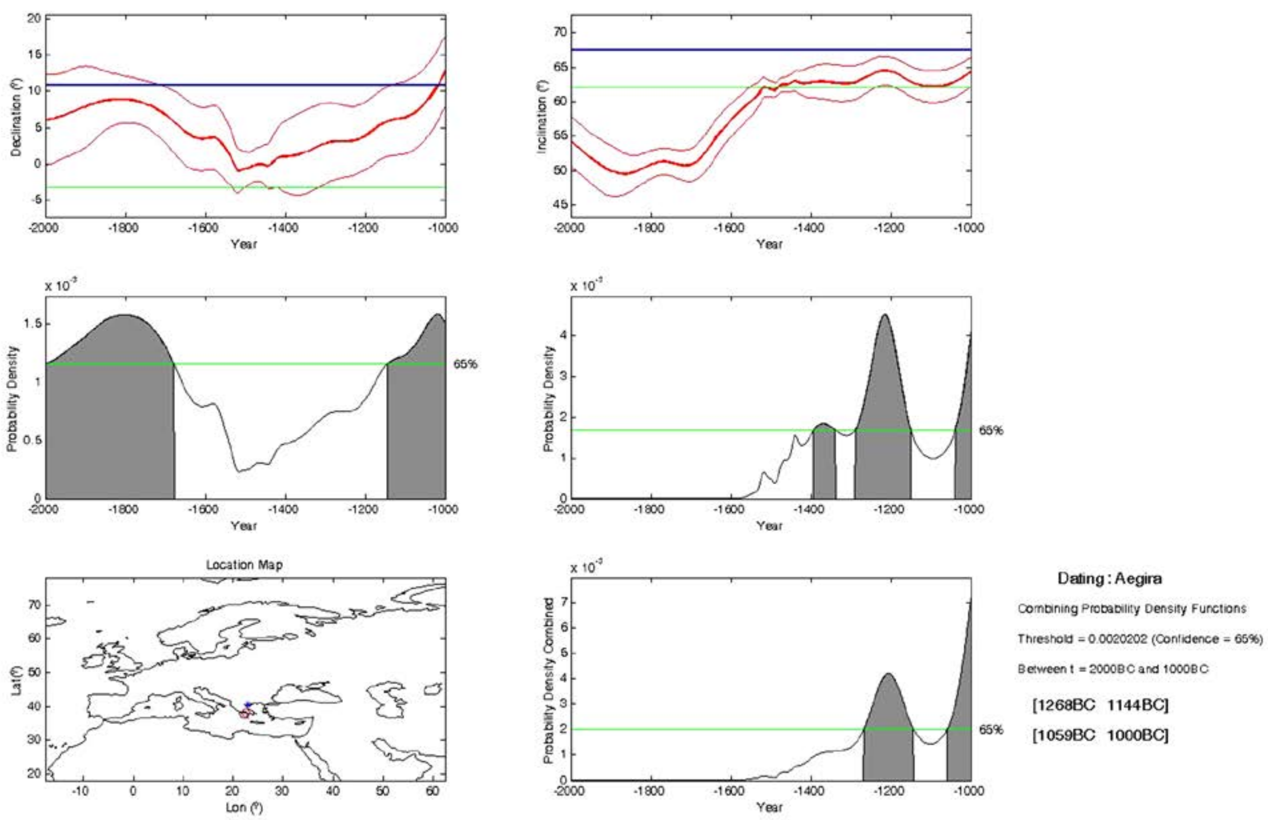

IMAGE6.JPEG

of archaeomagnetism by Greek researchers within the Aristotle University of Thessaloniki.

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Geoarchaeology:
a Review in Techniques

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Abstract: The aim of this work is to present the most established techniques used in geoarchaeological studies. Many books and articles concerning Geoachaeology are almost entirely devoted to geomorphology, sediments and soils. In the last 15-20 years, a plethora of other branches related to Geosciences have been involved in the archaeological research, such as Archaeogeophysics, Satellite Remote Sensing, Image Analysis and others, presenting very satisfactory results both at research level and in practice.

This work comprises a combination of an extensive literature research and examples from recent scientific papers on modern techniques applied in Archaeological Geology.

Keywords: Geology, Mapping, Geomorphology, Soils, Image analysis, Algorithm development.

1. Introduction

The term Geoachaeology is used to describe the contribution of Geosciences to Archaeology. The involvement of Geosciences in Archaeology originally came from the need of the archaeologists to have more information on the sediments and the stratigraphy of their excavation's features. Gradually the field of the geoarchaeological research began to include more applications such as:

- Locating archaeological sites using aerial photo analysis, geomorphological, geological and geophysical mapping (Tite 1972; Allen 1990; Crowther and Barker 1995; Crowther 2003).
- Landscape evaluation (Blum *et al.* 1992; Montufo 1997; Ferring 2001; Fowler 2002; Mexia 2014) in order to study the selection criteria of people in the past to build their settlements and the interaction with the environment (Armitage *et al.* 1987; Robinson 1992; Schuldenrein and Clark 2001) around them.
- Analyzing paleoenvironments (Macphail 1986; van Andel *et al.* 1990; Albanese and Frison 1995; Stewart 1999; Stern *et al.* 2002; Francus 2004; Clark *et al.* 2014).
- Sediment analyses (Barham and Macphail 1995; Canti 1995; Simpson *et al.* 2005) to determine the site-forming processes and to study the microarchaeological remains.
- Stratigraphic analyses (Stein 1990; Blum and Valastro 1992; Waters 2000; Courty 2001) and studying microstratigraphic materials (Macphail and Goldberg 2003) for relative dating.
- Geochronology (Morner 2014).

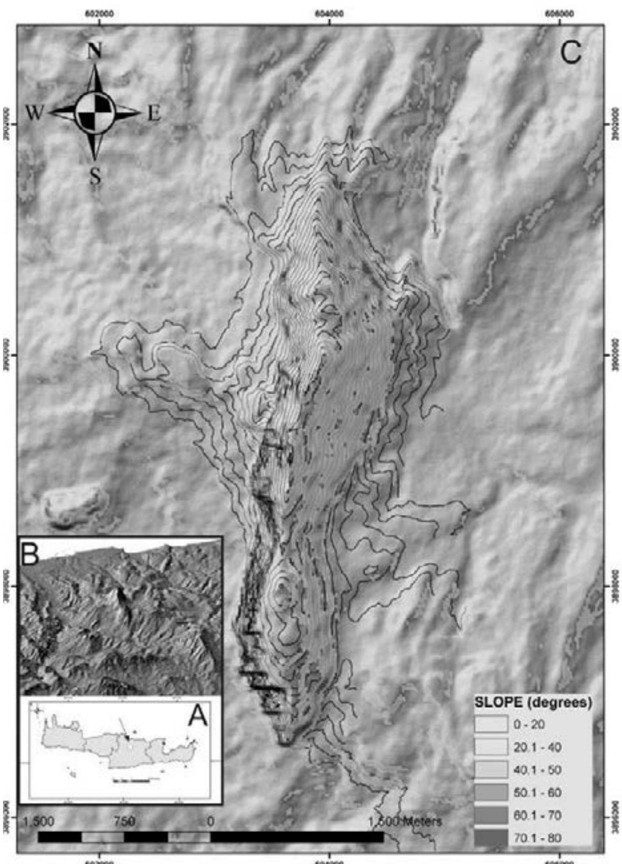
The contribution of Geology (Bullard 1970; Renfrew 1976; Rapp and Gifford 1985; Waters 1992; Nordt 1995; Rapp and Hill 1998; Akeret and Rentzel 2001; Sherwood 2005; Milek and Roberts 2013) in archaeological science became recognized in 1958 with the publication of relevant articles in the journal Archaeometry published by Oxford University. However, according to Rapp and Hill (1998) Georchaeology has its roots at least in the eighteenth century. The Journal of Archaeological Science (since 1973), Geoarchaeology (1986) and Archaeological Prospection (1994) are among the most famous scientific journals that publish articles in the field of Geoarchaeology. Additionally, both the Archaeological Geology Division established in 1977 by the Geological Society of America (GSA), and the Society for American Archaeology (SAA) have Geoarchaeology Interest Groups.

2. Techniques of the archaeological geology

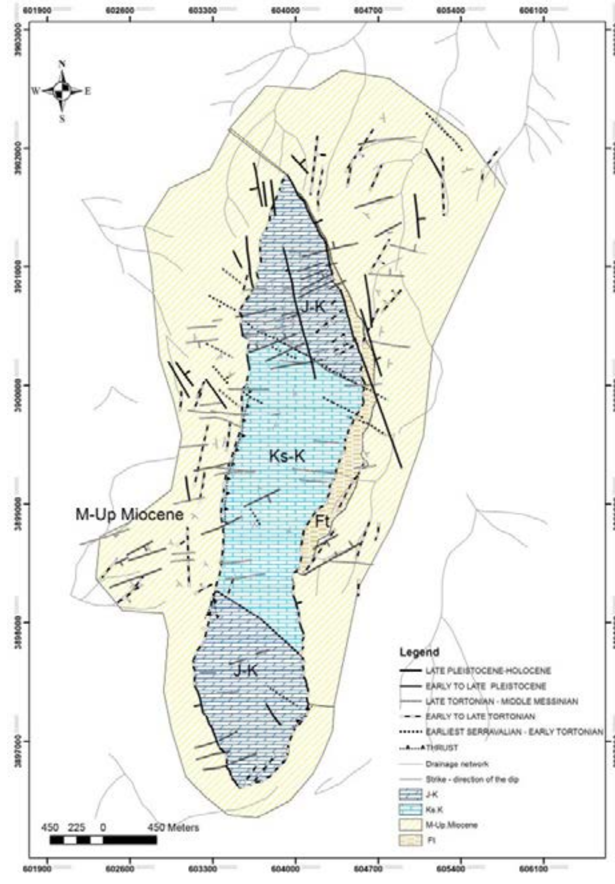
The geological methods used in Archaeology have been described since many years in several books (Thorson 1990; Herz and Garrison 1998; Goldberg 2001; Kvamme 2001; French 2003; Garrison 2003; Goldberg and Macphail 2006). However, new achievements and methodologies appear every year in this scientific field attracting the interest of a great part of the scientific community. In the present work part of the classification from Herz and Garrison (1998) was adopted to describe the archaeological methods.

Site Exploration

Geosciences are strongly involved in archaeological site exploration, using multiple techniques in order to correlate, check and better interpret (Panagiotakis and Kokinou 2014) the results of each applied methodology. Additionally, the geosciences contribute significantly in the study of the site formation processes by analyzing large scale geological systems (aeolian terrains, wetlands,



(a)



(b)

Figure 1. (a) Geomorphology /slope map and (b) Geological map of Giouchtas Mt. (Kokinou *et al.* 2010, 2015), where important archaeological sites, monuments of the Minoan Civilization are present, including four sanctuaries, a Minoan cemetery, ancient Eltyna and the Minoan settlement of Myrtia. In specifics in image (a) are included (A): Location of Giouchtas Mt.; (B): Topographic relief showing the wide area of study with the main structural features; (C): a slope map produced from 20 m digital elevation data. Image (b) provides information regarding the Geological map of the study area. J-K: Jurassic – Lower Cretaceous limestones, Ks.K: Upper Cretaceous limestones, Ft: Eocene to Lower Oligocene Flysch, M-Up. Miocene sediments.

streams and coasts). This term is used to describe the reconstruction of geomorphologic, pedologic, and biotic processes in an archaeological site and the interaction with human occupation in the past.

High accuracy geomorphologic and geological mapping (Fig. 1a,b) of the environs of an archaeological site comprises the initial step of the geoarchaeological exploration. The term high accuracy concerns the large scale mapping that has to be done. Large scale (the representative fraction is relatively large) mapping is used to show smaller areas in more detail. The results of the geomorphological and geological mapping are of high importance for the interpretation of the archaeogeophysical data.

Archaeogeophysical methods (Tite 1972; Allen and Macphail 1987; Allen 1990; Crowther and Barker 1995; Gage and Jones 1999; Crowther 2003; Gaffney and Gater 2003; Leucci *et al.* 2014) usually applied for the study of the geological mapping are seismic refraction, electrics (resistivity) and electromagnetics (conductivity), magnetics, magnetic susceptibility, ground penetrating radar, microgravity and thermography. At least 2-3 of the pre-mentioned methods (Fig. 2) should be combined in order to provide reliable results. Data interpretation is the last and most important step of the archaeogeophysical research. Besides the fact that two or more geophysical methods should always been applied, special attention should be given in the identification of the archaeological features (Panagiotakis *et al.* 2012, Fig. 3), in order to avoid as much as possible the human error in interpretation.

Another important part of the site exploration is the study of sediments (Rosen 1986; Brown 1997; Ashley 2001; Feibel 2001; Weiner *et al.* 2002) and soils (Arrhenious 1955; Bellhouse 1982; Fisher and Macphail 1985; Zangger 1992; Clark 1996; Carter 1998; Frederick *et al.* 2002). A very common term, used to describe the study of soils in their natural environment, is Pedology, dealing with pedogenesis, soil morphology and classification. Granulometry (grain size analysis) in combination with

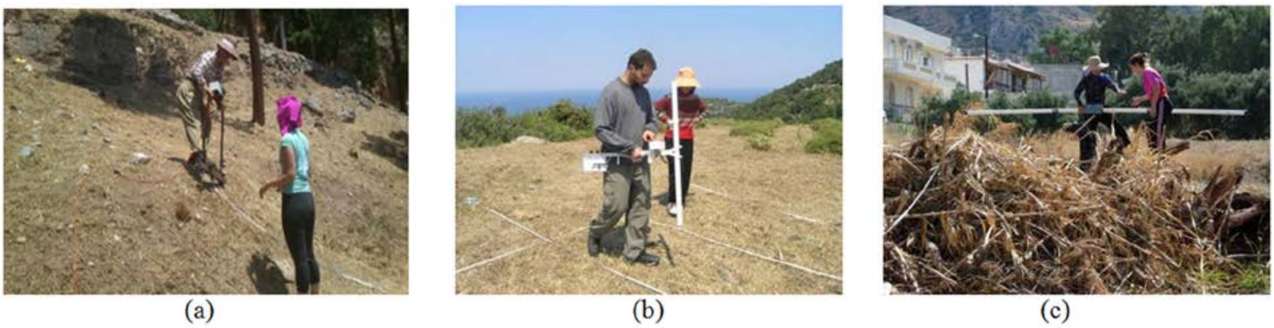


Figure 2. Archaeogeophysical survey methods: (a) resistivity, (b) magnetics, (c) electomagnetics.

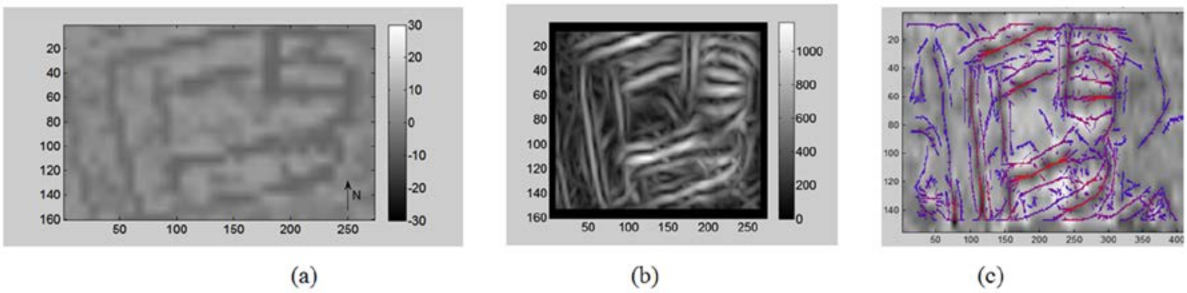


Figure 3. Automatic interpretation of archaeogeophysical data: (a) Original magnetic image, (b) Result of multiple filtering, (c) Thin curvilinear structure detection using the proposed by Panagiotakis *et al.* (2012) step filter.

determination of the grain physical properties (bulk density and mineralogy, shape) and chemical analyses (calcium carbonate, iron, organic matter, phosphate, etc.), belong among the most used methods, applied in pedological studies. The importance of the pre-mentioned studies lies in the fact that they can help archaeologists to understand what happened in the past and to be more efficient in their excavations and interpretations.

The term sediments (Fig. 4a) is usually referred to layered, unconsolidated materials of lithic or organic origin. Soils (Fig. 4b) correspond to unconsolidated sediments that are mixtures of organic and lithic materials capable of supporting plant growth. Among the most important parameters, used to describe the sediments and soils are: (a) Texture/particle size – lithological fraction, (b) shape/surface – degree of angularity (c) contact relations (sharp <0.5cm , abrupt 0.5-2.5cm, clear 2.5-6cm, gradual 6-13cm, diffuse >13cm), (d) color, (e) structure – physical organization (size, shape, aggregation) of particles in a horizon or stratum (f) coats (clay coals are termed argillans, sand or silt coats are the skeletons, organic coals are organans, carbonate coats are calcans), (g) occupation surfaces, (h) mineralogy, (i) chemistry (pH, cation exchange, conductivity, TOC, calcium, magnesium carbonates, C/N) and Paleoclimatology (plant microfossils).

Site exploration cannot be completed without a reference to the contribution of soil phosphate method in archaeological surveys. The soil fertility, in areas inhabited by humans, is higher than in uninhabited areas. Phosphate (PO_4^{-3}) comprises an important plant nutrient, highly concentrated at ancient sites -mainly due to the animal husbandry activities- that increases the soil fertility. The analysis of the Phosphate/nitrogen/carbon is used as a geochemical exploration tool to locate ancient settlements. According to Herz and Garrison(1998):

- In desert or agricultural land P: [0.01 % - 0.2%] in the uppermost 10 cm , while N: [0.1 % - 1.0%]
- In human environment of 100 people in 1 hectare: P: [0.5 % - 1.0%] in the uppermost 10 cm, while N: [0.7 % - 7.0%].

Dating techniques

Geochronology is the discipline of Geosciences that determines the age of rocks, fossils, and sediments within a certain degree of uncertainty. Numerous dating techniques (Zeuner 1953; McClure 1976; Valladas *et al.* 1988; Aitken and Valladas 1992; Bar-Yosef *et al.* 1996; Amos *et al.* 2003; Ellwood *et al.* 2004) facilitate the geoarchaeological research. These methods (Table 1) are classified (Lewis *et al.* 2009) in Chronometric or Absolute dating methods, based on a physical property to determine the age of the sample, and Relative dating methods that determine the approximate age (not accurate year) of an artifact by comparison to other objects/features in its vicinity. Radiocarbon dating and thermo-luminescence belong to the most widely used Chronometric methods. The radiocarbon method is applied for dating the 50000 years while the thermo-luminescence to date artifacts subjected to extremes of heat.

Figure 3. (a) Sediments (photo from the geological mapping of Giouchtas Mt. according to Kokinou *et al.* (2010, 2015) (b) Soils (photo from the geological mapping of the area around Karteros river in Heraklion, Crete)

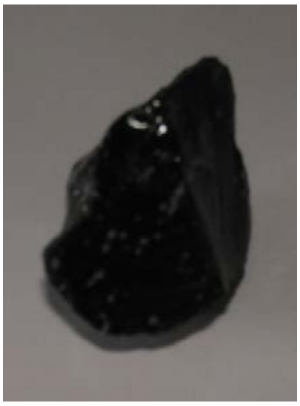
Table 1. Summary of relative and absolute dating methods (according to Lewis *et al.* 2009) in Archaeology.

Relative Methods	Chronometric/Absolute Methods
Stratigraphy: Superposition of strata	**Potassium-Argon (K/Ar):** Radioactive decay of potassium isotope
Biostratigraphy: Determination of consistent modifications in evolving lineages of animals: presence/absence of species	**Argon-argon (^{40}Ar/^{39}Ar):** Similar to potassium-argon technique
Cross-dating: Comparison of similarities between material remains of unknown and known age	**Fission-Track dating:** Regular fission of uranium atoms leaving microscopic tracks
Seriation: Sorting of artifacts from different sites or contexts into series according to the presence/absence or frequencies of shared attribute	**Paleomagnetism:** Regular shifts in Earth's geomagnetic pole; evidence preserved in magnetically charged sediments
Fluorine analysis: Determines age of bones based on fluorine content	**Radiocarbon dating:** Measures the ^{14}C/1^{2}C ratio in samples of organic materials
	Thermo-luminescence: Measures the accumulated radiation doses since the last heating or sunlight exposure of an object
	Electron spin resonance: Measurement (counting) of accumulated trapped electrons
	Uranium series dating: Radioactive decay of short-lived uranium isotopes
	Dendrochronology: Tree-ring dating

Artifact Analysis

Artifact analysis (Leigh 2001; Howard *et al.* 2015) comprises a very important task in Archaeology, concerning the study of archaeological materials (Kapur *et al.* 1992; Hill and Forti 1997; Karkanas *et al.* 2002; Schiegl *et al.* 2003), metallic minerals (Oldfield *et al.* 1985), ceramics (Williams and Jenkins 1976; Whitbread 1995, Stoltman 2001), and the development of instrumental analytical methods (Bull and Goldberg 1985; Schiegl 1996). The contribution of the Geosciences in artifact analysis is mainly in determining the sources (provenances) of raw material (Fig. 5) used in the manufacture of artifacts. Trace element analyses are necessary to estimate a potential geological source (Herz and Garrison, 1998). The following procedure is applied:

1. Determination of the geological boundaries of the deposit.
2. Collection and analysis of ten or more samples, statistically dispersed in the geological deposit.
3. Determination to what extent the modern mining/quarrying techniques have affected the original sediment deposits.



(a) Obsidian

(b) Calcite

(c) Quarz

(c) Hematite

(d) Anthracite from Etna Volcano

(e) Marble from Tinos

(f) Granite from Tinos

(g) Post-Minoan Lava from Nea Kameni in Thira

h) Minoan tuff in the Akrotiri quarry in Thira

(i) Pumice from Thira

Figure 5. Geological materials (from the personal archive of the author) used in the manufacture of human constructions and artifacts

Robust techniques to determine the origin of the raw materials include:

1. Mineralogy, 2. Petrography, 3. Trace elements (optical emission, spectroscopy, x-ray, atomic absorption e.t.c.) and 4. Stable isotopes (isotopic ratios of oxygen, carbon, and strodium are used for classical marbles and strodium for alabaster and gypsum).

Landscape reconstruction - Palaeoenvironment analysis

Scope of the Landscape reconstruction is the study and rebuilding of the past archaeological landscapes and palaeoenvironments. The final product of such a process is often a 3D spatial digital reconstruction of the archaeological environment. The reconstruction of the past natural and anthropogenic landscape is a faceted approach based on:

- Satellite imagery analysis, photogrammetry and laser scanning of ancient relics
- GPS localization of the evidences
- Geological-, land use-, and paleo-botanical maps
- Geophysical prospection
- Palaeoclimatological analyses using rocks, sediments, ice sheets, tree rings, corals, shells and microfossils
- GIS-based techniques (spatial analysis or predictive modelling) for cultural heritage management.

3. Conclusions

Geoarchaeology has become prominent in the last 55 years through the publication of a large number of books, monographs, reports and journal articles. This is because the archaeological environment is inextricably linked to the natural environment. Geoscientfic methods are involved almost in all phases of the archaeological research, i.e. the site exploration, the geochronology/dating and the artifact analysis. In this work all methods related to Geoarchaeology have been briefly analyzed. Depending on their context of application, these methods can be classified in four large categories as previous mentioned:

1. Site Exploration:

- Geomorphological, geological and archaeogeophysical mapping of the sites
- Study of the sediments and soils with special emphasis to soil phosphate technique

2. Dating techniques:

- Absolute/Chronometric methods
- Relative methods

3. Artifact analysis in sourcing geologic deposits:

- Petrography
- Mineralogy
- Trace elements
- Stable isotopes

4. Landscape reconstruction - Palaeoenvironment analysis

A variety of information is provided by many disciplines of the Earth Sciences to Archaeology to facilitate the landscape reconstruction of a site. Apart the contribution of classical disciplines (stratigraphy, sendimentology, chronology, u.o.) a wealth of information is nowadays provided by modern disciplines of the Earth Sciences such as satellite imagery, GIS techniques and image analysis.

In concluding this work, Geoarchaeology comprises a multidiscipline strongly linked to archaeological studies because of the need to explain phenomena in a number of dimensions of the archaeological landscapes.

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Inorganic Geochemical Methods in Archaeological Prospection

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Abstract: Geochemical survey can define variations (or anomalies) in element concentrations of soil samples as a proxy of past human occupation. Whilst inorganic chemical analyses have demonstrated their potential in archaeological prospection, there is a lack of standardised methodologies and procedures to undertake these surveys. This work reviews some general principles, common methods and current approaches in geochemical prospection of archaeological sites and provides some guidelines and fieldwork strategies to be used in future surveys.

Keywords: Geochemical survey, inorganic chemical soil analysis, archaeological prospection, minimally-invasive methods

1. Introduction

There is a strong link between past human activity and its footprint left in soils. Soils can act as a sink of anthropogenic organic matter and retain some inorganic components as a fixed input over the general soil chemical signal (Heron 2001:565) leading to anomalous concentrations of certain elements. These inputs may remain within the soil over a long time and can reveal evidence about past human occupation. The spatial distribution of anomalous concentrations of soil elements may help to: locate archaeological sites and determine their extension (Bintliff *et al.* 1990, Schlezinger & Howes 2000, Eckel *et al.* 2002, Linderholm 2007); provide information about past land use (Entwistle *et al.* 1998, Wilson *et al.* 2006); and identify activities areas and features within settlements (Middleton & Price 1996, Wells 2004, Cook *et al.* 2005, Wilson *et al.* 2005, Wilson *et al.* 2009, Jones *et al.* 2010, Salisbury 2012).

Geochemical survey is regarded as a minimally invasive method in archaeological prospection. Whilst the soil has to be systematically sampled, only a few grams are required for the analyses. Typical approaches in archaeo-geochemical prospection generally involve the quantitative measurement of a single chemical attribute (e.g. phosphate analysis) or a range of elements (multi-element analysis) comprised in a soil sample. Most of the analyses are done in a laboratory environment and very often they require of laborious, specialised and relatively costly procedures (e.g. preliminary soil digestion for chemical analysis). Constant technological developments are providing increasingly affordable instruments, such as portable XRF spectrometers (hereinafter pXRF) or rapid soil digestion microwaves systems, which are improving the cost and time-effectiveness of these analyses.

Despite the potential of geochemical methods, these are not as routine in archaeological prospection as, for example, geophysical surveys. The reasons behind this situation may be partially explained because of the important methodological issues that are still unresolved in the discipline (Oonk *et al.* 2009a). One of the main issues highlighted by Oonk *et al.* (2009a) is that distinguishing ancient chemical anthropogenic inputs in soils from geological signals remains problematic. Furthermore, they report that the discipline lacks standardisation in methods and procedures, especially in sample digestion and analysis, and thus research findings are difficult to compare and develop. There remains a scarcity of published guidelines on survey strategies to use during fieldwork (e.g. sampling methods) or recommendations in the selection of the available analytical techniques. A rare exception is the Soil Analysis Support System for Archaeologists (SASSA), a free on-line tool developed to familiarise archaeologists with a wide range of scientific soil analyses (Wilson *et al.* 2008).

1.1. Factors involved in the retention of chemical elements in archaeological soils

Certain anthropogenic chemical compounds can be fixed to the mineral surfaces of sediment grains. The deposition and retention of these compounds in archaeological soils are influenced by soil properties and environmental factors including: soil parent material, incorporation of organic matter, climate, and abundance and type of source input (e.g. manure, burning). The sequestration of elements in soils depends on interrelated soil physical and chemical processes such as soil texture, precipitation of elements, CEC, soil pH and soil redox conditions (Hawkes 1957, Gonzalez-Carrillo *et al.* 2006). The rate at which these processes lead to the concentration of chemical elements in archaeological soils is influenced by the topography, vegetation, soil fauna and time (Haslam & Tibbett 2004).

Recent land management and industrial practices can also modify soil element concentrations and disturb the concentrations related to archaeological horizons. For example, modern agricultural activities such as ploughing, addition of fertilizers and pesticides, modern sewage sludge and the proximity to major roads, can result in intermixing of recent and archaeological inputs resulting in the obscuring of soil element concentrations of interest.

1.2. Common archaeo-anthropogenic elements

Archaeological soils are characterised by their chemical complexity and diversity. However, frequent elements used in archaeological prospection are phosphorus (P), calcium (Ca), potassium (K), sodium (Na) and magnesium (Mg) as well as trace metals such as manganese (Mn), copper (Cu), lead (Pb) and zinc (Zn) (Aston *et al.* 1998, Schlezinger & Howes 2000, Middleton & Price 1996, Holliday and Gartner 2007, Zgłobicki 2013). Many of these elements occur naturally in soils to a higher or lower degree, and their anomalous concentration in archaeological soils is the result of a higher incorporation rate as a product, for example, of a specific activity carried out at the area. Past human activity can also introduce compounds that might not be naturally found in soils or not common locally.

P, Ca and K are established indicators in the prediction and location of settlements (Oonk *et al.* 2009a). P is unique among the elements in demarking human activity (Holliday and Gartner 2007). P exists in soils in both organic and inorganic forms, usually of phosphate (PO_4^{3-}). Organic forms of P in soils are found in humus and other organic materials and consist of easily decomposable phosphate compounds in the form of, for example, esters, nucleic acids and phospholipids. The decay of organic matter releases organic and chemical compounds to the soil and the interactions between soil minerals, organic matter and microorganisms stabilise soil P. Due to its particular chemistry, P strongly binds with Fe, Al and Ca cations to form fairly stable and insoluble substances. Some forms of soil P are highly resistant to normal oxidation, reduction or leaching processes. When humans add phosphate to soil (i.e. addition of organic matter into the soil), it often accumulates and, if the site of the deposition had a prolonged occupation, it becomes fixed in soils. Such P concentrations are quite high in comparison to the natural phosphate in the soil. General sources of anthropogenic phosphorus include human refuse and waste, burials, livestock and the products of animal husbandry or intentional enrichment from soil fertilizer.

P, Ca and K can also be found in association with particular areas within a site and specific features. Ca can be released from bone material (Adderley *et al.* 2004) and be sequestrated in archaeological soils in its mineral form, calcium-phosphate apatite (Oonk *et al.* 2009a). For example, high concentrations of Ca has been documented at metal working sites in England in association with cupellation furnace production that is consistent with the use of ashes of calcined bones in this technique (Cook *et al.* 2005). Elevated Ca concentrations have been also measured in soils sampled from hearths, dwellings, byres and middens on different 19th C farm sites in Scotland (Wilson *et al.* 2006). Cu and Pb enrichments have been reported as an indicator of production areas (mining, smelting and fuel combustion) at a wide range of archaeological sites (Parnell *et al.* 2002, Wilson *et al.* 2007). Cu and Pb are retained in soils through interactions with soil pH, clay content and OM (Cerqueira *et al.* 2011) and constitute promising anthropogenic indicators because they are relatively stable in soils (Paterson 2011).

Whilst the above-mentioned elements are some of the most studied in archaeological prospection, other elements and type of concentrations (e.g. depletions instead of enhancements) should not be excluded as indicative of human activity. As an example, enhancements of Mn have been reported as an indicator of human activity, however, depletions of Mn have been also found in association with archaeological features at sites in the Netherlands and Scotland (Oonk *et al.* 2009b, Cuenca-García *et al.* 2013). These depletions appear to be caused by the reductive dissolution of Mn oxides, due to the decomposition of organic matter incorporated in the soil, or in these specific cases, in particular features.

2. Soil sampling

To conduct successful geochemical surveys it is fundamental to plan carefully, collect representative soil samples and select adequate analytical techniques. There are three key aspects to consider during the planning stage: the elements likely to be associated to the targeted site or feature; the chemical properties of these elements; and the geological or other environmental factors (e.g. topography) that may have an effect on the average chemical soil enhancement of the site (site baseline) and natural background. Before undertaking any fieldwork, it is important to seek permission from the pertinent local authorities and landowners.

The use of an appropriate sampling strategy (resolution), sampling depth (soil horizon) and an understanding of autochthonous soil elements (background) are vital to identify anthropogenic chemical inputs at archaeological sites (Haslam and Tibbet 2004). Sampling strategies may vary according to the particular objective of the prospection. Typically, samples are collected on a regular grid pattern (Fig. 1) to study horizontal variations in the concentration of elements at a specific soil horizon in either large-scale or intra-site surveys. The optimum spacing between sampling lines and sample points generally depends on the expected size of the feature to investigate and the total size of the area to survey. Common soil sample spacing varies between 20m x 20m or 10m x 10m for reconnaissance surveys down to 5m x 5m, 1m x 1m or less for detailed chemical characterisation. It is essential that samples are taken densely enough to properly characterise the average chemical soil enhancement of the site (site baseline) and allow, particularly in intra-site approaches, potential hotspots of element concentrations to be distinguished. Alternative sampling strategies may include: the collection of samples along single lines strategically located across a site, measuring one or several depths (e.g. soil profiling), to assess rapidly the extent of a site; and the sampling of soil taken from exposed sections to characterise in detail particular archaeological features.

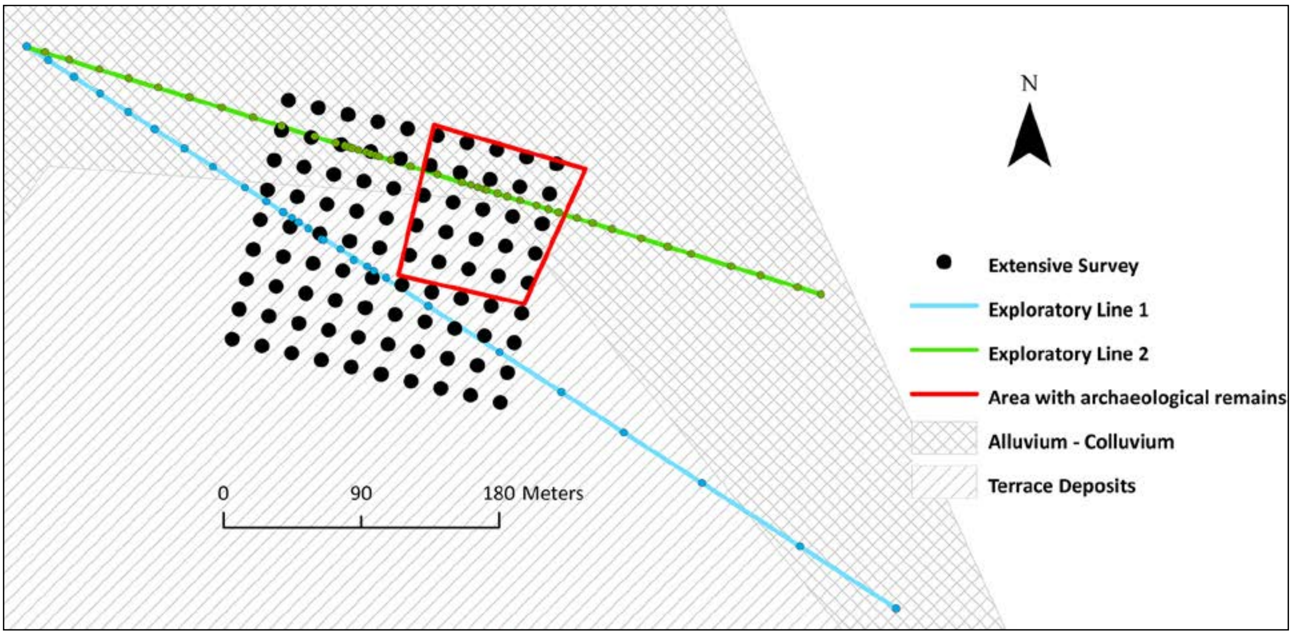

Figure 1: Example of a combined sampling strategy carried out by the author at a Bronze Age site in Cyprus. The soil samples were collected using an extensive grid pattern and exploratory single lines.

It is very important that soil samples be collected from the same soil horizon. General soil horizons targeted in geochemical surveys in archaeological investigations include the bottom of the ploughsoil, the top of the cultural layer, and the top of the subsoil. To establish an adequate sampling depth, information from previous excavations or geophysical surveys carried out at the site may be helpful. Exploratory coring/augering can be also used to characterise the soil profile and assess the best sampling horizon. Fresh archaeological soils exposed during excavations (e.g. open trench, exposed floor sediments and sections) are good cases for sampling in detailed intra-site studies. Sampling tools such as trowels and power or hand augers may be used to collect bulk soil samples (Fig. 2). Corers, gouge augers or Kubiena boxes (for exposed archaeological soils/sections) can be used if the research plan requires the collection of undisturbed soil samples. The amount of soil to be collected will depend on the type and number of analyses to be carried out and should be carefully determined in the research plan and before the survey. Most geochemical analyses require only a few grams of soil therefore, it is important to collect only a nominal amount to ensure the survey is as minimally invasive as possible.

Collected samples should be placed in chemical-free paper, suitable for drying in the sun, and kept in labelled and air-free plastic bags after removing any living/organic material (e.g. worms, roots). The sampling tools should be cleaned of sediments between each sample point to avoid contamination. It is critical to air-dry (or oven-dry) the samples as soon as possible to avoid any chemical alteration in the soil (e.g. oxidation of organic matter). The sampling points should be located with a GPS/Total station, and after the sampling, the holes excavated have to be back-filled and the vegetation/turf replaced.

Establishing the geochemical background is one decisive step to determine the location and magnitude of geochemical anomalies derived from ancient human activity. This may involve further sampling at areas outside the known settlement (Entwistle *et al.* 2000, Middleton 2004, Oonk *et al.* 2009c, Wilson *et al.* 2009). This sampling should target off-site areas, with the same type of natural soil as the study site, that have not been impacted by human activity. Ideally, the off-site soil collection has to target a buried horizon that is contemporary with the occupation of the site. Since this scenario is seldom possible, the best available non-human-impacted area/s should be sampled at the same depths as those inside the study site. Other strategies that may help in assessing the off-site geochemical background are the characterisation of profiles at different depths and the sampling of natural sections exposed in the area surrounding the archaeological site.

3. Soil sample preparation

Sample homogenisation of fully dried soil samples is the first step in sample preparation. This must be done to avoid any matrix effects in the analysis resulting from variations in the physical character of the sample (i.e. settled fine particles at the bottom of the sample bag). Sample homogenization can be achieved just by shaking each original sample before any manipulation. Samples are generally sub-sampled in the case of multiple analyses and it is good practice to reserve some original sample. Sometimes the samples need to be grounded with a sterile mortar to break up the lumps with a pestle.

Figure 2: Soil sampling for geochemical analysis using an auger at a Neolithic tell-site in Thessaly (Greece).

Most of the chemical methods involve the selection of a soil fraction by sieving. Soil geochemical analysis is focused on the analysis of the finer soil fraction, as available cations will be mostly adsorbed onto clays. However, the type of clays largely influences this, for example kaolinite has very low cation exchange capacities. Cations can be also hosted in the coarser fraction as occluded particles of other host minerals (e.g. metal-oxides, rock and quartz grains). Therefore, the general procedure for geochemical analyses is to sieve a bulk sample of soil material using a grid aperture size of less than 2 mm, which will include finer clays and carbonates and grains of lithic material. The sieving should be carried out as consistently as possible (i.e. using mechanical shakers during the sieving), minimising any potential contamination between samples, and using a dust collection system and adequate personal protective equipment (e.g. dust masks, earplugs).

Often, the chemical concentration analysis involves a preliminary digestion (or extraction) procedure for the dissolution of elements present in soil samples before their subsequent measurement. Taking into account that individual elements are retained within different soil fractions, the choice of an adequate extraction method is decisive for the analysis and the interpretation of the results. There are different methods that have been suggested, ranging from mild acid extractions that essentially recover the plant available fraction (Middleton 2004, Wells 2004) to more aggressive total (HF) or pseudo-total methods (aqua-regia) that also break down the more resistant soil minerals (Wilson *et al.* 2005, Holliday and Gartner 2007). Given the occurrence of elements in highly resistant soil fractions, the use of more aggressive total or pseudo-total extraction has been shown to be beneficial (Wilson *et al.* 2006, Oonk *et al.* 2009a), although this may not be the most suitable approach in all the cases. Whilst all these extraction methods are time-consuming and costly procedures, the use of increasingly developed microwave-digestion technology may allow speeding up the digestion of samples. These systems facilitate a more rapid digestion, an evaporation of acids in a closed and safer environment and accurate analytical results with high recovery values (Melaku *et al.* 2005, Da Silva *et al.* 2014, Butler *et al.* 2014, Kanthilatha *et al.* 2014).

4. Inorganic soil chemical analyses

This section describes the most common techniques used in geochemical surveys of archaeological sites: phosphate analysis, inductively coupled plasma spectroscopy (ICP) and x-ray fluorescence spectroscopy (XRF). The surveys are generally performed using one or a combination of complimentary techniques. Except XRF, these techniques generally require the digestion and consequent destruction of the original soil samples, although, only a small amount of a sample is required. Geochemical data have an intrinsic multivariate character because the processes that have generated the anomaly commonly involve an association of elements. Thus, the opportunity to explore multi-element concentrations may be more successful in locating anomalies and able to provide a better understanding of the causes behind their formation. Nevertheless, other approaches may prefer focusing on the study of a specific group of elements characteristic of a particular activity, for example, Cu and associated elements to study metalworking sites (Carey *et al.* 2014) or even on a single but strong anthropogenic indicator, such as P (Nielsen and Kristiansen 2014).

4.1. Phosphate analysis

The purpose of this analysis is to determine phosphate concentrations in soil samples in order to locate settlements or identify activity areas within a site. Phosphate analysis

Table 1: Phosphate methods in archaeological investigations.

Form	Description	Advantages	Limits
Total phosphate	It is based in the extraction of both anthropogenic and geological phosphate derived from organic and inorganic phosphate forms. The extraction is done using a range of aggressive re- agents (e.g. sodium hypobromite, sulphuric acid, hydrofluoric acid) to break the bonds between P molecules and their hosts and release all the contained phosphate).	Produces comparable quantitative data. It is a good approach to identify anthropogenic inputs especially when comparisons are made with natural soils. It is commonly used in archaeological investigations, including detailed site prospection.	This approach may not work at sites with natural high phosphate levels as these may mask any anthropogenic input. Total phosphate analysis involves lab-based measurements that are relatively low-cost, but they are time-consuming.
Inorganic phosphate	Taking into account that even phosphorus derived from organic materials becomes mineralised, these methods focus on the extraction of inorganic phosphate for fractionation studies and look at individual phosphate compounds. Generally, three fractions are extracted: fraction I (solution phosphates); fraction II (bounded phosphate forms to Al and Fe oxides); and fraction III, (occluded Ca-phosphates).	Phosphate fractionation methods have been used in archaeological investigations to identify and characterise the type and intensity of past land-use (Eidt 1977, Lillios 1992). These extractions tend to correlate with those from total phosphate.	An important limitation of this approach in archaeological applications is that study areas intensively cultivated for a long time are not suitable because of the mixture of phosphate forms in the ploughsoil (Lillios 1992). In addition, fractionation methods are time consuming and costly given the number of samples to extract.
Organic Phosphate	It is considered as the difference between total and inorganic phosphate. It can be calculated as the difference in phosphate content between two samples from the same soil, one ignited to oxidise the organic matter and one not ignited. The analysis is done using an extraction method for inorganic phosphate (e.g. HCl, sulphuric acid). Alternatively, organic phosphate can also be measured using a standard extraction for inorganic phosphorus followed by ignition-oxidation.	The few archaeological investigations using this approach seem to focus on assessing agricultural contexts. Organic and inorganic phosphate measurements tend to correlate when measuring crop residues.	According to Holliday and Gartner (2007), organic P concentrations tend to be lower in archaeological soils that those measured with total extractions. This may be due to the rapid mineralisation of organic phosphates at archaeological sites where the microbial activity is high.
Plant-available phosphate	These methods measure soil-solution phosphate and easily displaced inorganic phosphate. The procedures include qualitative ring and spot test (the Gundlach method) and a semi-quantitative field-based method and measurement using colorimetry. These procedures are relatively easy and they have been used in field situations (Terry *et al.* 2000, Rypkema *et al.* 2007, Salisbury 2013a).	The portability and the rapid and easy character of the procedures made them ideal for site prospection where the aim is the identification of spatial patterns to locate a site, rather than calculate the accurate absolute concentration of phosphate.	It provides a rough indication of the phosphate status of a soil. The measurements do not correlate with any particular phosphate form so the results may be more difficult to interpret in detail. In addition, phosphate availability to plants is strongly influenced by soil conditions and varies from soil to soil. Therefore, these measurements may be less comparable than those obtained from total phosphate analysis, especially if different types of soil are analysed.

Figure 3: Different stages of molybdenum blue colorimetric method for determination of phosphate in soil samples: soil digestion and filtration (a), standards preparation (b), preparation for addition of developing solution (c) and measurement of the absorbance (d).

is a well-established method in archaeological prospection and it has been used since the 1920s-30s with the pioneering work of Arrhenius in north-western Europe (see Bethell and Mate 1989 for an historical review). Basic facts in the particular chemistry of P and its significance as a marker in archaeological prospection are explained in section 1.2.

Phosphate analysis involves the extraction of phosphate from soil samples and the measurement of its concentration in the extractant.. The many methods available for phosphate analysis target different phosphate forms (organic and inorganic). There is no known method able to extract, exclusively, phosphate directly derived from an anthropogenic related source. Extraction methods and procedures used in archaeological investigations generally focus on the measurement of one of the categories shown in Table 1. Reference to specific protocols for such extractions can be found in Holliday and Gartner (2007).

In archaeological investigations, the measurements of extracted phosphate are generally carried out using colorimetry and spot tests. Colorimetric procedures often are based on the molybdenum blue colorimetric method (Fig. 3) of Murphy and Riley (1962). Following the extraction of a particular phosphate fraction, the samples are reduced in an acidic environment that gives them an intense blue colour. The intensity of the coloured solution is directly proportional to the concentration of the particular phosphate fraction in the sample. The concentration is measured as a function of absorbance of particular wavelength of light by the sample solution using a spectrophotometer or a colorimeter. The quantification of the phosphate content is achieved by the measurements of a series of standards samples of a known phosphate concentration and the calculation of a calibration curve. The values of each sample are plotted against the calibration curve and the concentrations derived.

4.2. Inductively-Coupled Plasma Spectroscopy (ICP)

ICP is used in multi-element concentration analysis and it has been applied in archaeological prospection since the 1980s (Bethell and Smith 1989, Konrad *et al.* 1983). The technique is based on the decomposition of a liquid sample into its constituent atoms or ions using the intense heat produced by inductively coupled plasma (a state of matter containing electrons and ionized atoms of Argon). The high temperature causes excitation and ionisation of the sample atoms. Once the atoms or ions are in their excited energy states, they can decay to lower energy states whilst emitting light of specific wavelengths that can be detected and quantified with either an Optical Emission Spectrometer (OES) or a Mass Spectrometer (MS). ICP-OES is sometimes referred to as Atomic Emission Spectrometry (ICP-AES). In ICP-OES (Fig. 4), a large suite of major and trace elements can be measured within the 0.1 to >100 parts per million (ppm) range. ICP-MS is characterised by its extremely high sensitivity and very low detection limits (parts per billion and parts per trillion range). It is good in the determination of trace and ultra-trace elements and it can measure the isotopic ratios of some elements.

Whilst the measurements are rapid (up to 60 elements per single sample can be analysed in just a few minutes), the soil digestion (required to introduced the sample to the ICP torch as a liquid) increases substantially the time and costs in this analysis. The selection of an adequate extraction method and an understanding of the character of the recovered fraction are also fundamental for the interpretation of the results (see section 3 for a review on digestion methods). The technique requires calibration for quantitative analysis, which involves comparing the measurements of known element concentrations with that of unknown sample solutions. There is a series of potential problems that must be taken into account. During sample preparation, part of the sample can be lost (e.g. weighing the samples, dilution steps during the digestion stage). Moreover, spectral interference between different elements with similar wavelengths and matrix effects caused by high concentrations of an element in a sample may be taken into account as they could lead to either an under or overestimation of concentrations. The accuracy and the quality of the digestion process and the measurements are generally assessed using the certified reference material. Whilst the reproducibility of this technique is normally fairly good, it can be evaluated by repeating measurements of two samples of the standard reference material.

4.3. X-ray Fluorescence (XRF)

This is a non-destructive technique used to detect and measure the concentration of multi-elements in materials. Some early XRF surveys of archaeological sites were done

Figure 4: Trace/metal clean laboratory gear (a) and equipment (b) for soil digestion using a microwave digestion system (c) and ICP-OES measurements (d).

during the mid-late 1980s (Frahm and Doonan 2013) and they started to appear more frequently in the literature since the 2000s (Cook *et al.* 2005, Marwick 2005). XRF is based on the reaction of atoms when they interact with x-ray radiation. Atoms can be excited when they are hit with high-energy x-rays, becoming ionized. This produces the ejection of low energy electrons from the outer-electron shells of atoms. The vacancies left by the expelled electrons are filled by electrons 'dropping in' from the outer shells, releasing radiation (fluorescent radiation). The energies of fluorescent x-rays are characteristic of the energy levels of the electron shells in the element. These energy levels are different for each element. Thus, by detecting and analysing the energies of the spectrum of fluorescent x-rays emitted by a material, it is possible to determine what elements are present and at what concentration.

XRF can simultaneously measure major and some trace elements from a 100% to few parts per million concentration. Lighter elements, such as aluminium (Al), silicon (Si) or P, may be more difficult to detect. Sometimes, the use of a helium purge device or a vacuum pump chamber with XRF instruments can increase their sensitivity to lighter elements. Since ionisation is the underlying principle of operation for XRF instruments, there are some health and safety risks associated with operating these instruments. Often, the use of XRF has to comply with national and/or institutional ionising radiation regulations in some countries. In these cases, operators have to pass safety training and carry a dosimeter to monitor any radiation dose acquired during the measurements.

One of the main advantages of XRF is that it is not required to digest the soil samples, which speeds up and reduces the costs associated with this technique. Minimally processed samples (i.e. dried, homogenized and >2mm sieved soils) can be analysed. The XRF is predominantly a surface analysis technique (x-rays penetrate a few mm into the sample) therefore, the more homogeneous a sample, the more accurate the results. In recent years, the use of pXRF instruments have gained considerable attention within the archaeological community as these instruments are uniquely suited for in-situ analysis (Frahm and Doonan 2013). In archaeological prospection, the applications of in-situ pXRF, including the direct measure of unprocessed soil samples, are now starting to be assessed (Hayes 2013, Grattan *et al.* 2014, Hunt and Speakman 2015). In laboratory/benchtop measurements using a pXRF (Fig. 5), a few grams of processed soil sample are transferred into XRF sample cups and covered with x-ray film (e.g. polypropylene, Mylar film). The sample cup is positioned under a portable shielded lead chamber stand that provides a safe platform for analysis. In-situ pXRF measurements are taken directly on the exposed soil (Fig. 5). Lab-based measurements provide a higher analytical grade of accuracy since the samples are more homogeneous and the measurements are taken in a more controlled environment. In contrast, in-situ analysis may be adequate as a field-screening method to map patterns in chemical concentration without the need of great accuracy in total counts.

XRF instruments are sensitive to a number of interference effects. Physical matrix effects can result from variations in the sample (particle size, homogeneity, surface condition). Changes in temperature during operation may affect the readings (e.g. drift effects). Moisture content in the samples may affect the instrument's accuracy as the higher the soil moisture in a sample, the lower the recorded concentration. Inconsistent positioning of samples in front of the probe window can also affect the measurements (x-ray signal decreases as the distance from the x-ray source increases). Chemical matrix effects can result from differences in the concentrations of interfering elements (as peak overlaps or as x-ray absorption and enhancement phenomena of elements with similar energy). Calibration checks using international standard samples or control samples can be used to determine the accuracy of the instrument in addition to monitoring the stability and consistency of the measurements. The precision of the analysis can be assessed by analysing samples repeatedly during the day.

5. Data analysis

The purpose of geochemical prospection in archaeological investigations is to measure, map and identify soil chemical concentrations that significantly differ from the surrounding natural chemical patterns. Whilst this seems a fairly straightforward objective, soil environments are complex and one of the principal challenges in these analyses is distinguishing relevant geochemical concentrations from

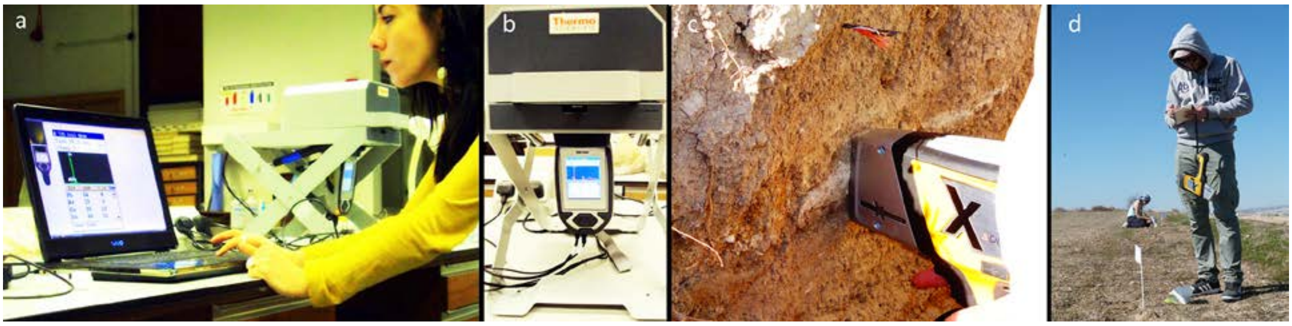

Figure 5: pXRF analysis using a benchtop set-up (a & b) and in-situ measurements (c & d).

other dispersion patterns of no archaeological significance. According to Hawkes (1957: 233), the key parameters to identify and interpret geochemical anomalies include the range of non-significant variations in background, the threshold between non-significant and anomalous values (cut off established with off-site/on-site soils), the contrast (or ratio) between anomalous and background values and the homogeneity and consistence of the anomalous pattern.

In most cases, assessing the geochemical background is a difficult task because of the natural variations in the chemical makeup of the soil. In many archaeological investigations the background levels are assessed by taking off-site samples as mentioned in section 2. Other studies integrated more than one strategy such as bivariate comparison of on-site/off-site and regional indicators from existing databases (Oonk *et al.* 2009b)

Geochemical investigations generally result in the generation of large amounts of data. In order to understand such datasets, they need to be summarized and analysed using a wide range of statistical methods, graphical techniques and spatial analysis tools. Statistical methods are the primary way to analyse geochemical datasets and define anomalies. Since geochemical data seldom fit a normal distribution pattern (the data are typically spatially dependent), statistical methods need to be used cautiously (McQueen 2008). Univariate statistics are commonly used, for example, to assess background ranges and anomaly thresholds for single elements. Potential correlations and associations between several elements can be investigated with multivariate statistical methods such as bivariate plots (Oonk *et al.* 2009b), correlation matrices (Entwistle *et al.* 2000), cluster analysis (Middleton and Price 1996), principal component analysis (Linderholm and Lundberg 1994), analysis of variance (ANOVA) (Knudson and Frink 2010) and discriminant function analysis (Wells 2004).

6. Current approaches

Rather than studies focused on the application of isolated chemical analysis, the discipline of geochemical prospecting appears to be developing towards a more integrated perspective. Increasingly many geochemical surveys are implemented in combination with a range of geoarchaeological and other non-destructive prospection methods. The aim of these combined and generally intra-site approaches is to maximize the information extracted from the investigated sites. For example, geochemical analysis combined with soil micromorphology, artefact distribution, geophysical survey and other soil characterisation analyses of floor sediments have been used to assess activity areas in Neolithic (Jones *et al.* 2010) and Viking (Milek and Roberts 2013) houses, in Scotland and Iceland, respectively. In larger scale surveys, geophysical prospection and soil geochemical analysis have been combined to map features and activity areas at prehistoric settlements in Hungary (Yerkes *et al.* 2007, Salisbury 2013b), including remote sensing methods and hyperspectral methods (Sarris *et al.* 2013). Soil geochemical analysis, magnetic susceptibility survey and artefact distribution used in a historic site in Tanzania allowed determination of the functionality of open spaces within an urban area (Fleisher and Sulas 2015). A more particular application of integrated strategies was the study published by Nowaczinski *et al.* (2013) where they combined chemical analysis (phosphorus content analysis) and geophysical surveys to estimate population size of a Bronze Age site in Slovakia.

From a more methodological perspective, the integration of soil geochemical analysis with geophysical prospection was also demonstrated to develop a better understanding of how the setting of a site may affect the geophysical and geochemical results, distinguishing between natural and man-made anomalies and improving their interpretations (Cuenca-García *et al.* 2013, Dirix *et al.* 2013). The technique reappraisal capabilities of this particular combination of methods are based on the complementary information provided by these two disciplines.

Taking into consideration the rapid development of instrumentation, current methodological studies also include comparison between techniques to evaluate their accuracy in measuring elements of particular anthropogenic interest (Nielsen and Kristiansen 2014) or the assessments of less specific but potentially more cost-effective techniques as preliminary screening prospection methods (e.g. pXRF review in section 4.3).

The analytical techniques considered in this work only measure total element concentration of soil samples, independent of the mineralogical form. Future studies may consider further integration with isotopic analysis, organic chemistry and mineralogical analysis to improve elucidation of the original sources responsible for such chemical anomalies.

7. Conclusions

Geochemical techniques are becoming more frequently applied for site prospection, mostly as part of intra-site studies and in combination with other techniques such as geophysical surveying and other geoarchaeological methods. Beyond statistical approaches used in multi-element data analysis, the integration of other methods (e.g. geophysical techniques, mineralogical analysis) are also providing good strategies to validate anomalies and determine their the natural or man-made origin.

The increasing use of geochemical surveying in multi-disciplinary studies may be partially explained by the developments in instrumentation that are improving the cost-effectiveness of geochemical analysis (e.g. pXRF and rapid microwaves for sample digestion). Despite these advances, the selection of the type of analysis and instrumentation should be carefully assessed against the research questions and the objectives of the investigation (e.g. detailed intra-site chemical characterisation, less specific preliminary chemical screening of an area). Furthermore, it is fundamental to maintain efforts in testing and to compare results between instruments in order to assess the capabilities of new technology and continue to improve field and laboratory geochemical methodologies.

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Mineralogical and Petrographic Techniques in Archaelogy

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Abstract: The interdisciplinary investigation of archaeological artefacts by means of mineralogical, petrographic and chemical techniques is nowadays a common practice. This study is an introduction to the mineralogical and petrographic techniques which are being employed to analyze archaeological samples. Three case studies from different archaeological sites are presented, in order to comprehend the significance of the mineralogical and petrographic techniques in archaeology. The first case study is the mineralogical and petrographic analysis of pottery samples from the Medieval Castle of Arta, Epirus by means of powder X-ray diffraction and stereo microscopy. The second case study is the mineralogical and petrographic analysis of mortar samples from Koule Castle in Heraklion, Crete. The historical mortars have been studied by optical microscopy, scanning electron microscopy (SEM) and X-ray diffraction (XRD). Furthermore, a thermogravimetric analysis and a grain size distribution were carried out. The third case study is a comparison between mineralogical (XRD) and chemical (XRF) analysis in archaeological samples from a Byzantine church in Koronissia, Arta, Epirus.

Keywords: *Mortars, Ceramics, XRD, SEM, DTA.*

1. Introduction

It has been widely recognized that analyzing the properties of the archaeological samples provides revealing information about the artefacts (Banning 2002). At the present day, a large variety of analytical techniques exist, providing information on the components, origin and structure of many archaeological samples (e.g. ceramics, mortars, slags, marbles etc.). While these methods may generate useful information on one or more aspects of the studied samples when applied stand-alone techniques, recent studies on archaeological survey strategies have underlined the importance of a multi – analytical approach in order to understand the complex history of archaeological samples (Annamalai *et al.* 2013; Miriello *et al.* 2011; Maravelaki 2005; Markopoulos *et al.* 2003). This study is an introduction to the petrographic and the mineralogical techniques employed in the analysis of a variety of archaeological samples. Three case studies are presented in order to enlighten the importance of these techniques.

2. Materials and methods

Many analytical techniques are being employed in archaeological samples, each with particular strengths and limitations. The established techniques are:

1. **Non-invasive techniques** such as photography; visual inspection; and touch and feel. Photography is useful for documentation of the stones pathology.
2. **Chemical techniques** such as XRF and wet chemical analysis. Chemical techniques are widely used for quantitative chemical analysis.
3. **Physical testing**. Physical properties of archaeological samples are determined. A mortar particle size analysis can define the nature of the constituents and evaluate the inert to binder material ratio. The sum of the 2mm – 0.125mm fractions is regarded as inert material, whereas the material finer than 0.125mm is regarded as the binder (Markopoulos *et al.* 1994). All reliable data indicates a complex interrelationship between grain size distribution, porosity, permeability, pore size distribution and durability.
4. **Mechanical testing**. Testing for compressive, tensile or flexural strength on prepared samples determines suitability for different applications.
5. **Dating technology** such as radiocarbon dating. This technique has recently been used to date mortars to an accuracy of about 30 years.
6. **Stereo microscopy.** The historical mortars are studied mainly by means of stereo microscopy. The stereo microscope is a low powered microscope which provides a stereoscopic view of the sample, commonly used to identify the texture and the coarse components of the mortar.
7. **Light microscopy - Optical microscope.** Initially, we are able to study the samples under an optical microscope. The optical microscope equipped with incident and transmitted tungsten light, with the potential for observation of samples in thick sections of 25μm thickness in cross-polar, allows determination of the minerals and their distribution in the matrix of the rock.
8. **Instrumental techniques used for the analyses of component materials such as Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). SEM** high resolution images of the surface of samples with magnification of up to 100,000x show mainly the structure of the sample. A combination of SEM/EDX allows elemental analysis of samples and is used for characterization of morphologies, textural and compositional interrelationships of the sample

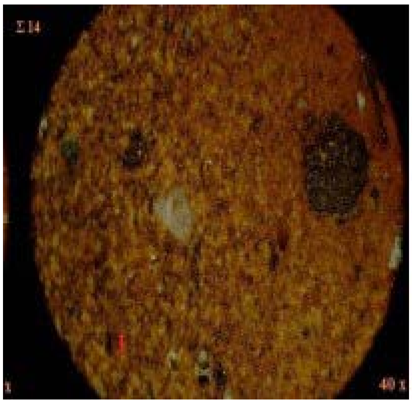



Figure 1 - Macroscopic and stereoscopic photographs of the potsherds.

components. **X-Ray Diffraction** allows analysis of crystalline materials and crystallized alteration products. This technique leads to the identification of all the mineral phases of the studied sample.

9. **Instrumental methods used for characterization of organic and inorganic materials.** These methods include Differential Thermal Analysis (DTA), Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry Analysis (DSC) and Infra-Red Spectroscopy (IR). **Thermal analyses** can be carried out on very small samples and can positively identify the composition of certain components. One of the most effective collaborative techniques is **TGA** in which the mass of the sample is recorded continuously while the temperature is increasing linearly up to 1200 ^{o}C. The components of the sample are determined through the interpretation of the produced thermal curves. **Infrared Spectroscopy** (IR) is the spectroscopy that deals with the infrared region of the electromagnetic spectrum of minerals which contain anions (e.g. (OH)-, SO_4, PO_4 etc.).

3. Case studies

In order to comprehend the significance of the mineralogical and petrographic techniques in archaeology, three cases studies are presented. The case studies concern the investigation of properties of archaeological samples from the archaeological sites of Arta, Epirus and Heraklion, Crete, by means of mineralogical and petrographic techniques. All of the analyses were conducted at the Laboratory of Petrology and Economic Geology of the School of Mineral Resources Engineering in Technical University of Crete.

3.1. Mineralogical and Petrographic analyses of pottery samples from the Medieval Castle of Arta, Epirus.

Chemical and mineralogical characterization of ceramics, is of extraordinary interest from an archaeological point of view, because it is one of the principal means to determine the origin, period and techniques used to manufacture the ceramics.

X-ray diffraction of the samples provides information about the mineralogical composition which corresponds to the firing temperatures of the original materials. The samples of Ottoman potsherds from the Medieval Castle of Arta shown in Fig. 1 were examined by means of powder X-ray diffraction (Andriopoulou *et al.* 2013). The mineral phases detected by XRD are quartz, diopside, anorthite, gehlenite, microcline and hematite. The results of the mineralogical analysis lead us to the following conclusions:

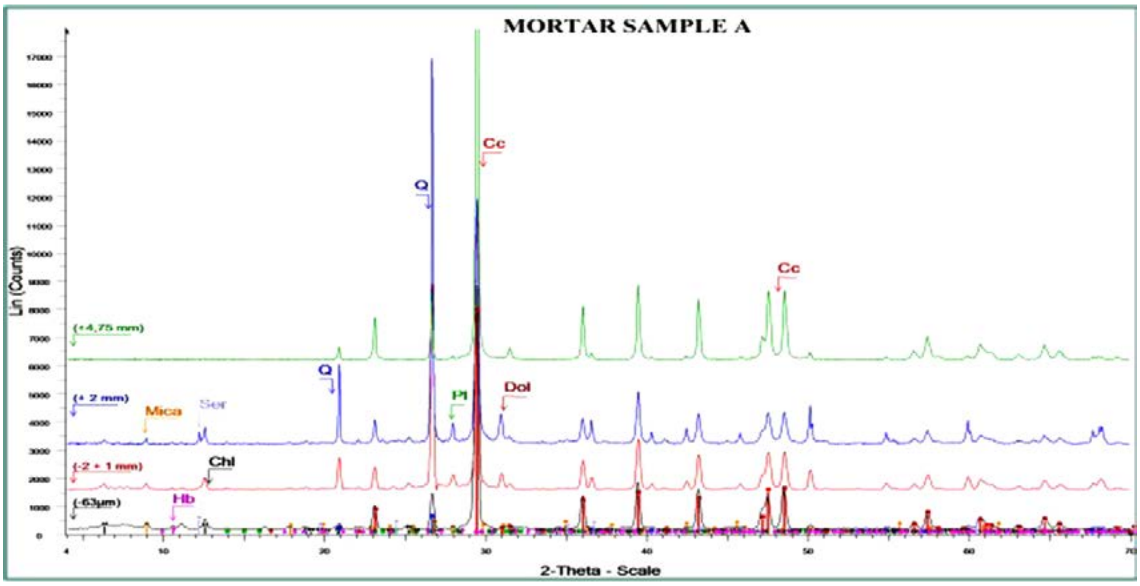
- Specific phases detected by XRD serve as firing temperature markers. In this group of ceramics, the lack of high temperature mineral phases and the presence of dolomite suggest low firing conditions. Dolomite starts decomposing at temperatures higher than 650^{o} C and is completely destroyed at 850^{o} C. So the samples were fired at temperatures between 650^{o} C and 800^{o} C.
- In addition, the presence of hematite suggests that the artefacts were manufactured by firing in an oxidizing atmosphere. Hematite starts composing between 700^{o} C-750^{o} C. Thus, the kiln method and not the open fire method is the most likely way of the firing procedure of those ceramics.

3.2. Mineralogical and Petrographic analyses of mortar samples from Koule Castle in Heraklion, Crete.

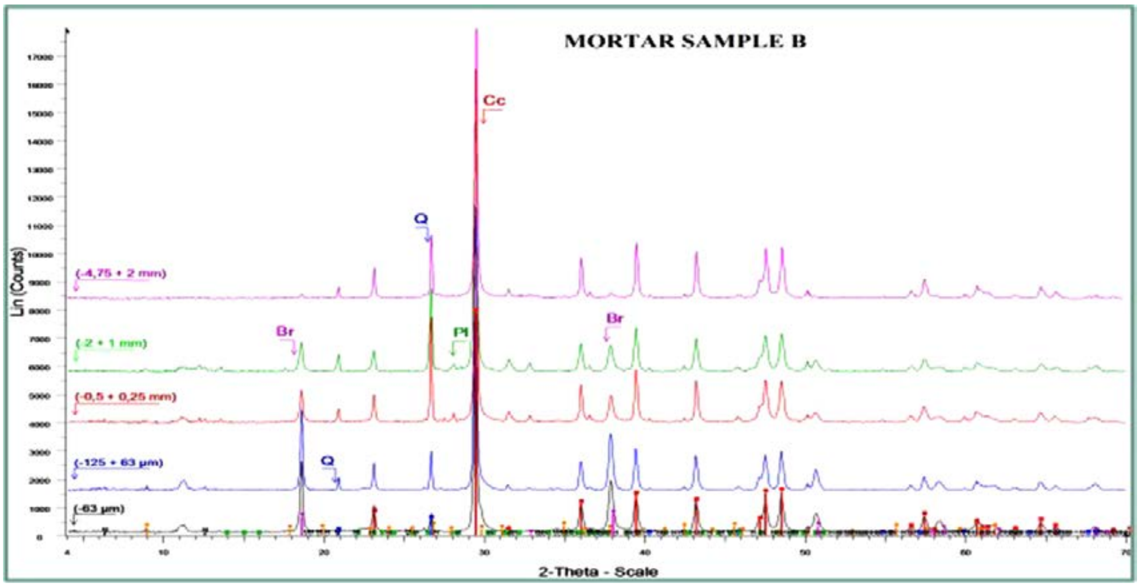
The choice of the mortar components varies according to historic period and regional habits. In the past, mostly local building materials were used. Mineralogical analysis in mortar samples is necessary in order to select the appropriate materials for future restoration works and to make conclusions about the origin of the natural materials of the mortars.

The aim of the following case study is to determine the physical and technical characteristics of the mortars of the Koule Castle in Heraklion, Crete, in order to use compatible materials in future restoration works (Karampatsou *et al.* 2013).

Three mortar samples were extracted by the 13th Municipality of Byzantine Antiquities from different parts



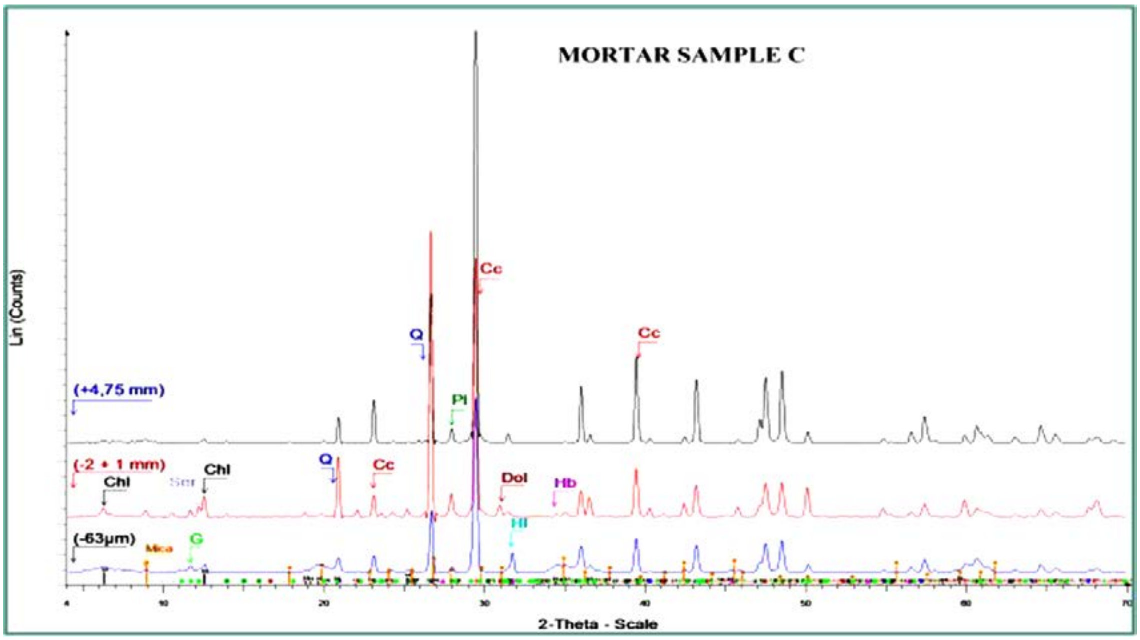
Cc: Calcite, Q: Quartz, Dol: Dolomite, Ser: Serpentine, Chl: Chlorite, Pl: Plagioclase, Hb: Hornblende
Figure 2 - XRD pattern of the binder and inert material of mortar sample A.



Br: Brucite
Figure 3 - XRD pattern of the binder and inert material of mortar sample B

of the monument. The mineralogical properties of the samples were investigated by means of XRD, SEM/EDS and thermal analysis. Also, a mortar particle size analysis was carried out by wet sieving. The mineralogical phases identified by means of XRD of the mortar samples are presented in the XRD patterns below (Figs. 2, 3 and 4).

Calcite and quartz were detected in the binder and in the inert material of the mortars. The quartz peaks in the XRD spectra are greater for the inert material while the calcite peaks are greater for the binder material of the mortars. Plagioclase, mica, chlorite and hornblende were detected in the binder and in the inert material of mortar samples A and C (Fig. 2, Fig. 4), while dolomite (Fig. 5) and serpentine exists only in the inert material of these mortars. Plagioclase, brucite and traces of mica and chlorite, were detected in the binder and in the inert material of mortar sample B. Consequently, the binder of the studied mortars consists mainly of calcite as a result of the lime carbonation. The inert material of the mortars is made of quartz and secondarily of calcite. The presence of brucite in sample B (Fig. 3) is probably associated with the



G: Gypsum Hl: Halite
Figure 4 - XRD pattern of the binder and inert material of mortar sample C

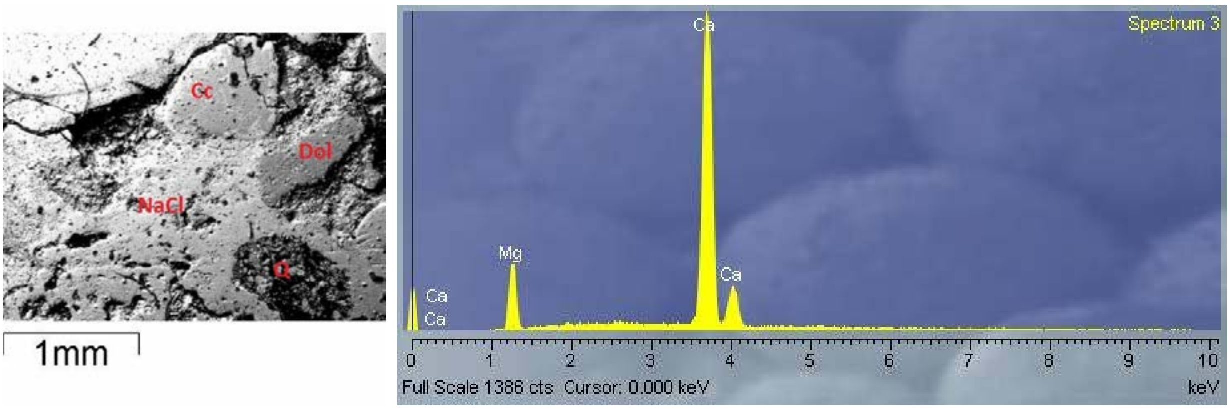


Figure 5 - Backscattering image of the mortar A and EDS analysis of dolomite.

absence of adequate carbon dioxide in the interior parts of the castle. Furthermore, the presence of gypsum in sample C (Fig.4) is attributed to the process of mortar deterioration by sulfating. The sulfates, coming from the marine environment, were deposited on the surface and reacted with $CaCO_3$ present in the mortar, according to Eqs. 1a and 1b. The mechanism of sulfating has not resulted in the formation of ettringite because of the absence of 'calcium aluminate hydrate' ($3CaO\ Al_2O_36H_2O$) (Sabbioni *et al.* 2001).

$$\mathbf{CaCO_3 + SO_2 + 0.5\ H_2O \rightarrow CaSO_3{\bullet}0.5H_2O + CO_2} \quad (1a)$$

$$\mathbf{2CaSO_3{\bullet}0.5\ H_2O + O_2 + 3H_2O \rightarrow 2CaSO_4{\bullet}2H_2O} \quad (1b)$$

Thermogravimetric (TG) analysis is necessary to establish the characteristics of the historical mortars. TG analysis indicated a notable effect of calcite decomposition at about 900° C, as a result of the carbonation of the original lime binder (Figs. 6, 7 and 8). Chlorite and mica decomposition took place at 500° C – 600° C in the samples A and C (Fig 6, 7).

A greater loss of mass occurred between 20° C and 200° C in sample C (fig. 7), which indicates the decomposition of the content gypsum.

For the TG curve obtained of sample B (fig.8), an endothermic peak was observed at about 400° C which corresponds to the dissociation of brucite. The losses of mass of the three mortars between 20° C and 200° C corresponded to the loss of water and organic elements.

According to the histogram of Fig. 9, sample B presents a normal granulometric distribution. The inert to binder material ratio was determined 1.4:1, by volume. Sample

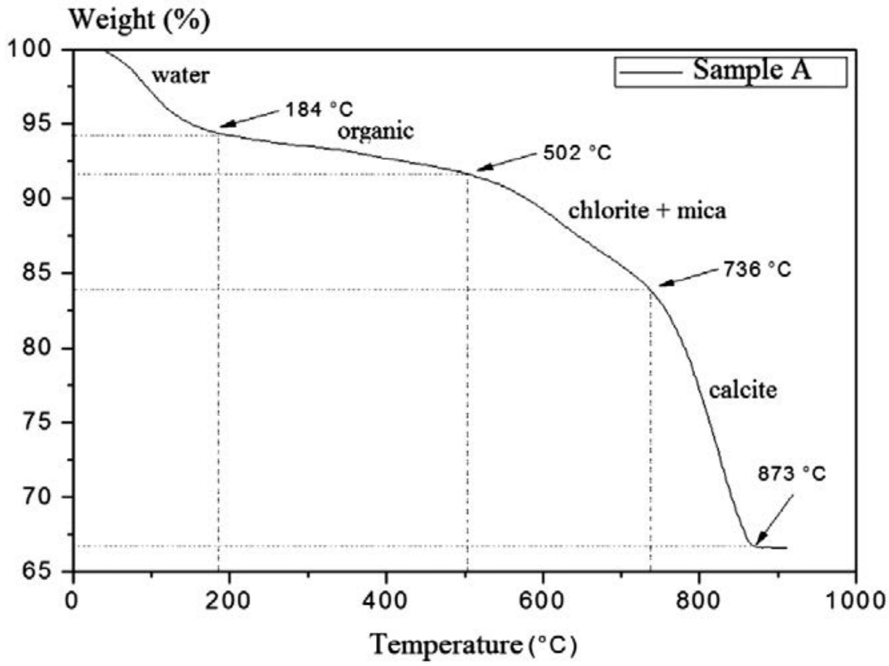


Figure 6 - Thermal curve of sample A.

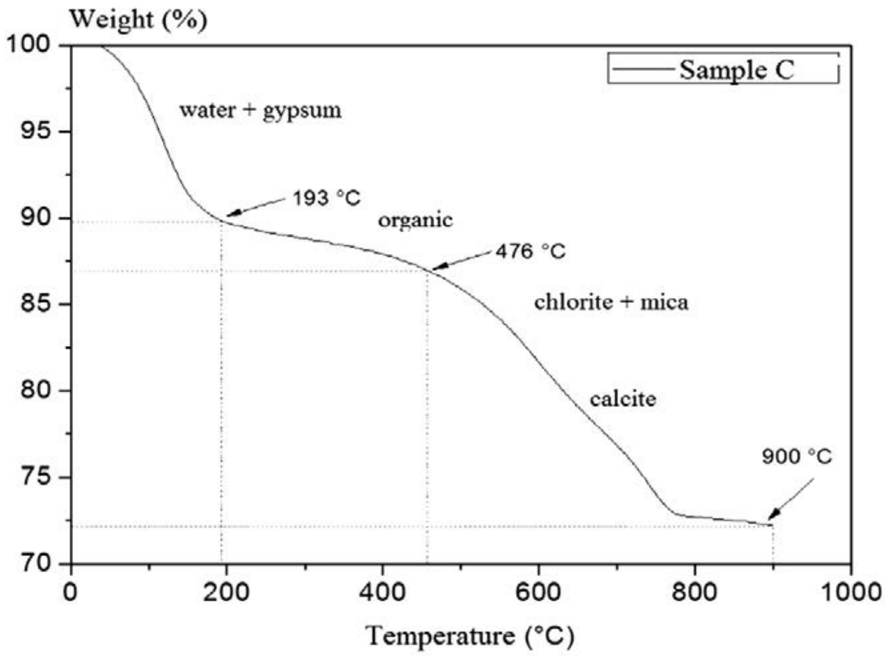


Figure 7 - Thermal curve of sample C.

A is the finest of the three studied mortars, due to the fact that more than 50% of this material is concentrated in the base sieve. The inert to binder material ratio for the sample A was determined 0.96:1 by volume. Sample C contains much more aggregates than the other mortar samples. The inert to binder material ratio for the sample C was determined 2.6:1 by volume.

The following conclusions can be drawn from the study:

- The inert material of the mortars consists mainly of quartz and secondarily of calcite. The inert to binder material was determined by volume from 0.96:1 to 2.6:1. Their examination revealed that beach sand has been used as inert material.

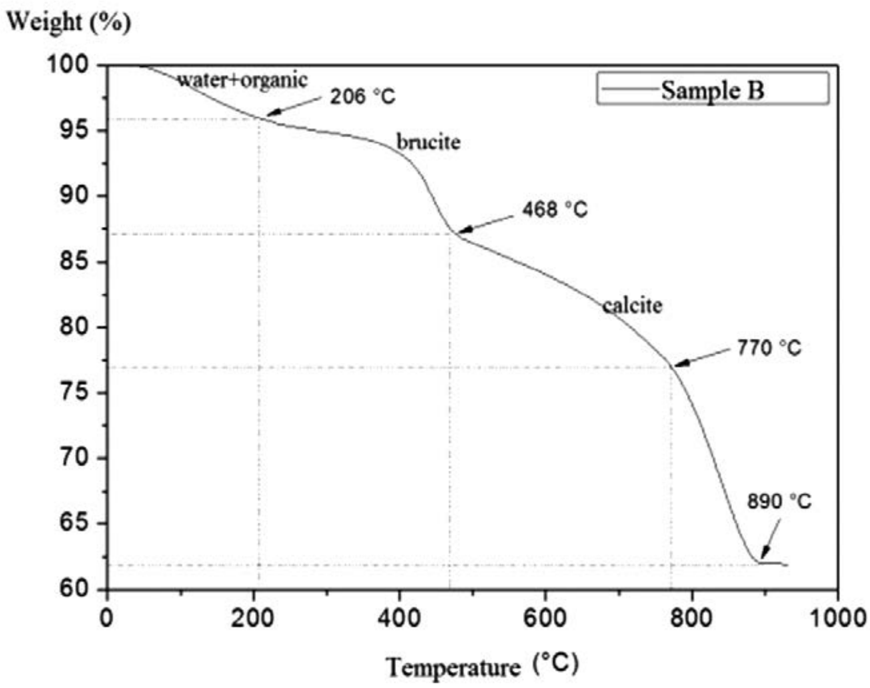


FIGURE 8 - THERMAL CURVE OF SAMPLE B

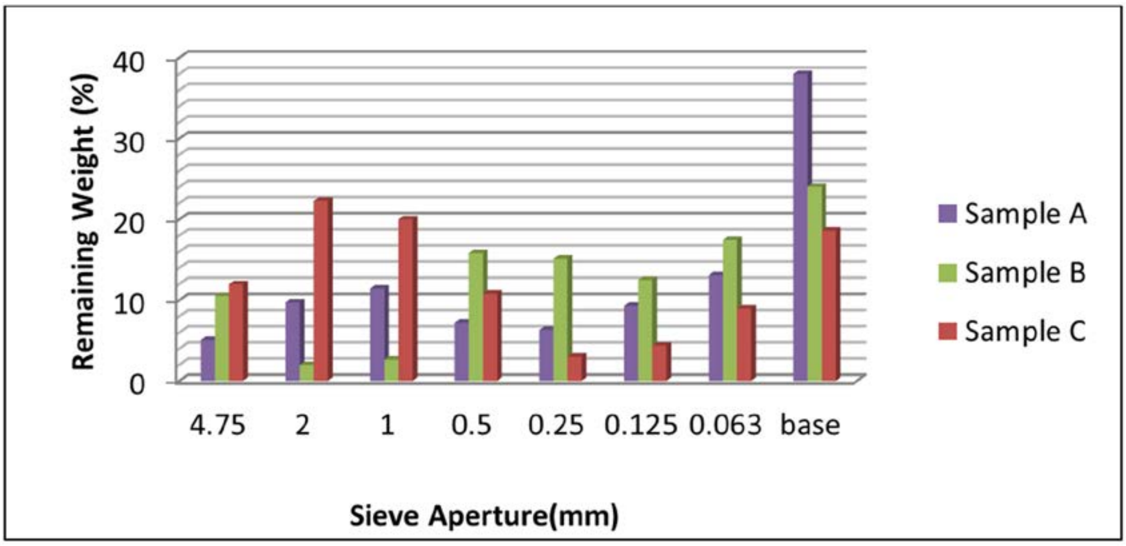


FIGURE 9 - WEIGHT (%) OF THE SAMPLES WHICH REMAINS IN EVERY SIEVE APERTURE.

- The presence of brucite in the inert material of mortar B, as well as the presence of dolomite in the inert material of mortar A and mortar C, indicates the use of dolomites or Mg-rich limestones as aggregates. Due to the absence of adequate carbon dioxide, brucite was never converted to magnesium carbonate.
- The binder of the studied mortars consists mainly of calcite as a result of the lime carbonation. The lime used as binder of mortar A and mortar C came from bioclastic limestones, while the presence of brucite in the inert material of mortar B indicates that the lime used as binder of this mortar came from dolomites or Mg-rich limestones.
- The mortars to be used in future restoration works should consist of compatible materials to the old mortars. The inert materials of the mortars should consist of quartz (70%) and secondarily of calcite (30%) and the binder of hydraulic lime NHL 3.5, in an inert material/ binder ratio of 2,5:1, in order to protect the mortars against marine corrosion.

Table 1 Chemical and mineralogical analysis of the mortar sample n2.

Sample N1α										
Chemical Analysis	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	K_2O	Na_2O	MnO	L.O.I.	Total
Binder	47.39	3.85	0.41	1.35	2.84	0.09	traces	0.02	42.88	98.83
Aggregate	47.05	4.43	0.47	1.36	2.90	0.30	0.20	0.01	43.01	99.73
The main amount of CaO belongs to Calcite, Aragonite, Dolomite, MgO to Dolomite, K_2O to Potassium Feldspar and Na_2O to Albite										
Mineralogical analysis of the Mortar										
Aggregate	**Calcite($CaCO_3$), Aragonite($CaCO_3$), Dolomite ($CaMg(CO_3)_2$, Quartz(SiO_2), Potassium Feldspar($KAlSi_3O_8$), Albite($NaAlSi_3O_8$)**									

Figure 10 - Photograph of the N2 mortar sample through a stereo microscope.

3.3. Mineralogical analysis in comparison to chemical analysis in archaeological samples from a Byzantine church in Koronissia, Arta, Epirus.

Analysis of archaeological samples should not be limited to chemical tests. The investigation of the samples by one or more collaborative instrumental techniques such as DTA, XRD, SEM and microscopy is necessary in order to obtain reliable results.The present case study shows the importance of both chemical and mineralogical analysis in archaeological samples.The chemical and mineralogical analysis of the mortar sample N2 of a Byzantine church in Koronissia, Arta is presented in table 1 (Triantafyllou *et al.* 2013).

The mineralogical analysis of the mortar indicates that the containing minerals, among others, are calcite and aragonite. Calcite, aragonite and dolomite are carbonate minerals so they are the source of the CaO. Calcite and Aragonite have the same chemical formula but different crystal shapes. Aragonite is formed by biological and physical processes, including precipitation from marine and freshwater environments. The presence of aragonite in the mortar explains the fact that the aggregates consist mainly of marine shells as it is shown in fig. 10, which was confirmed by both mineralogical and chemical techniques.

4. Conclusions

The results of the present study demonstrate that the investigation of the archaeological samples requires a multidisciplinary approach. Suitable combination of the mineralogical and petrographic techniques, help us to predict and/or confirm data such as the nature of the raw materials used in the manufacture of the ancient ceramics, the possible origin and the production conditions and firing techniques. This provides very important information for dating and restoration work. Furthermore, the determination of the physical and technical characteristics of the historical building materials by means of petrographic and mineralogical techniques help us to use compatible materials in future restoration works. Consequently, a multi – analytical approach including petrographic, mineralogical and chemical investigations is of great significance, in order to obtain reliable data and to broaden the horizons of the archaeological research.

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Provenance of Ceramics: Methods and Practices

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Abstract: Archaeology uses a variety of methods and tools to reconstruct the cultural past. Based on the excavation finds, concerted efforts are made to shed light on the structure of the ancient societies and their exchanges within sites or regions. Determination of the provenance of pottery found in archaeological excavations plays a significant role towards this direction. The study of ceramics seem ideal for provenance investigations due to their use in numerous activities of daily life and resistance to weathering. The archaeometric analysis of the ceramic materials can complement the archaeologists' observations of the local or imported character of the pottery and help to evaluate both practical and social aspects of ceramic production.

The above is mainly accomplished through the synergy of archaeology and various fields of natural sciences, which allow the characterisation of ceramics by means of advanced analytical methods. Although, in most cases, the approach adopted during provenance studies of ceramics involves only one type of analysis (chemical, mineralogical, morphological, physicochemical), an 'integrated' approach is favoured recently; this combines different analytical techniques thus enabling the extraction of a multitude of information minimizing the uncertainty towards the identification of their origin.

The present work provides an overview of the methodology followed during the provenance studies of ceramics and the main approaches usually adopted. Indicative published works are also presented as representatives of the state-of-the-art in the field.

Keywords: Provenance; Ceramics; Chemical analysis; Mineralogical analysis; Multivariate statistics

1. Introduction

Archaeology aims towards the reconstruction of the cultural past and the understanding of the lifeways of the people through the material remains of past societies. The re-creation of the material culture reveals the social, political, economic and cultural structure and evolution of ancient societies as well as their interactions within sites or regions.

A significant contribution to this direction is the determination of **provenance** of ceramic artifacts, usually pottery, found in archaeological excavations, namely seeking the answer to the question of where the pottery was produced. Ceramics represent a sophisticated merge of separate domains of human knowledge and experience. Thus, the identification of a pottery production location is vital, since it illuminates various aspects of the civilization that produced them, such as their technological level, cultural contacts and economic interactions between communities in a broader area (Rice 1987; Tite 2008).

Ceramics are a simple and convenient means for this purpose due to their abundance in excavation sites, their resistance to weathering and erosion, tolerance through time, easy transportability and many functions, which allow the evaluation of their initial state and the extraction of valuable information from their composition (e.g. Padeletti and Fermo 2010). The starting point of provenance studies is that there are specific, repeated and definable dependent relationships between raw materials and the finished products derived from them (Buko 1984). These studies are also based on the assumption that pottery from specific locations (sources) exhibit unique features (such as composition), distinct from pottery produced elsewhere. Also they consider that feature variations between sources should be greater than within sources (Rice, 1987).

Based on these assumptions, in order to assign a production location to certain ceramic artifacts of unknown origin or to compare objects of possibly common origin (from an archaeological perspective), one should first characterize them, identify their 'fingerprint' (stylistic, chemical, physical, structural) and then compare the various fingerprints using advanced statistical techniques to search for similarities and differences. This procedure allows to group together pottery with similar features and to distinguish groups of ceramics of different properties (Rice, 1987; Sterba *et al.*, 2009; Tite, 2008).

In the recent years, archaeology interacts increasingly with natural sciences and informatics to reduce the subjective element. The characterisation of archaeological ceramics and their classification into compositional groups, which comprise the fundamental basis for the interpretation of provenance, is mainly accomplished through the synergy of archaeology and several fields of applied sciences, such as chemistry, physics, petrography, geology, mathematics and informatics, individually or jointly. Using analytical methods several measurements can be conducted to determine the chemical composition, physicochemical properties and structure of the materials along with the morphology and the physicochemical parameters of the excavation environment. Although each one of the above can individually be used in provenance studies, an 'integrated approach' is more favoured, since results are considered to be much more trustworthy when two or more of the above methods are applied to provide different information stored in the pottery (Mommsen 2004).

The scope of the present work is to provide an overview of the past and recent trends in provenance studies of ceramics and to assess the most widely employed analytical methods for this purpose.

2. Methodology and Scope

Whilst the general methodology adopted in provenance studies of ceramics is widely applied, there are variations relating to the specific ways to characterise the ceramics. More specifically, a small fragment of a ceramic sherd is subjected to one or more laboratory analytical methods (described later) towards its qualitative and quantitative characterisation and the identification of its unique fingerprint. This will allow its discrimination among others of different origin or its grouping with those exhibiting similar features. Following, multivariate statistics are used to determine similarities and differences between the specimens, which will ultimately lead to their classifications into distinctive groups according to their provenance.

The most commonly used types of such analysis are the Principal Component Analysis (PCA) and the Hierarchical Cluster Analysis (HCA). PCA involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. On the other hand, HCA refers to a group of techniques of multivariate analysis whose objective is to select and group together homogeneous data. The result of such analysis is the grouping of a set of objects in such a way that objects in the same group are more similar to each other than to those in other groups. An example of a PCA and a HCA towards the identification of the origin of ceramic objects is illustrated in Fig. 1.

The final conclusions of the study are usually reached with the juxtaposition of the laboratory/statistical and the archaeological data the latter been primarily based on stylistic features (observation of style, clay texture, color, decoration etc.)

The provenance studies of ceramic artifacts provide information on the origin and choice of the raw materials used for their manufacture, while they also allow the documentation of the studied objects, such as their physicochemical, mechanical and/or other properties. In this respect, provenance studies can have various scopes and the used methodology may involve additional steps or follow specific constrains. More specifically, provenance studies can aim at:

The identification of the provenance of ceramic artifacts of unknown origin

In this case, the archaeological observation alone is not adequate to serve as a representative guide for the provenance study. As a result, the use of *reference* samples, namely samples of known provenance (ideally ceramics found at a workshop) is necessary. To this direction, as a starting point of the study, it would be very helpful to have an adequate number of reference samples from the excavation site (or the near area) available, which would be indicative of the local pottery production. Such a comparison of the under-study ceramics with samples from the excavation site would provide valuable information towards the origin of the ceramics. If the comparison is not satisfactory, then relevant material (reference samples) from candidate sites of the wider area or from areas that archaeologists suspect that commercial transactions existed should be further employed, until reasonable similarities are found that would shed light to the origin of the samples.

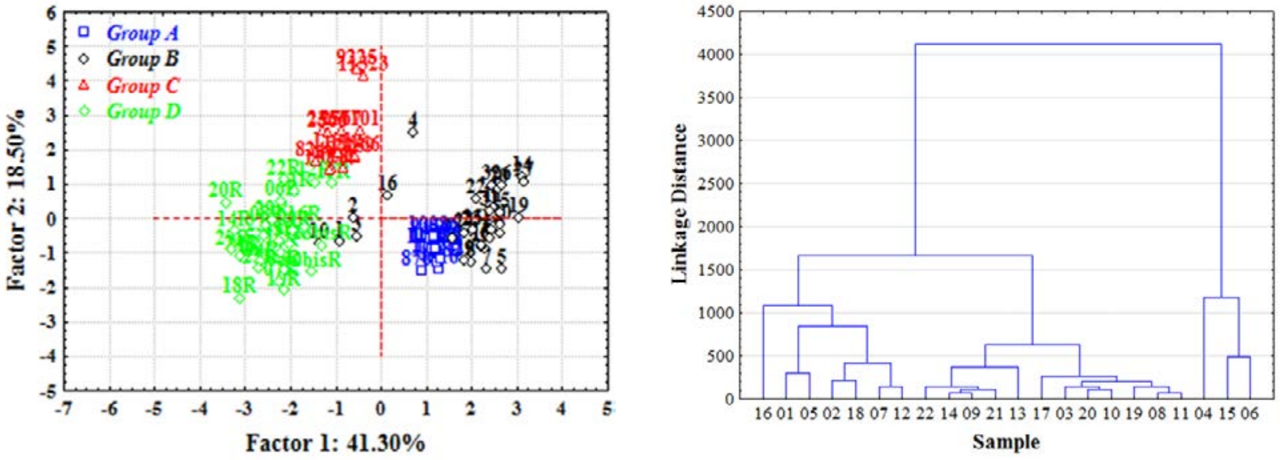
The classification of ceramics of the same region

In several cases, archaeologists seek to identify the know-how and craftsmanship of certain production workshops in the same region, thus discriminating them (Mommsen 2001; 2004). In addition, it may be desired to classify ceramics of different use or type (bowls, amphorae, vases, figurines etc). For such a study, an adequate number of samples of each potential group are mandatory in order to assure the credibility of the results. The resulting grouping of the under-study ceramics could indicate the existence of more than one workshop in the same region and ultimately shed light on the technology of ceramic production for the various types. In this case, the use of reference samples is not mandatory, since the actual scope of the study is to test the homogeneity of pre-defined groups rather than their provenance.

In addition to the above described goals, provenance studies may also serve two more scopes of more special interest:

Confirming the provenance of ceramic samples with 'suspected' origin

A typical and often repeated in various excavations, archaeological problem is the origination of pottery which appears to have many stylistic similarities with one of the major and 'popular' ceramic categories (e.g. the Attics or the Corinthian in ancient Greece) with historically known production workshops. Each of these categories of ceramics has always a distinctive style and clay quality, rendering it a distinguishable and easily identifiable group of pottery.



A B

Figure 1. Examples of statistical processing of the chemical data from the clay bodies towards the identification of the origin of ceramic objects: a) PCA and b) dendrogram resulting from HCA

However, during excavations in areas away from the known workshop establishments (e.g. Attica, Corinth etc.) archaeologists come across ceramic objects whose appearance is quite similar to those of the original items. These finds can have characteristics that are either indistinguishable from those of the genuine articles and in this case are usually classified as 'imports' or have some characteristics that create doubts to the archaeologists as to their origin and constitute another category known as the 'look-like', whose provenance cannot be determined by visual observation alone.

An additional related category is the 'imitations'. As implied by the name of the category, this type of ceramics has many similarities with the 'genuine' articles, but archaeologists are fairly confident that they are 'local' productions that simply imitate the visual characteristics of the respective known category.

In this case, the provenance study becomes in practice an authenticity study, since scientists are assigned to confirm or dismiss the archaeologists' doubts about the authenticity of such ceramic finds and are not particularly interested in identifying their true origin. Of course, in such a study the use of a reference group of 'genuine' ceramics is a prerequisite for the successful provenance study.

Building archaeological databanks

Besides answering individual questions of archaeologists regarding the classification/provenance of specific ceramic finds, provenance studies also contribute to the creation of large archaeological reference datasets. Provenance studies allow the complete documentation of the under-study artifacts combining archaeological and scientific data along with their identified provenance. As a result, new reference groups of various ceramics of known origin (and physicochemical properties) are created, while existent ones expand with new samples, leading to the building of an incessantly growing reference database. Such a database is of major importance since it provides scientists with more knowledge and facilitates future provenance studies, assuring at the same time their credibility. In many cases, match-ups can be made between profiles of samples of unknown origin taken from an excavation, and those of known origin previously determined and stored in a data bank, thereby documenting the location of origin and the flow of ancient trade (Harbottle *et al.* 1986).

Regardless the scope and/or the analytical methods employed, several important factors should be taken into account when conducting a provenance study (Mommsen 2004; Tykot 2004):

- Samples taken should not have been subjected to any treatment after their excavation.
- The samples should be representative of the whole ceramic artifact. For heterogeneous materials it is important to take enough mass/volume for the measurements.
- Reference standards should be similar in composition to the samples of interest, in order to ensure consistent results on a single instrument and to allow comparison with results obtained in other laboratories.
- When determining the chemical composition of bulk samples, many elemental concentrations should be measured (at least about 20), and the more the better. In particular, the trace elemental concentrations, rather than those of the major elements (e.g., Al, Ca and Si), are recognized to be vital for provenance.
- Before applying statistical processing of the results, individual elemental error margins from the measurement, which are not the same for each element and which depend on the analysis method, should be taken into consideration.

- Efforts should be made to decrease all error margins during the measurements, by measuring multiple specimens of the same sample, measuring only the region of interest in the sample (e.g. only the clay avoiding any inclusions and/or contaminants) etc.
- Evaluation of the geological background of the excavation site and all relevant geological sources should be known. Sufficient samples of geological source material must be available to establish the variability within a single source (>15).
- An adequate number of reference samples should be employed when needed in order to minimize the statistical error.

3. Main approaches, past research and state-of-the-art

As previously mentioned, provenance studies of ceramics are based on the characterization of the material of the finds and their comparison by means of statistics. In this respect, the characterization begins with macroscopic visual observations of any stylistic properties and easily employed measurements of various physical properties of the clay, such as color (e.g. Munsell color system), density and hardness. However, the above cannot be objectively conclusive of the origin of the artifacts. A thorough analysis of the clay using analytical methods is imperative to shed light on the raw materials used for the manufacturing of the ceramics.

Provenance studies of ceramics have been conducted for many decades and they were mainly accomplished with two approaches: **chemical analyses** of the elemental bulk concentrations and **mineralogical investigations**.

Chemical analyses are oriented towards the identification of the chemical elements constituting the ceramic fabric, present in major or minor or trace amounts, which could provide a unique chemical profile allowing ceramics made from the same raw materials to group together. Although the complete chemical composition of the clay is significant, however many works support that the concentrations of the trace elements and, more specifically, the rare earth elements are extremely valuable and can substantially contribute to the characterisation of ceramics from a given region. At the same time they constitute good discriminators among the chemical profiles typical of different areas (Tsolakidou and Kilikoglou 2002).

The most widely employed analytical methods in provenance studies which rely on the chemical analysis of the clay are the neutron activation analysis (NAA) (e.g. Harbottle 1970; Vitali and Franklin 1986; Balla *et al.* 1990; Mommsen *et al.* 1992; Taylor and Robinson 1996; Munita *et al.* 2003; Dias and Prudêncio 2008), the X-ray fluorescence spectroscopy (XRF, EDXRF, WDXRF, μ-XRF) (e.g. LaBrecque 1988; Punyadeera 1997; Morgenstein and Redmount 2005; Papageorgiou and Liritzis 2007; Sakalis *et al.* 2013), the atomic absorption spectrometry (AAS) (e.g. Rotunno 1997), the electron microprobe analysis (EMPA) (e.g. Kamilli and Lamberg-Karlovsky 1979; Freestone *et al.* 1985; Mallory-Greenough *et al.* 1998; Cultrone *et al.* 2001; Abbott *et al.* 2008; Tschegg *et al.* 2009; Ionescu *et al.* 2011), the proton-induced X-ray emission (PIXE) (e.g. Pio *et al.* 1996; Swann and Nelson 2000; Roumie *et al.* 2006), the scanning electron microscopy (SEM) combined with energy dispersive spectroscopy (EDS) and/or wavelength dispersive spectroscopy (WDS) (e.g. Spataro 2011; Abbott *et al.* 2012; Belfiore *et al.* 2014), the inductively coupled plasma-atomic emission spectroscopy (ICP–AES) and inductively coupled plasma-mass spectrometry (ICP–MS) (Bruno *et al.* 2000; Fermo *et al.* 2004; Li *et al.* 2005).

In many cases though, two (or more) chemical analysis methods may be employed in the same study in order to increase the validation of the results. Since accuracy and sensitivity of the various methods varies and in some cases they are element dependent, one method may be used for the determination of the major elements, while a second one may be employed for the trace elements (e.g. Mirti *et al.* 1990; Sanchez Ramos *et al.* 2002).

On the other hand, the main objective in *mineralogical studies* is the speciation of the chemical components in the ceramic fabric and assessment of the potential origin of the raw materials. Besides clay, potters often used temper in order to modify the properties of the clay and to achieve the desired quality. Consequently, the geological information obtained from these components can provide an insight into how potters selected and used local and non-local resources.

The mineralogical analysis of ceramics may be accomplished using thin-section petrographic analysis by means of a petrographic microscope (e.g. Quinn and Day 2007; Gabriele and Boschian 2009; Whitbread and Mari 2014), X-ray diffraction (XRD) (e.g. Pavía 2006; Vecstaudža *et al.* 2013) and scanning electron microscopy (SEM) with or without electron backscatter diffraction analysis (EBSD) (e.g. Freestone and Middleton 1987; Knappett *et al.* 2011; Peruzzo *et al.* 2011).

Each of these approaches provides different kinds of data which complement each other for the ceramics characterisation (Rice 1987; Wilson 1978). The chemical composition of a ceramic can provide important information on its origin, but chemical data alone do not identify fully the geological resources (raw materials) used. Mineralogical composition, on the other hand, is directly related to the geological characteristics of the locale, but petrographical analysis alone cannot account for possible phase transitions of the minerals due to the firing of the ceramics.

Unfortunately, the majority of the provenance studies published so far in the literature have been accomplished employing only one of the two aforementioned approaches for the characterization of the ceramics, with those involving the determination of chemical composition outnumbering the studies using a mineralogical approach (Tite 2008).

These approaches are usually applied separately, and therefore, depending on the personal beliefs of the archaeologist conducting the research, either chemical or petrographic analysis is given primary distinguishing significance (Buko 1984). However, as Mommsen (2001, 2004) claims, such a unilateral approach in provenance studies can lead to results with high uncertainty, while presently there is a general tendency to question the results of studies employing only one of the above approaches (Mommsen 2004).

Instead, voices from the scientific community which support the idea that mineralogy and chemistry complement each other in ceramic provenance investigations are constantly increasing, since the two fields look at different records of information stored in the ceramics. As a result, the **state-of-the-art** in the provenance studies of ceramics dictates the adoption of an 'integrated' approach combining mineralogy and chemistry in the effort to make secure and geographically specific inferences about sources (e.g. Mommsen 2004; Neff 2012). Several works using the integrated approach can be found in the recent literature (e.g. Buxeda i Garrigos *et al.* 2001; Iordanidis *et al.* 2009; Ownby *et al.* 2014).

Microstructure and other physicochemical properties can provide also additional information regarding the manufacturing techniques, the firing conditions and the technological level of ceramics production in a given time and area (e.g. Mirti *et al.* 1996; Moropoulou *et al.* 1995; Tite 2008; Tite and Maniatis 1975). Therefore, a methodology which combines the mineralogical and chemical approach together with additional measurements of physicochemical properties (e.g. microstructure, porosity, hardness, color) that reflect manufacturing parameters, would contribute even more substantially to the creation of a complete picture of the studied ceramics. For this reason, chemical analysis and mineralogical study combined with physicochemical data have the prospective to offer the optimal characterization of ceramics (Rice 1987), which, aided by advanced specially tailored statistical methods, will provide an accurate and distinct classification of ceramics leading to satisfactory, secure conclusions on its origin.

4. Analytical methods and instrumentation

The principles of the common chemical and mineralogical analysis of ceramics in provenance studies are described next. Table 1 summarizes these methods and provides details regarding the analyzed sample (e.g. size/amount, physical state) and other important features (e.g. sensitivity, accuracy), which could be used as a guide for the selection of the most appropriate method in each occasion.

It should be noted that all methods are using only a small portion of the object for the preparation of the samples and in this sense they can be considered as non-destructive. The characterisation of the methods as destructive or non-destructive refers to the sample and not to the archaeological object itself. Thus a destructive method of analysis affects the sample used (the extracted mass) in a way that deems the sample unusable for the repetition of the original or for further measurements while a non-destructive method allows the sample to be used in the future for any type of measurements.

In addition the various methods can be classified according to their capacity to analyze the surface only or the bulk or both (in some cases) of an object.

4.1 Chemical analysis

Neutron activation analysis

In neutron activation analysis, the sample is irradiated with neutrons usually in a nuclear reactor. As a result the elements form radioactive isotopes which de-excite (or decay) emitting one or more characteristic γ-rays at a rate that is directly related to the unique half-life of the isotope. The chemical elements present in the sample can be identified from their characteristic γ-ray energy in the γ-ray spectrum, while their concentration is directly connected to the number of the detected characteristic γ-rays. This method is destructive and allows the determination of the complete chemical composition at once with high precision and accuracy. Due to the high penetration of neutrons it is classified as 'bulk analysis'. However, its major drawbacks are the need to have access to a suitable nuclear reactor for sample irradiation, its dependence on the product half-life, low sensitivity for light elements (e.g. Garcia-Heras *et al.* 2001).

X-ray fluorescence spectroscopy

When a specimen is irradiated with X-rays, ionization of its constituent atoms may take place leading to the emission of secondary X-rays, which are characteristic of the different chemical elements present in the sample. As a result, the acquired spectrum of the fluorescent X-rays makes it possible to determine both qualitatively and semi-quantitatively the elements present (Hall 1960). The most important advantages of this method are its multi-elemental (direct determination of the complete chemical profile of the ceramic) and non-destructive character, while it can be applied for surface and/or bulk analysis. However, special attention should be paid in removing few μm of the external layers of the ceramic before the measurement to ensure that no contaminants contribute to the resulting X-ray spectrum.

Atomic absorption spectrometry

In this method the atoms of the sample are promoted to higher orbitals (excited state) for a short time by absorbing radiation from a light source of a certain wavelength, which is specific to a particular electron transition in a particular element. As the amount of energy passed through the atomized sample is known, by measuring the quantity of light after the sample it is possible to determine the

Table 1. Instrumental methods of elemental and mineralogical analysis of ceramics.

Method	Type of analysis	Characterization	Object of analysis	Analyte	Sample size	Sample pretreatment	Sensitivity	Accuracy	Speed	Cost
NAA	chemical	Multi-element, destructive, bulk analysis	75 elements	solid, powder	50-100 mg or the whole object	pulverization/ pellet or none	major, minor and trace elements (few ppb)	high (1%-5%)	high	very high
XRF	chemical	Multi-element, non-destructive, surface or bulk analysis	80 elements (Z>12)	solid, powder	100 mg -2 g or the whole object	pulverization/ pellet or none	major, minor and trace elements (>50 ppm)	semi-quantitative -high (2%-5%)	high	low/ average
AAS	chemical	Single-element, destructive, bulk analysis	70 elements (except rare earth elements or nonmetals)	solution	10 mg-1 g	Pulverization, acidic digestion	major, minor and trace elements (few ppb)	high (2%)	slow	average (per element)
EMPA	chemical	Multi-element, non-destructive, surface analysis	elements with Z>12	solid	few g	thin section	major, minor and trace elements (>100 ppm)	good	high	high
PIXE	chemical	non-destructive, surface analysis	elements with Z>11	solid	few mg	pulverization/ pellet or none	major, minor and trace elements	high (5%)	high	high
SEM	chemical/ mineralogical	non-destructive, surface analysis	elements with Z>5 and/or crystals	solid	whole object (up to 10x10x20 cm) or part of it	none or carbon coating	major, minor and trace elements (>50 ppm)	good	high	high
(ICP–AES) (ICP–MS)	chemical	Multi-element, destructive, bulk analysis	70 elements, >130 isotopes with the ICP-MS	solution	5-100 mg	pulverization, acidic digestion	major, minor and trace elements (>50 ppt)	high (1%-3%)	high	high
Thin-section petrographic analysis	mineralogical	non-destructive, bulk analysis	crystals	solid	few g	thin section	-	non-quantitative	slow	low
XRD	mineralogical	non-destructive, surface or bulk analysis	crystals	powder	2-20 mg	pulverization	major and minor elements (>1%)	semi-quantitative	average	average

NAA: Neutron activation analysis
AAS: Atomic absorption spectrometry
PIXE: Proton-induced X-ray emission
ICP–AES/ICP–MS: Inductively coupled plasma-atomic emission spectroscopy -mass spectrometry
XRF: X-ray fluorescence spectroscopy
EMPA: Electron microprobe analysis
SEM: Scanning electron microscope
XRD: X-ray diffraction

concentration of the element being measured. The method is suitable for bulk analysis and its major advantage is the high sensitivity which allows the determination of trace elements with high accuracy. On the other hand, it is a destructive method and it requires a liquid feed, rendering the acidic digestion of the ceramic requisite. In addition, the chemical profile (qualitatively) of the ceramic must be known beforehand to be used as a guide, since the researcher decides which element will be measured. Finally, multiple reference solutions and calibrations are needed, since only one element can be measured in each run.

Electron microprobe analysis

In the electron microprobe analysis the sample's surface is bombarded with a beam of high-energy electrons causing the emission of secondary X-rays. The analysis of the detected wavelengths and the relative intensities of the X-rays created at each wavelength are indicative of the element present and its concentration respectively (Birks 1971). It is a non-destructive, surface analysis method and its advantage for ceramic studies is its potential of selecting tiny areas of a sherd's cross-section for analysis, avoiding small-sized temper particles. As a result, chemical composition can be determined independently for the clay and the temper fractions (Freestone 1982). Among the shortcomings of the method are the inability to provide structural information, the difficult identification of mineral components of the matrix and the incapacity to give data on the internal structure of a crystalline substance (Ionescu *et al.* 2011).

Proton-induced X-ray emission

The proton-induced X-ray emission belongs to the analytical techniques of X-ray emission spectroscopy along with the X-ray fluorescence. This method is similar in its fundamental approach to XRF; when an electron is ejected from an inner shell of an atom, another electron from a higher shell drops into this lower shell to fill the void left behind. As a result, an X-ray photon with energy equal to the energy difference between the two shells is emitted. The major difference of the proton-induced X-ray emission from the XRF method lies in the mode of excitation. More specifically, the inner-shell electrons are ejected when protons or other charged particles, like He-ions, are made to impact the sample. As in the XRF, the energies and the number of the emitted X-rays are directly linked to the chemical elements present in the ceramic and their concentration respectively. Proton-induced X-ray emission is a multi-element, non-destructive, surface analysis technique with higher precision than XRF, but it requires a particle accelerator and it cannot detect elements with atomic number lower than 11.

Scanning electron microscopy

This method can be employed for both chemical analysis and mineralogical study of ceramics. The basic principle is that an accelerated beam of electrons hits the surface of the specimen causing the emission of secondary electrons which are collected by a suitably-positioned detector, allowing the image construction of the surface. Images can also be acquired detecting the back-scattered beam electrons that are reflected from the sample by elastic scattering. Thus, it is possible to examine the topography of the ceramic and to gain an insight into the clay and the temper present in it. If the scanning electron microscope is used in conjunction with the closely-related technique of energy-dispersive X-ray microanalysis (EDX, EDS, EDAX), the chemical composition of the clay or the temper can also be determined. The method is multi-elemental, non-destructive and capable of surface analysis and its most important advantages are its capacity to analyze inhomogeneous ceramics with coarse inclusions and create compositional area mappings or point-focused analyses of the clay and the temper compounds (e.g. Spataro 2011). However, the study of ceramics, as non-conductive materials, requires the use of a scanning electron microscope capable of working in a low-vacuum mode.

Inductively coupled plasma-atomic emission spectroscopy and inductively coupled plasma-mass spectrometry

Using a plasma source the sample is dissociated into its constituent atoms or ions, which are excited to a higher energy level. When they return to their ground state photons of a characteristic wavelength depending on the element present are emitted, while the intensity of this emission is indicative of its concentration in the sample. The only difference between the ICP-AES and the ICP-MS is that in the latter after ionization of the sample in the plasma, the ions pass into a mass spectrometer for separation and measurement. The method is suitable for bulk analysis and although it has the ability to analyze small samples and with low detection limits (Tykot and Young 1996), it is destructive thus samples cannot be re-analyzed if necessary.

4.2. Mineralogical investigation

Thin-section petrographic analysis

The thin section petrography is the study of the microscopic features of minerals using a 'polarizing' or 'petrographic' microscope. Thin sections are made cutting a thin slice of the sample with a diamond saw, which is then mounted on a glass slide and grounded to a specified thickness (~30 μm). At this thickness most minerals become more or less transparent and can be studied by a microscope using transmitted light allowing the extraction of colorful images and/or charts. One of the main drawbacks is that thin sections are time consuming and costly to prepare. The method is suitable for bulk analysis and it is non-destructive.

X-ray diffraction

X-ray powder diffraction is an instrumental technique used to study crystalline materials. When a crystal is bombarded with a finely focused monochromatic X-ray

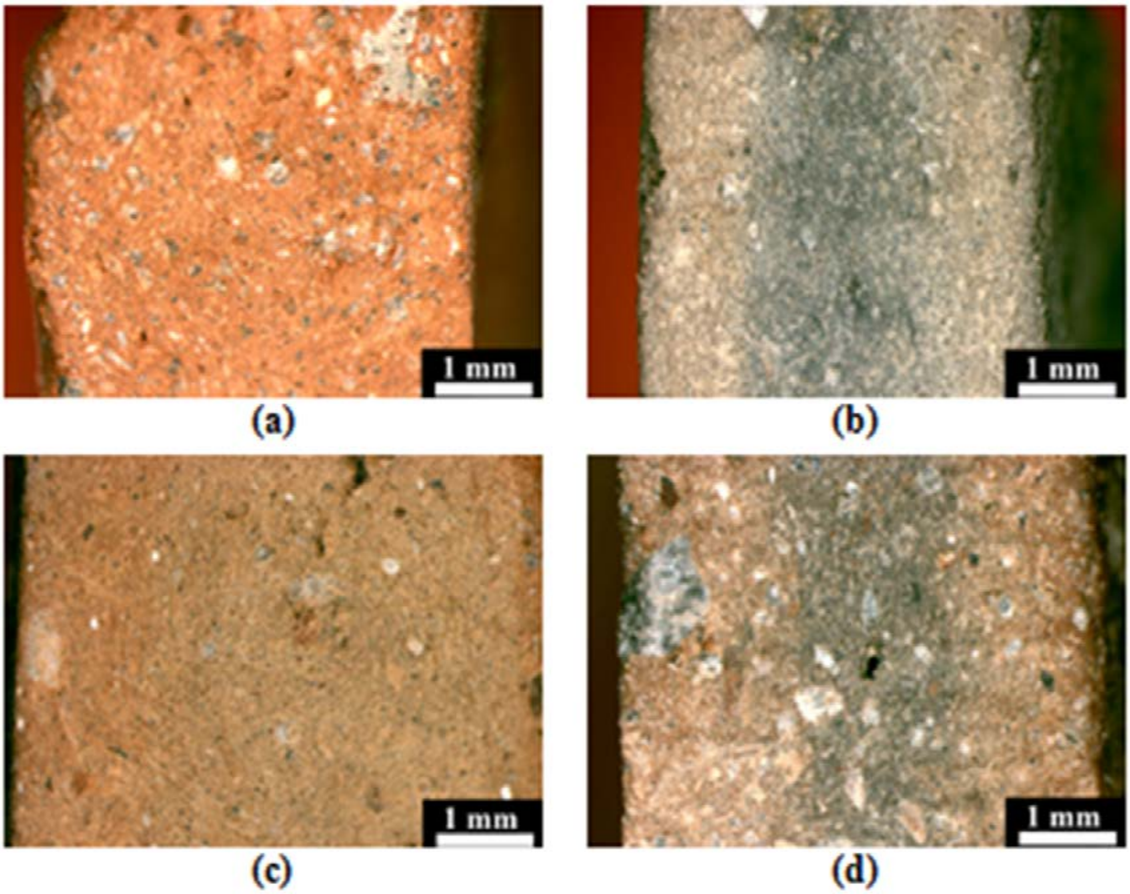


Figure 2. Typical clay body stereoscopic photomicrographs of representative samples of the four wares: (a): BoR; (b): C; (c): CD; (d): CoR

beam, part of the beam is diffracted. Applying the X-rays at various angles on the crystal by altering its orientation, a unique diffraction pattern of regularly spaced spots is produced, which is a 'fingerprint' of the phases present in the sample. Comparison of this pattern with standard reference patterns ultimately leads to the identification of the material. This is a non-destructive, surface or bulk analysis method and it is accurate for measuring large crystalline structures. However, small structures that are present only in trace amounts may not be detected with this method.

Scanning electron microscopy

As previously discussed, this method allows the detailed observation of the ceramic surface and the temper and/or crystals present in it. When it is employed in conjunction with electron backscatter diffraction analysis system additional information can be provided such as the crystallographic orientation of crystalline materials and their phase and structure.

5. Examples of Provenance studies

In this Section examples of recently published provenance studies of ceramics which adopt the 'integrated' approach as previously discussed, will be briefly presented. These works combine chemical and/or mineralogical analyses along with additional measurements of physicochemical properties of the ceramics and can be regarded as examples of good practice in this field. It should be noted that these works have been selected as more representative of the integrated approach, since several other similar provenance studies can be found in the literature.

5.1. Analytical Study of Ancient Pottery (Iordanidis et al. 2009)

This study is a multi-analytical approach on the characterization of several potsherd samples, dated from prehistoric to Hellenistic times, found in Aiani, ancient Upper Macedonia, northern Greece, towards the identification of their provenance. For this purpose, chemical, morphological and mineralogical analyses were conducted by means of XRF, ESEM-EDX and XRD. Results from the chemical analysis, with main focus on the trace elements, indicated a rather local provenance of the analyzed ancient pottery samples. In addition, further inferences were also possible due to the macroscopic observations and the mineralogical analysis. More specifically, it was found that pottery had a finer texture and thus better ceramic manufacture as getting to hellenistic era. In the same respect, observation of the presence of certain minerals allowed to make suggestions about the firing temperatures employed during the manufacturing of the pottery.

5.2. Characterisation of Clayey Raw Materials for Ceramic Manufacture (Montana et al. *2011)*

The object of this study was not the analysis of ceramic samples, but the detailed characterization of textural, compositional and technological properties of nine clayey deposits cropping out in the territory of Western and Central Sicily potentially used for ceramic production, which would facilitate the origin identification of ceramics found in the area. To accomplish this, an integrated approach was adopted which combined the chemical and mineralogical characterization, along with the investigation of some relevant properties affecting the performance of clayey materials (grain size distribution, plasticity and linear shrinkage) by means of granulometric analysis, XRD and XRF. This study is of great interest and aims at setting a good basis to approach the study of Sicilian production. However, such a detailed study of the deposits allows the development of chemical profile maps of an area and thus the discrimination of pottery production centres.

In addition, such a study is essential when comparing clays and ceramic artifacts during provenance studies, while it is useful towards the identification of the source of raw materials to already known workshops. Its major contribution is evident in provenance studies when kiln materials are not available and therefore there is no possibility to establish reference groups.

5.3. Study of Neolithic Pottery (Sakalis et al. *2013)*

The object of this study was the thorough analysis of several Late Neolithic decorated sherds found in Polyplatanos, Greece, namely Crusted ware (*C*), Cream-on-Red ware (*CoR*), Classical Dimini (*CD*), Black-on-Red ware (*BoR*) and Graphite ware (*G*) (Fig. 2). The scope was to enrich the existent knowledge concerning the provenance and the technology of the above decorative styles and especially of the Crusted ware, since the studies found in the literature are limited. To accomplish the above, several techniques were employed, namely chemical analysis of the paints, slips and clay bodies by means of μ-XRF, stereoscopic study of the sample clay paste by means of a high-performance stereoscopic microscope (Fig. 2), allowing the inspection of the clay body morphology and microstructure (the Wentworth scale was employed for the qualitative evaluation of the inclusions and grains of the clay body) and measurement of the clay colour of the sherds using a spectrophotometer (Munsell system).

The chemical data were evaluated though elemental biplots and the use of multivariate statistical analysis (PCA) (e.g. Fig. 1). Combination of all acquired data led to the distinctive classification of the samples studied indicating their different provenance. In addition, this study shed light on the methods employed that period regarding the time of addition of the paints on the ceramics (i.e., before or after the firing process).

5.4. Geochemical Evidence for Integrated Ceramic and Roof Tile Industries (Weaver et al. *2013)*

In this work a provenance study on ceramics, tiles, and local sediments from the Poggio Colla Etruscan archaeological site north of Florence, Italy was conducted. For this purpose, samples were analyzed by XRF to determine their chemical profile and by XRD to identify their mineral content. In addition, thermogravimetric analysis also took place in order to consider the effects of firing, while macroscopic observations using a stereoscopic microscope helped to gain insight into the qualitative content and textures. Chemical data were then statistically processed by means of 3D PCA considering the concentration of 14 elements (Fig. 3).

Although results from the geochemical analysis allowed the grouping of the samples, the petrographic and mineralogical analyses led to more conclusive evidence about the provenance of the pottery studied. As a result, due to the similarities of the samples in all aspects (chemical and mineralogical compositions), it was further supported the hypothesis that diverse components of a ceramic industry were all being conducted in close proximity to, and perhaps somewhere on, the Poggio Colla hill.

6. Conclusions

Establishing the origin of a particular archaeological artifact usually involves the study of its cultural, physical, and chemical properties using a variety of techniques. The combined information from the various scientific disciplines allows the investigation of hypotheses and interpretations that shed light on the human past and environment. Provenance studies of ceramics may be accomplished with several approaches, employing only chemical or mineralogical analysis of the artifacts. However, the use of an integrated approach is rapidly gaining ground recently, dictating the amalgamation of the scientific data retrieved by more than one method, allowing the complete chemical, physical and mineralogical characterization of the ceramics. Researchers should be careful when deciding which analytical methods to use, taking into account all the advantages and disadvantages of each method, in order to extract from the available ceramics the maximum of information which could shed light on their origin with as low uncertainty as possible.

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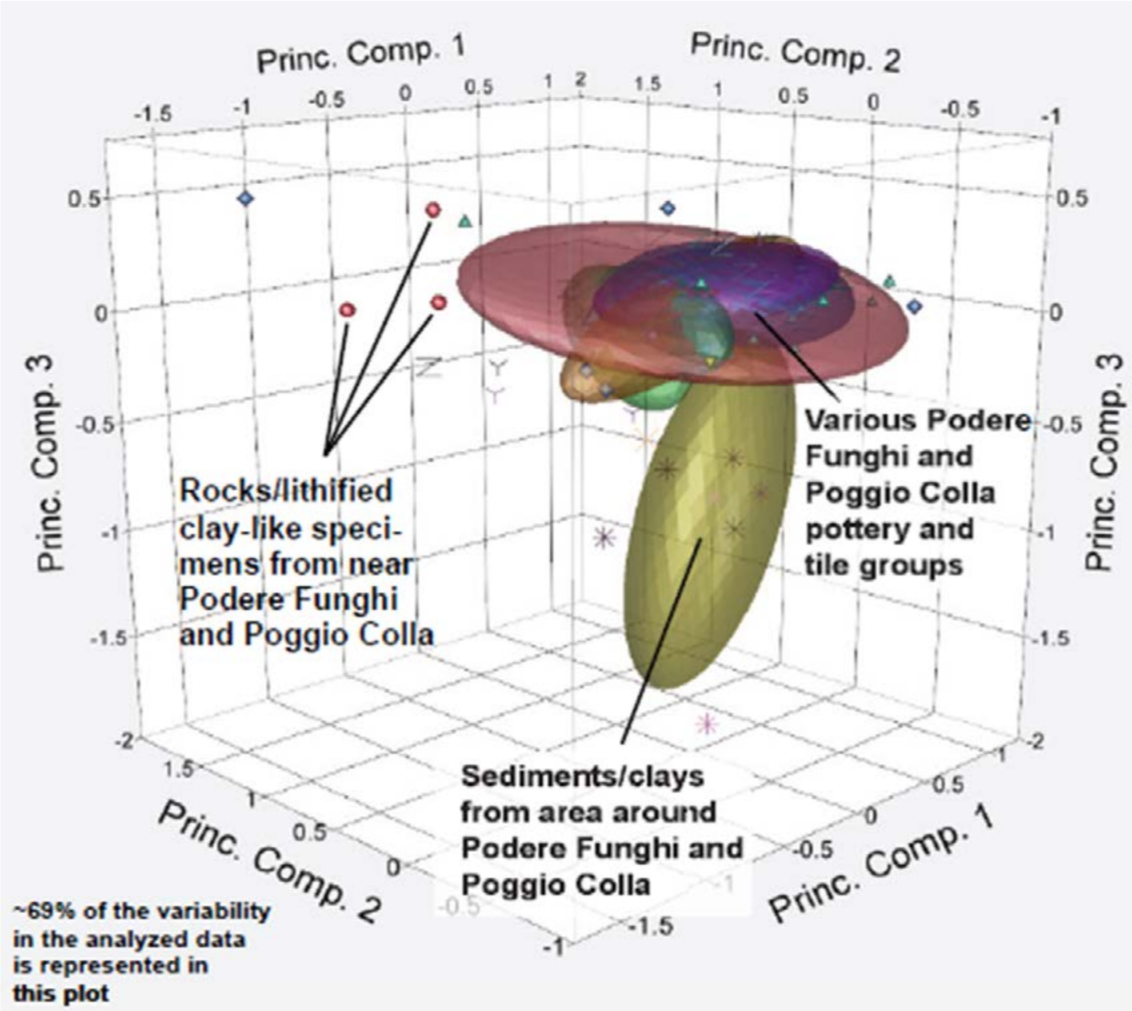

Figure 3. 3D principal components plot of center log-ratio transformed trace elements of the Podere Funghi and Poggio Colla geochemical data set [Reprinted from 'Geochemical evidence for integrated ceramic and roof tile industries at the Etruscan site of Poggio Colla, Italy' by Weaver, I., Meyers, G.E., Mertzman, S.A., Sternberg, R. and Didaleusky, J., 2013, Mediterranean Archaeology and Archaeometry, 13(1), p. 39, Figure 6. Copyright 2013 by the MAA. Reprinted with permission]

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Sustainable Data Management in the Study of Ancient Materials – Using the Example of Archaeological Ceramics

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Abstract: Archaeological material studies complement conventional archaeological research and contribute to our knowledge on material culture, in terms of production technology, and the origin, movement and utilization of materials. Furthermore, they provide information that assists restoration and conservation. On the other hand analytical studies always imply an intrusion in the integrity of an archaeological object even if the methods applied are non-destructive. A major concern of any analytical study should be the restriction of this intrusion to a minimum. Beyond that, the analytical data which can be generated from the selected method should be able to answer specific questions set by the research design. In realistic terms this is rare and usually combined data from more than one technique may provide partial answers. Subsequent to the actual analysis, the data have to be processed and placed in a general cultural, spatial and historical context on the basis of reference and comparative data. The present paper provides an overview over data treatment, data management and data availability using the example of integrated studies of archaeological ceramics.

Keywords: analytical data, archaeological ceramics, provenance studies, data interpretation, databases, statistical analysis

1. Introduction

The first analytical approaches to the study of archaeological materials go back as far as the end of the 19th century (Riederer 1981). During the early stages the studies were focused mainly on answering questions related to the technology of different production processes. Later, the focus shifted to questions concerning the origin and the distribution of materials and finished products, providing rich information about cultural, economic and political relationships. The starting point of all archaeological materials studies is the thorough examination of the materials and the objects and their classification, using archaeological criteria (stylistic, design, fabric). At a second level, the introduction of parameters that characterize the materials, such as microstructure, mineralogy and chemistry, becomes essential. These parameters increase dramatically the discriminative power of the conventional classification methods and for this reason the introduction of analytical programmes in archaeological materials studies has increased dramatically in recent years. Studies of archaeological materials are, therefore, principally of inter-disciplinary nature combining archaeological approaches with other methods from natural sciences. It is inevitable that a common level of conversation has to be established, which should span from the project design to data interpretation. Furthermore, analytical methods have to be carefully selected in order to extract the maximum amount of information by avoiding unnecessary analyses which do not offer anything new and which at the same time may jeopardize the integrity of the studied objects. In many cases it is not possible to repeat sampling or examination of an archaeological object once it has already been included in a previous analytical study. Therefore, data collection has to be planned also in view of evaluation and processing in the future, which implies certain requirements for the quality of analytical data in terms of reproducibility and representative value. Furthermore, not only results and interpretations based on the data of an analytical study have to be published, but the actual data also have to be made accessible and potentially combined with further data on the objects and materials. This requires the development of common databases. In the present paper basic concepts for sustainable data management in archaeological science will be discussed using the example of chemical studies of archaeological ceramics. Furthermore, the development of databases will be exemplified including perspectives on how these databases can be combined and integrated in the future.

2. Data types

During the examination of an archaeological object or material, various parameters are determined generating different kinds of data. The data, which are primarily describing the object, can be basically divided into continuous and categorical variables. Examples for continuous variables are elemental concentrations, spatial dimensions or absolute age, while typical examples for categorical variables are object type, cultural period or petrographic information, such as presence or absence of certain minerals. For a full interpretation of the object an integration of all these kinds of data is necessary.

Continuous variables

For the measurement of continuous variables the real value of a specific parameter, such as the concentration of a particular element in the examined material, is estimated by using a particular method. The quantification of the parameter includes necessarily an uncertainty which is expressed as the measurement error. On the one hand the uncertainty is based on the statistical scattering of independent observations or measurements which depends basically on the precision or reproducibility of the applied method. On the other hand uncertainty is based on the closeness to the real value which is the accuracy of the applied method. The real value is normally defined by the standard reference materials and each set of data is adjusted to this through the procedure of calibration. In order to explore significant similarities or dissimilarities of objects on the basis of continuous variables the uncertainties of the applied methods have to be considered.

Categorical variables

Categorical variables, on the other hand, allow for classifying and dividing the objects according to predefined categories. In the case that the variance within a specific category appears to be too large, sub-categories are defined. Indeed, the categories are often based on sets of continuous variables. Nevertheless, categorical variables can imply uncertainties as well. These start from the definition of specific categories which might be interpreted differently by different scholars. But also in the case of well-defined and generally distinguishable categories particular objects might present ambiguous parameters which allow for assigning them to different categories.

Metadata

Apart from the data which are directly describing the object there are metadata which are actually describing the primary data. These metadata can provide for example information about the discovery context of the object, about applied analytical methods or about the present location of the object. They are essential in order to organize all collected data about the object.

Raw data

All data associated with the object are ultimately based on raw data. These comprise for example photographs, drawings, measurement series or analytical spectra, which were evaluated and processed in order to produce the above-discussed more meaningful data. Nevertheless, the raw data have to be archived as well, because in some cases a reevaluation appears to be reasonable and in some case absolutely necessary.

3. Chemical analyses as basis for provenance studies of ceramics

Some basic concepts for data management in archaeological science can be discussed using the example of ceramic provenance studies on the basis of chemical analysis. The beginnings of this well-established approach are actually going back to the late 1950s when first studies were initiated applying neutron activation analysis (NAA) (Sayre and Dodson 1957) or optical emission spectroscopy (OES) (Richards and Hartley 1960). Basis for the feasibility of the approach is the assumption that '[…] there exist differences in chemical composition between different natural sources that exceed, in some recognizable way, the differences observed within a given source', also known as 'Provenience Postulate' (Weigand *et al.* 1977). The natural sources in this case are clay deposits which were exploited for the production of particular ceramic wares. Because it can be assumed that at different production places or even in different pottery workshops clays from different sources were processed, it is possible to distinguish pottery productions by means of their chemical composition. Apart from the natural variation of the selected raw materials the clay paste preparation introduces additional variation to the ceramic composition as individual recipes were followed in terms of mixing and refining raw materials. Therefore, the chemical variability within one production group is indeed commonly much smaller than the chemical differences compared to other production groups. The characteristic chemical composition or pattern of a pottery group coming from a specific production place is hence often compared with the chemical 'fingerprint' of the local pottery production. This 'fingerprint' is estimated by measuring a number of reference samples, representing the respective production group, and calculating the average concentrations of a series of elements. Furthermore, the standard deviations of the individual element concentration provide an estimation about the chemical variation within the production group. Once a reference pattern for a pottery ware group from a specific site is established, ceramics of unknown origin can be compared with this pattern by assessing similarity or dissimilarity under consideration of the variation. In this way ceramics can be assigned to their most probable place of production.

Analytical method

It has to be considered, however, that the 'fingerprint' is considerably affected by the analytical method used. The measured concentrations can deviate from the real values and the statistical measuring error introduces additional variation. As a consequence existing differences between different production groups can be obscured by analytical uncertainties and inaccurate values can result in misinterpretation, particularly if analytical results based on different methods are compared. Finally, the suite of the measured elements is also important. In terms of geochemistry, trace elements appear to be more useful for differentiating raw material sources. Distinguished distinction can be made, however, between geochemically immobile elements and geochemically mobile ones with accordingly larger natural variations. Concentrations of major elements, on the other hand, such as silicon, aluminum, iron, potassium or calcium, reflect mainly the types of raw materials and provide technological information rather than information about distinct raw material sources. Therefore, the analytical method has to be carefully selected so that precision, accuracy and determined parameters are sufficient for examining compositional differences between ceramics from different production sites. In order to assess the significance of analytical results the performance of the applied method has to be tested. A common way for testing analytical performance is the measurement of standard reference materials (SRM). Replicate measurements allow for an estimation of the relative standard deviation at different concentration levels of the particular elements and the determination of lower limits of determination (LLD) and lower limits of quantification (LLQ) (Hein *et al.* 2002). Furthermore, the closeness to the real values, which are actually also only estimated by the given reference values, can be determined and the potential use of additional calibration factors for particular element concentrations can be explored. The latter is essential for the correction of the possible off-sets among different techniques of elemental analysis.

Data evaluation

Data evaluation in chemical provenance studies of archaeological ceramics concerns basically the determination of the degree of similarity among elemental compositions which provides evidence on whether ceramic objects were produced (or not) at the same place using a consistent clay paste (or not). Because two independent measurements will never yield identical results, due to the statistical measuring error, the question is reduced to whether the difference or the distance between two compositions is significant. This can be answered only under consideration of the variability of the examined parameters. In this way probabilities can be determined, or at least estimated, for the assumption of similarity or of dissimilarity of chemical compositions, respectively.

In order to explore the variation within a chemical dataset concerning ceramics, however, certain constraints have to be considered. Element concentrations are not completely independent among each other. Particular elements or groups of elements are correlated as they are related to the same minerals, which can be specific clay minerals as well as accessory minerals. On the other hand, varying content of one component affects the relative content of other components, affecting again elements related to the respective components. This variation can have technological reasons, such as the addition of temper or purification of the clay paste (Kilikoglou *et al.* 1988, Cogswell *et al.* 1996), it can be related to natural mineralogical variation within the same clay deposit (Hein *et al.* 2004) or it can emerge due to post-depositional alteration of the ceramics (Buxeda i Garrigos 1999). Another characteristic of geochemical data is that the variation of an individual element concentration, at least in the case of trace elements, can be commonly described by a log-normal distribution rather than by a normal distribution. Therefore, logarithmic transformation of the data before their statistical treatment appears to be mathematically correct. The use of log-transformed data has the further advantage that this is also a way of normalization, which is necessary because the concentrations of different analyzed elements range over levels from sub-ppm to percent-weights.

One way to tackle the above discussed constraints during the exploration of compositional data and their chemical variation is the determination of their total variation following the approach of Buxeda i Garrigos and Kilikoglou (2001). Therefore first the $n \times n$ variation matrix $\boldsymbol{T}$ is generated with n, the number of element concentrations, and $\tau_{ij} = var\{\log(x_i/x_j)\}$ (Aitchinson 1986) the matrix elements presenting the variances of the logarithms of the element concentration ratios. The total variation of the data is then given by the sum of all matrix elements divided by $2 \cdot n$.The absolute value is a first indication as to whether a dataset comprises ceramics from different production sites, such as typically in the case of an assemblage from a trade or consumption site, or whether the ceramics were fabricated at one production site. The variation of an assemblage, however, can be further explored by determining the total variation of randomly selected sub-sets of the original data. Eventually, the distribution of the total variations determined in repeated tests can be interpreted in view of the number of compositional groups to be expected in the data (Buxeda i Garrigos and Kilikoglou 2001, Kilikoglou *et al.* 2007).

With regard to the variation matrix of the entire dataset the sum $\tau_{.s}$ of the variances in a particular column provides the contribution to the total variation, in the case that element *s* is chosen as divisor. Therefore, a high ratio $vt/\tau_{.s}$ indicates small variability of the respective element (Buxeda i Garrigos 1999). For further statistical evaluation, using for example cluster analysis or principal component analysis, the element with the lowest variability can be chosen as common divisor for a log-ratio transformation of the dataset. Using logarithmic ratios of element concentrations the above discussed correlations among elements can be considered while the use of logarithms incorporates data normalization and log-normal distribution.

An alternative approach for taking in consideration element correlations is the determination of the Mahalanobis distance for comparing samples with chemical groups in order to decide about similarity or dissimilarity (Bieber *et al.* 1976, Beier and Mommsen 1994). This distance is based on the covariance matrix of the chemical compositions of a group of samples, in this way the data are normalized by their variability. During an iterative procedure, similar samples can be incorporated in the group and the covariance matrix can be determined again until a stable group of similar samples is formed from which other samples can be distinguished. A similar but simpler distance, more suitable for small groups, is the Euclidian distance, weighted by the standard deviations of the element concentrations (Beier and Mommsen 1994, Kilikoglou *et al*. 2007). This corresponds to the Mahalanobis distance considering only the diagonal elements of the covariance matrix. Additionally, in order to adjust differences due to varying content of certain components, a best relative fit can be applied (Harbottle 1976, Beier and Mommsen 1994). If for example a non-plastic temper poor in trace elements has been added to the ceramic paste, such as quartz or calcite, this will result in a depletion of the concentration of trace elements. With a best relative fit a variation of the temper materials in content can be corrected and the composition of a particular group of ceramics can be more precisely defined.

Once groups or clusters of chemically similar samples have been formed, the next step is to define reference patterns for particular ceramic wares. If these are related to a place of production they can serve as reference patterns for these areas. Furthermore, apart from average concentration values, the variations, commonly in the form of standard deviations, also have to be considered and imparted as they play important role in the estimation of relationships among groups..

4. Databases

During the last 60 years since the start of systematic chemical studies of archaeological ceramics large amounts of data have been generated. In regions like the Eastern Mediterranean in particular, tens of thousands of ceramic objects have been analysed using different methods. During the early years, the study approach was usually project based. Ceramics of unknown provenance were analysed and compared with reference material from possible production sites. With the number of projects increasing, the data amount accumulated became gradually very large, including more and more reference patterns from productions sites. Due to methodological and technical developments, the long term reproducibility of the analytical methods became sufficiently reliable. Hence, reference patterns, which were already determined with the same method in a former study, could be used for comparison with newly measured material. More recently, with the advancements in computer applications during the 1970s reference databases were established at individual laboratories. These databases had the advantage that redundant measurements of already analysed reference material could be avoided and ceramics analysed in ongoing studies could be compared with a considerably larger number of reference patters from various production places.

The drawback, however, was that reference patterns measured in another laboratory using a different or (even sometimes the same) method could be used only under certain limitations. While longtime reproducibility and precision of the particular methods had been substantially improved, less importance was usually set on accuracy. Even though each method was commonly calibrated or at least monitored by analyzing standard reference materials (SRM) (Harbottle 1982) there was no consistent calibration in the sense of common SRMs and sufficient documentation. Furthermore, common standards for data formats were missing so that it was indeed easier to exchange data as printed hard copies than transforming digital data from one data format into the other. In the early years of computerization and limited memory capacity, in-house data formats tended to be particularly quite inscrutable. Thus, (if it was attempted at all), the average patterns of reference groups measured in other laboratories were used for comparison rather than the compositional data of individual samples. However, the use of average group patters introduces a possible bias due to the grouping procedure applied in the other laboratory to the original data, while a large amount of information about the individual samples remained disregarded.

Eventually, some research groups working in the field started to provide datasheets for selected assemblages for download via the Internet, such as the Archaeometry Laboratory at the University of Missouri Research Reactor (http://archaeometry.missouri.edu/datasets/datasets.html) or the Helmholtz-Institute of Nuclear Physics at the University of Bonn (http://www.hiskp.uni-bonn.de/gruppen/mommsen/data.html). The data sheets are provided in standard binary or ASCII formats, which can be imported straightforwardly into common spreadsheet applications for further statistical evaluation and comparison with other data. Sufficient documentation of the analytical methods and particularly the calibration standards used (Glascock *et al.* 2007, Mommsen and Sjöberg 2007) allows for an estimation of accuracy and a potentially necessary adjustment of specific element concentrations during the comparison with data measured at a different laboratory.

Nevertheless, for a thorough utilization of existing ceramic data collected by individual laboratories the development of a common database concept appeared to be essential. The main requirements for such a database are the flexibility of the data format in order to include data from different sources, possibly comprising variable element suites, and the incorporation of metadata regarding calibration and analytical parameters. Furthermore, the database should be expandable towards other data apart from the chemical compositional ones, allowing for inter-comparison among different techniques and the implementation of multidisciplinary studies. The starting point for the development of a new type of database was an inter-laboratory calibration study, between the NAA laboratories at the Institute of Materials Science at N.C.S.R. 'Demokritos' (IMS-DEMO) and the Helmholtz-Institute of Nuclear Physics at the University of Bonn (HISKP), in the framework of a large-scale inter-comparison analytical exercise (Hein *et al.* 2002). In both laboratories several thousand chemical compositions of ceramics from the Aegean and the broader Eastern Mediterranean region have been analysed, covering periods from the Neolithic until the Byzantine period. The combination of the two databases appeared to be worthwhile as they comprised to a large extent complementary data in terms of production sites and chronological periods. The new database was expected to provide a valuable collection of chemical ceramic reference groups from the Eastern Mediterranean region. The scope was to set up an open data format as much as possible and to incorporate at the same time calibration factors based on the above mentioned study (Hein *et al.* 2005). Considering broader compatibility and the capability to include further types of data in the future the concept of a relational database management system (RDBMS) was found to be suitable (Codd 1970). The concept was eventually implemented as a prototype database *ceraDAT* on a MySQL server at IMS-DEMO (Hein and Kilikoglou 2012). Access to ceraDAT through the Internet is provided via a dynamic web page (www.ims.demokritos.gr/ceradat) which allows also for basic statistical evaluation.

Relational databases and SQL

The relational database model was introduced in the early 1970's in order to overcome problems of database management in terms of the lack of portability and static data structures (Codd 1970). Up to that stage the data in common databases were organized strictly hierarchically, while the relational database design allowed the use of records, which were stored in tables linked among each other via indexes. In practice each data record in a table was uniquely identified by a primary key, which could be either a field or a combination of fields in the table. The tables were related to other tables through pointers on foreign keys. In this way the data structures became more dynamic. They could for example easily be extended to further types of data stored in new tables which could be gradually added, with references to the original data structure.

With the development of relational databases a new language was also developed, the Structured Query Language (SQL), in order to manage operations in relational database structures (Chamberlin and Boyce 1974). Data could be stored and accessed in a straightforward way, even in large numbers, and for sorting or selecting data records complex criteria could be defined using information from several tables. Eventually, SQL was accepted as standard by the American National Standard Institute (ANSI) so that databases could be transferred without problems between different platforms and implementations.

ceraDAT as a prototype database

The initial design of *ceraDAT* was based on the suggested structure of already implemented geochemical databases (Lehnert *et al.* 2000), which are accessible via the EarthChem web portal (http://www.earthchem.org). The main scope during the development of *ceraDAT* was the accessibility and dynamic use of chemical data generated by different analytical methods at different laboratories. While chemical data still constitute the core of the database they are combined with tables comprising categorical data, such archaeological classification, and metadata, such as information about the analytical method or the actual analyses. In future, tables with other types of analytical data, such as results of mineralogical or petrographic examinations or information about material properties can potentially also be added at any stage. At the moment three different categories of materials are included in the database: ceramics with the subcategories pottery, technical ceramics and building materials; geological materials, such as clays, and standard reference materials (SRM); which are used for the data calibration. According to the category, the metadata are stored in separate tables, containing archaeological information in the case of ceramics, geological information in the case of clays or details about the SRMs, in the case of reference materials. For the ceramic and clay categories additional geographical information is available in terms of archaeological sites and regions, which are for example used to generate maps. The analytical data are linked with the other tables via the central table *SAMPLE* (Fig. 1). A third part of the database contains metadata and categorical data about already existing data evaluation, such as links to published references or links among samples belonging to the same chemical reference group.

The basic data model of *ceraDAT* comprises 14 tables with the central table *SAMPLE* linking the different parts of the database to each other (Fig. 1). Concerning the analytical part of the database, *CHEM_VALUE* is the basic table which contains the chemical data. The primary key of this table is a combination of the fieldschem_ref and item, in which the measured item can be either an element or the respective oxide. In this way, each analysis corresponds to a series of separate records each of which contains an individual value and its estimated uncertainty. Considering that a chemical composition measured for example by NAA comprises typically 20 to 30 element concentrations the number of individual records becomes substantially large in this way. Nevertheless, this structure provides high flexibility in terms of different element suites measured with the different methods. Table *CHEM_ANALYSIS* contains information concerning the particular analysis, such as the sample_ID pointing to the foreign key in Table *SAMPLE*, a pointer to the specific method used, and references to possible batch codes and the date of the analysis in order to identify the measurement if necessary in the raw data. The primary key is the field chem_ref, which corresponds to the specimen which was actually used for the analysis, in contrast to sample_ID, which corresponds for example to a certain archaeological ceramic fragment or to a specific clay sample, which might have been analysed several times resulting in separate records for each analysis. The field method_ID refers to the Table *METHOD*, which contains information about the specific methods. Even though up to now *ceraDAT* contains exclusively NAA data, chemical data generated using other methods can be added at any stage. Concerning the comparison of data generated with different methods, calibration factors based on analyses of common standard reference materials are included in *ceraDAT*. The chemical data are stored in the way they are provided by the particular laboratories. The database user, however, can select between specific calibrations in order to display data coming from different laboratories to be used jointly in a statistical evaluation procedure.

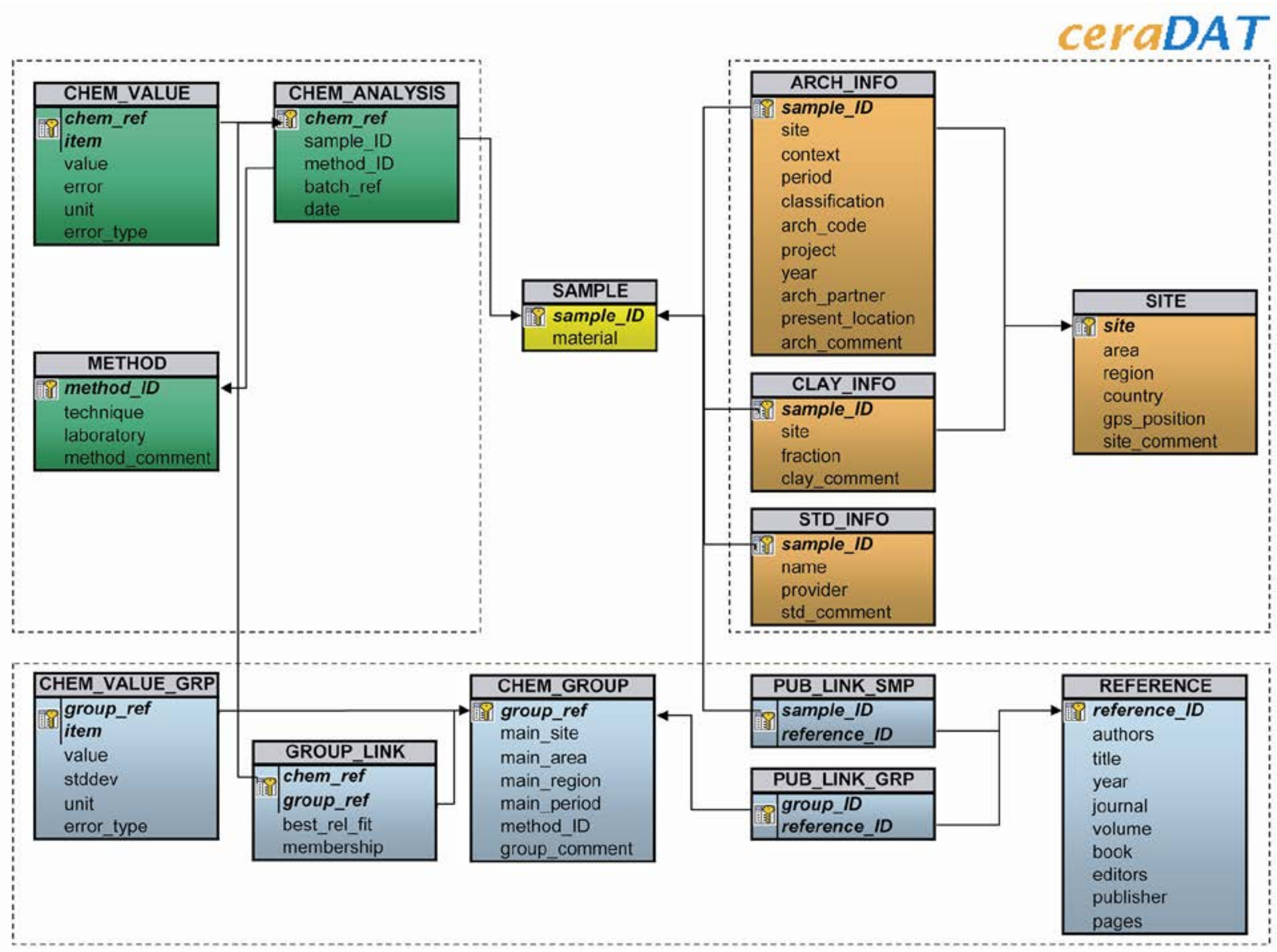

Figure 1 – The original design of the ceraDAT database comprising 18 tables (Hein and Kilikoglou 2012)

Searchable archaeological information about the samples, categorical data, as well as comments, is provided in table ARCH_INFO. The primary key is the field sample_ID pointing to the foreign key of the Table *SAMPLE*. In the case of geological samples the information about the samples is stored in the Table *CLAY_INFO* and in the case of standard reference materials correspondingly in the Table *SRM_INFO*. The Tables *ARCH_INFO* and *CLAY_INFO* are linked furthermore to the Table *SITE*, containing geographical information. Via the GPS position the sites can be presented in a map application (Fig. 2). The third part of the database comprises information about chemical reference groups resulting from the statistical analysis of the respective data. The table *CHEM_GROUP* with the primary key group_ID contains information about the site and the period, to which the reference group can be attributed to, and the method, used to analysed the samples belonging to this group. The table *CHEM_VALUE_GRP* has basically the same structure as Table *CHEM_VALUE*, but containing, the average values and standard deviations of the respective chemical group. Each group is defined through the table *GROUP_LINK*, which links the respective group members with the table *CHEM_GROUP*. Finally, samples or groups can be linked to specific publications stored in the Table *REFERENCE*.

Apart from direct access of the *MySQL* database server for authorized users, *ceraDAT* is accessible by the public via the web portal. The applications, which were developed in PHP, include various query options, such as searching for labels, sites, ware types and periods, searching for compositions within preselected concentration ranges or searching for a sample set included in a certain reference of related to a specific project (Fig. 3). Different output tables can be generated, such as detailed sample lists or data sheets with the analytical values. Unregistered visitors of the web page will have the right to read data, which are classified for common access. Enhanced use of the database is restricted to registered users, who can be granted for example access to specific still unpublished data. Registered users can be granted furthermore the right to upload their own data on the database, for example in order to search online for suitable reference groups. Whilst for a thorough multivariate data analysis the data tables can be downloaded and processed with suitable statistical software, for registered users the *ceraDAT* web portal provides some basic data evaluation routines in terms of determining average compositions of groups or testing similarity of sample data and reference data. As a dissimilarity measure the weighted Euclidian distance is used, which is as mentioned above a simplified version of

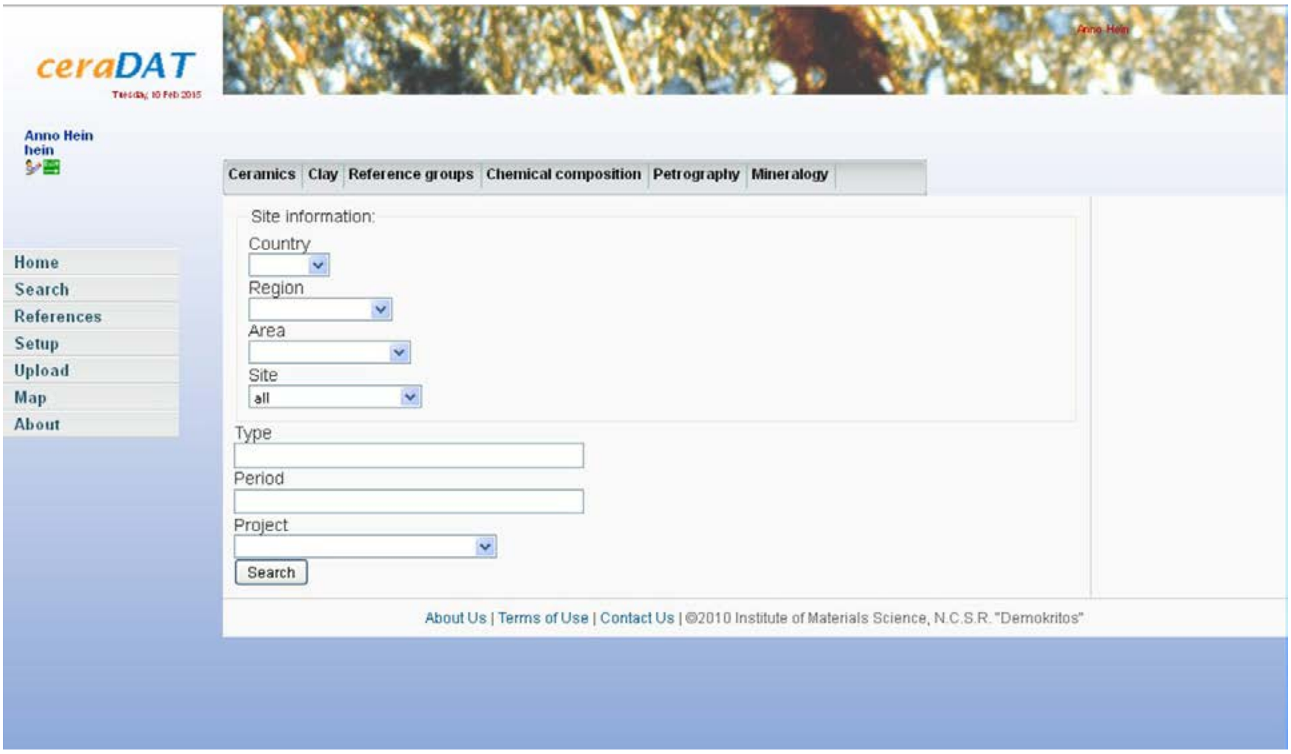

Figure 2 – Search form on the ceraDAT web portal: Queries for geographical parameters, for typological parameters, for certain periods and research projects are possible.

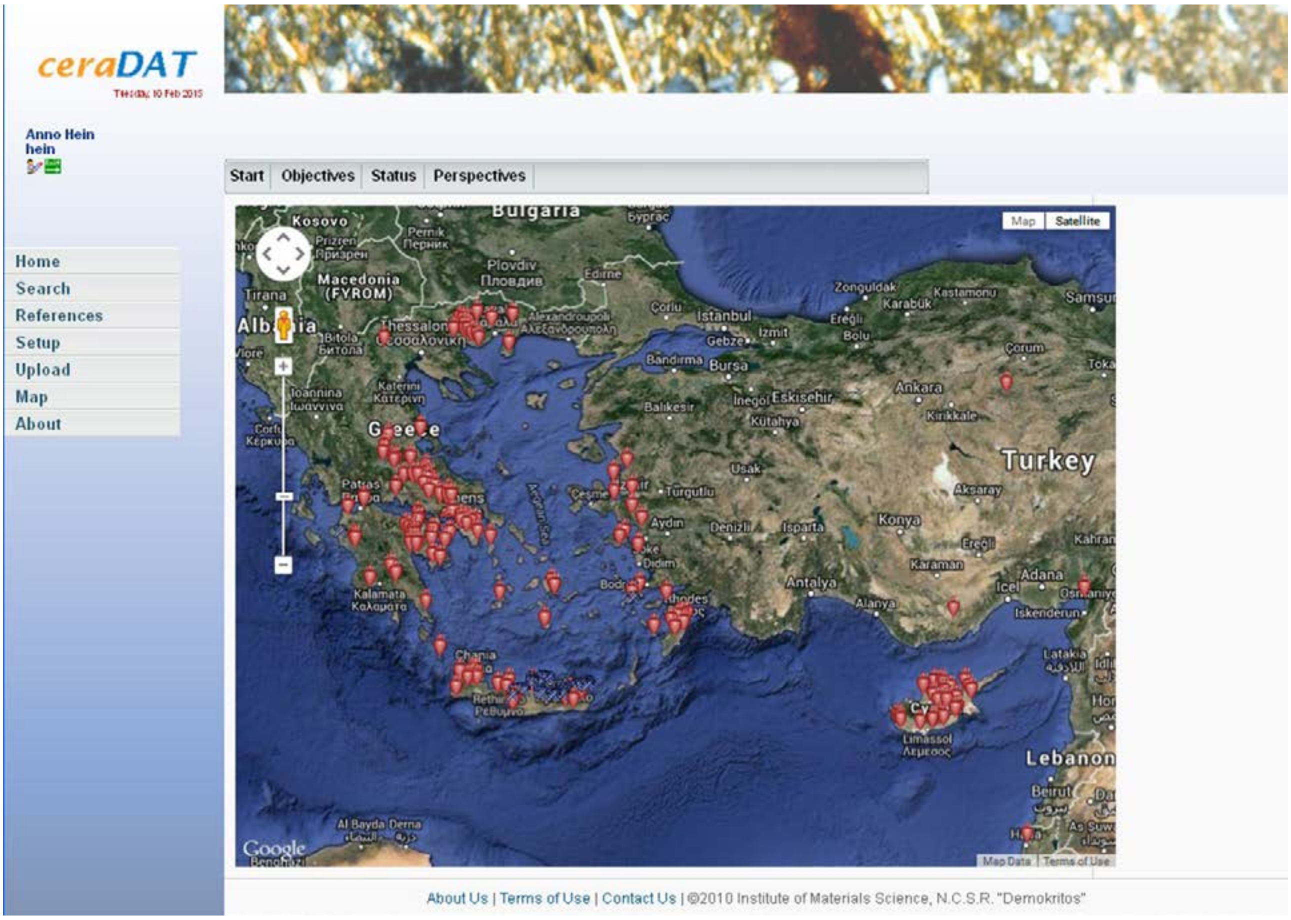

Figure 3 – Map application on the ceraDAT web portal: Finding sites of ceramics and clay deposits are stored with geographical position on the database and can be accessed via the map.

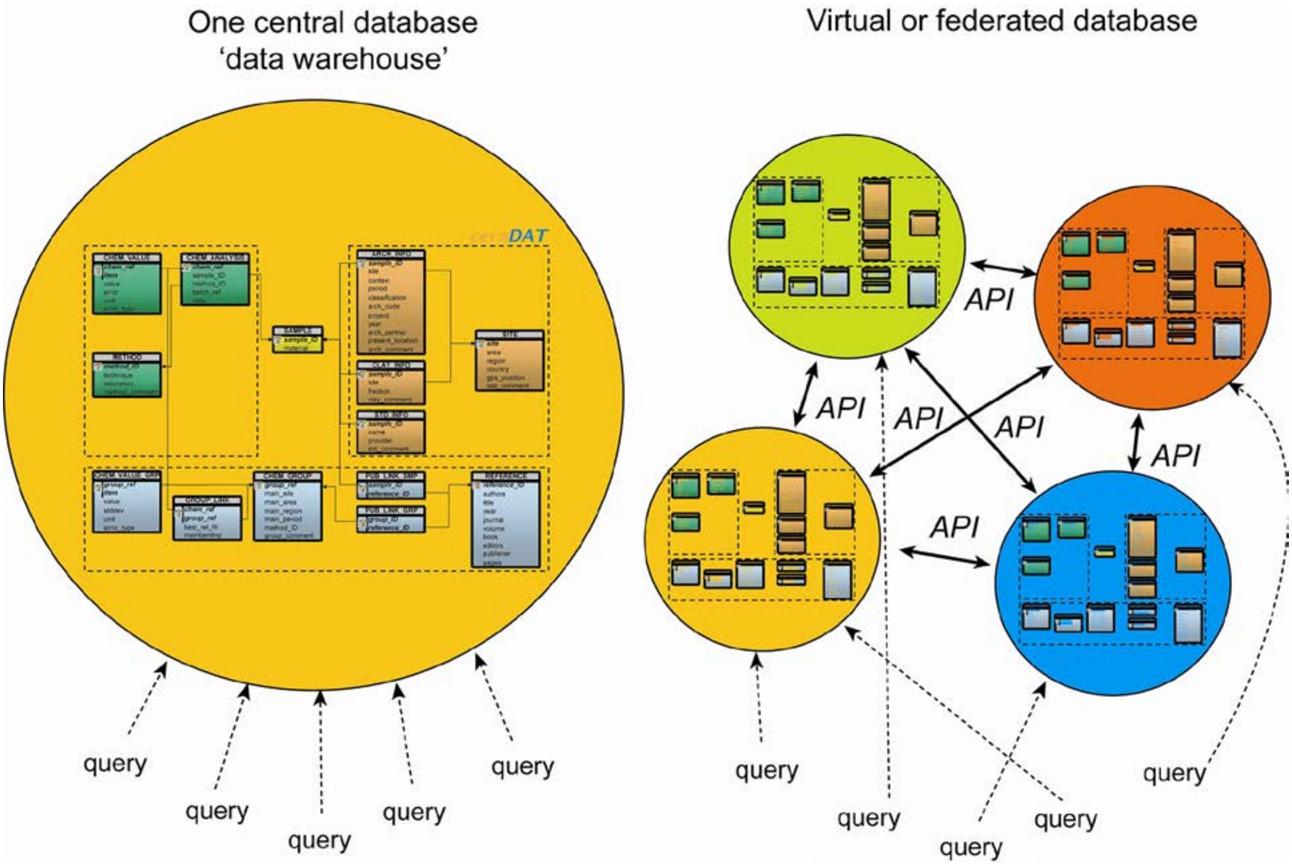

FIGURE 4 – ALTERNATIVE CONCEPTS FOR INTEGRATING DATABASES: THE DATABASES CAN BE COMBINED EITHER IN A CENTRAL DATABASE OPERATING AS A DATA WAREHOUSE OR THEY COULD BE VIRTUALLY COMBINED IN A FEDERATED DATABASE, STAYING INDEPENDENT BUT BEING CONNECTED WITH A COMMON API.

the modified Mahalanobis distance (Beier and Mommsen 1994, Kilikoglou *et al.* 2007).

In terms of legal issues particular importance is attached to the condition that all ceramic data, incorporated in the database, are based on examinations of ceramic fragments and artifacts conducted under the permission of the appropriate authorities of antiquities. The ceramics are either part of find assemblages of official excavations or part of documented and publicly accessible museum collections. The use of the database is free of charge and any commercial use is strictly forbidden. It is explicitly forbidden to use the database for authentication of artifacts of unclear, i.e. undocumented, origin. The administrator of the database reserves the right to set the individual user privileges.

Future perspectives and data integration

The presented prototype database *ceraDAT* is only one out of various running projects attempting to make data on archaeological ceramics accessible and searchable through the Internet.Scope for potential collaboration among the projects concerns exploring how the databases, which provide a large variety of information ranging from purely stylistic classification of ceramic wares, and petrographic examination up to chemical analysis as in the presented case, can be combined, One possible approach would be the setup of a central database containing the entire data and operating as a data warehouse (Fig. 4). The *ceraDAT* concept for example could be largely extended incorporating the respective data tables for all kinds of information and operating eventually as a central data warehouse. This would require, however, a high level of administration and maintenance. The alternative approach would be a decentralized virtual federated database (Fig. 4). In this case the individual databases are continuing to operate independently. The combination is realized via an application programming interface (API), which can be used to link information from different databases. The only requirement is that the community has to agree on a common wrapper API.

5. Conclusions

There are specific constraints for the collection of analytical data of archaeological materials because the examined objects are often unique and sampling should be restricted to a minimum while a maximum of information should be achieved. Therefore, careful project design which includes sampling strategy and selection of suitable analytical methods, is necessary. Furthermore, the data interpretation has to be adapted to the nature of the specific materials. The example of archaeological ceramics shows that for a sustainable data management in archaeological science not only a standardisation of analytical methods and statistical data treatment is necessary but also a standardisation of data storage and data exchange. Databases should be sufficiently flexible so that they can be extended towards incorporating further data types if necessary and the database structure should follow open standards. In this way the data are widely accessible and they can be combined in order to achieve as much information as possible about the ceramics. Nevertheless, they still can be stored in decentralized databases, which are virtually federated using a common language (API).

Finally, it should be emphasized that once data on specific archaeological materials have been properly published it is essential to make them accessible to the public through adequate databases. There is even the proposal that the incorporation of new data in a database could be accepted as a citable publication.

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Laser Tools in Archaeology and Conservation
How Far Can We Get?

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Abstract: In recent years, analytical spectroscopic techniques based on the use of lasers have been used increasingly to illuminate complex diagnostic problems in archaeological and conservation research and practice. Of importance, concerning the efficient utilization of such techniques, is their capability to work outside the framework of large facilities or specialized research laboratories, via transportable or portable instrumentation. Mobility expands the field of application of an analytical method and its versatility by permitting access to highly valued artworks and objects n museums or even field operation, for example, at excavation sites. In this paper the basic concept and instrumental ingredients are described concerning a versatile analytical methodology that combines the use of two mobile laser-based analytical techniques, laser-induced breakdown spectroscopy (LIBS) and Raman microscopy, for the analysis of materials in historical and archaeological objects and monuments. The LIBS technique relies on atomic emission spectroscopy and provides information on the elemental composition of materials while Raman analysis yields information on the molecular composition of materials on the basis of characteristic vibrational Raman spectra. Examples are presented from field campaigns, performed recently during an nvestigation regarding the type of pigments used on stone sculpture and wall painting on the island of Crete during the Venetian and Ottoman times.

Keywords: Laser analysis, mobile techniques, pigments, painted stone sculpture, Crete

Introduction

The scientific study and safeguarding of heritage objects relies largely on our capabilities to identify and quantify materials, understand corrosion or degradation processes and environmental impact and apply efficient restoration or preventive conservation treatments. As it turns out, this is a highly challenging task, considering the inherently complex, multi-component nature of materials in such objects, which calls for elaborate and quite often case-specific analysis and conservation procedures (Ciliberto and Spoto 2000, Price and Burton 2011, Stuart 2007). Furthermore, the increasing demand for minimal intervention in combination with restrictions in sampling and transportation of cultural heritage and archaeological objects has generated strong interest in developing and utilizing analytical techniques and mobile instrumentation capable of working in museum laboratories or even outdoors at historical sites or excavations. A number of laser-based methods offering different analytical capabilities have been investigated as regards cultural heritage research studies and several of them have received attention as promising analytical tools. Furthermore, given technological advances in lasers and spectrometers, compact mobile instruments have become available that nowadays enable field applications, opening up opportunities for testing instruments and methods under actual working conditions and for further instrument and methodological development (Abe *et al.* 2009, Anglos and Detalle 2014, Vandenabeele *et al.* 2004).

In this context, laser-induced breakdown spectroscopy (LIBS) and Raman microscopy, two well-established analytical spectroscopy techniques, have been successfully implemented in response to the need for transportable and/or portable instruments for applications related to materials analysis with the aim to support the work of art conservators, historians and archaeologists. The LIBS technique provides information on the elemental composition of materials while Raman spectroscopy probes characteristic bond vibrations in materials leading to molecular composition information. Considering that no single method can provide full compositional analysis, the combined evaluation of data derived from analysis by both LIBS and Raman has been shown to lead to useful, often complete, analytical information on materials found in works of art and historical or archaeological objects (Westlake *et al.* 2012). In this chapter, two mobile spectrometers, for LIBS and Raman analysis respectively, are presented along with a basic overview of a dual-technique methodology for the study and analysis of materials on/in cultural heritage objects. Besides technical and instrumental aspects, selected results from the actual in situ use of this dual-technique methodology are shown concerning the investigation of painted stone sculpture, dating from the Venetian (13th -17th century CE) and the

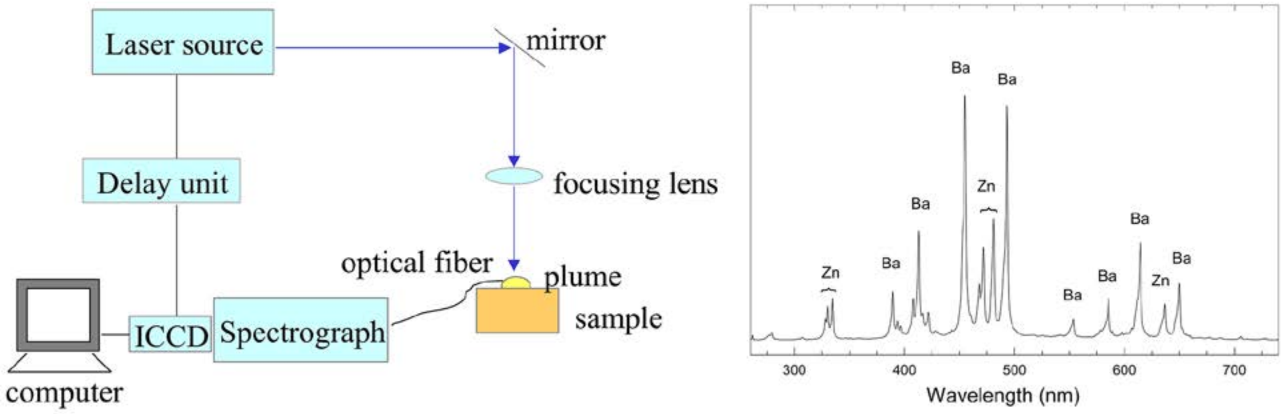

Figure 1. Schematic diagram for a typical LIBS experiment (left) and LIBS spectrum collected from a sample of the white pigment lithopone, ZnS·$BaSO_4$ (right).

Ottoman (17th -19th century CE) period at the Historical Museum of Crete (Greece) and at the medieval church of St George in the village of Kamariotis (Heraklion).

Techniques and instrumentation

The LIBS technique

Laser-induced breakdown spectroscopy (LIBS), also known as laser-induced plasma spectroscopy, is an analytical technique that enables the determination of the elemental composition of materials. It has been used in a wide variety of analytical applications for the qualitative, semi-quantitative and quantitative analysis of cultural heritage materials in oil paintings and frescoes, stone and metal sculpture, pottery and glass objects and results demonstrate that it can be a useful analytical tool.

Briefly, LIBS relies on focusing an intense nanosecond laser pulse (1 nanosecond = $1x10^{-9}$ seconds) onto the surface of an object/sample under analysis. This results in the formation of a transient micro-plasma which decays emitting radiation (fluorescence from excited atoms and/or ions). Recording this emission on a spectrometer produces the LIBS spectrum, which, through a straightforward analysis, yields compositional information about the material examined (Fig. 1). More specifically, the characteristic, sharp atomic emission peaks in the spectrum lead to the identification of the elements contained in the minute amount of material ablated, reflecting the local elemental composition of the sample (qualitative analysis). A typical LIBS spectrum is shown in Fig. 1 (right). The peak intensity or the integrated emission can in principle be associated with the number density of each emitting species in the plume and this, in turn, with the concentration of specific elements in the ablated material (quantitative analysis) (Anglos 2001, Lee *et al.* 2004, Tognoni *et al.* 2002).

An important feature of LIBS is that it can be applied in situ, namely, on the object itself, eliminating the need for sample removal and/or sample preparation. In most cases the interaction of the laser beam with the surface examined is practically non-invasive and the trace on the surface is hardly visible by the naked eye. In addition, LIBS can provide an equivalent of depth profile analysis. The basic principle behind this feature is that, during the analysis, each laser pulse removes from the surface a small amount of material and therefore the following pulse always probes a new section of the paint layer slightly deeper than the previous one. As a result, successive LIBS spectra on the same point reveal the stratigraphy of the paint layers performing essentially an in situ cross-sectional analysis (Giakoumaki *et al.* 2007, Osticioli *et al.* 2008).

Finally, as already stated in the introduction, LIBS instrumentation favors the development of compact mobile units, which can be employed in analytical campaigns at museums or historical and archaeological sites (Agresti *et al.* 2009, Cunat *et al.* 2005, Fortes *et al.* 2007). Several such instruments, primarily developed by research laboratories, have been described in the literature. An example of a portable LIBS instrument, developed at IESL-FORTH is described next.

LM$_{NT}$II+, a portable LIBS spectrometer

The portable LIBS system, shown in Fig. 2,consists of the following basic sub-units :

- Optical probe head with a nanosecond pulsed Nd:YAG laser operating at 1064 nm, an integrated camera for accurate pointing and other optics (1).
- Dual Spectrometer – Detector (covering the spectral range : 200-460 nm and 415-660 nm) (2) and
- Power supply unit (3).

The instrument fits in a compact case (dimensions of 46x33x17 cm^3) and weighs less than 9 kg. It is fully operated and controlled through a laptop computer via a custom-made software. A micrometer translation stage is used for accurate pointing and analysis while, in certain cases, a tripod or appropriate scaffolding is used.

In brief, the instrument is based on a passively Q-switched Nd:YAG laser operating at 1064 nm (10 mJ/pulse, 10 ns).

Figure 2. Main subunits of LMNT-II+ (left) and instrument in carrying case (middle). During a campaign for the analysis of silver Frankish coins at the archaeological museum of Ancient Corinth, Greece (right).

A dual fiber optic compact spectrograph is used to record the emission spectra across a wavelength range extending from 200 to 660 nm, with resolution of about 0.2-0.3 nm. The system is equipped with a miniature CCD camera that enables visualization of the object during analysis and aiming of the laser beam. All spectra were collected with a time-delay of 1.3 μs with respect to the laser pulse minimizing the continuum present at times immediately following laser ablation. In a typical analysis, the object/sample is placed at a given distance (70 mm) from the optical head of the instrument, namely at the focal plane of the laser pulse, and by means of a XYZ translation stage the laser beam is aimed accurately with respect to the area selected for analysis, which is viewed online through the CCD camera. An area corresponding to a diameter of about 0.2 mm is probed by the laser beam. A single pulse is adequate for obtaining a spectrum with high signal-to-noise ratio (S/N). A few pulses (2-6) are delivered at each point, and separate spectra are recorded, particularly when depth profiling information is sought for. The latter can be achieved because of the laser ablation effect that results in the removal of thin (on the order of a few microns per pulse) layers of materials during analysis.

The main features of LIBS and LMNT-II+ specifically, as an analysis and documentation tool, can be summarized as follows:

- The technique does not require sampling, so analysis can be performed directly on the object or monument.
- It provides qualitative and semi-quantitative elemental analysis results at a nearly microscopic spatial resolution.
- The instrument permits clear observation of the object, selection and accurate aiming of spots for analysis through the built-in camera.
- The instrument is supplied with a user friendly interface and can be operated by non-technical personnel following basic training.
- The software includes a reference library and provides an option to aid spectra interpretation. It also provides the option of overlaying the acquired spectra with reference ones. The reference library can be continuously updated with relevant data.
- It allows the stratigraphic study of corrosion layers by gradual in depth analysis. This however is subject to the experience and the expertise of the user.
- It allows the photographic documentation of spots during all stages of analysis (before, after the 1st, 2nd, 3rd etc. pulse and after the end of analysis). These documentation images are stored along with the spectral data.

Raman microscopy

Raman spectroscopy is a widely-established technique, an excellent analytical tool for art conservation and archaeological science that presents unique advantages over other molecular analysis techniques (Smith *et al.* 2004, Vandenabeele *et al.* 2007). Raman spectroscopy offers high sensitivity and specificity enabling analysis of a wide variety of organic, inorganic and bio-materials, often directly on the object under study, non-invasively, at speed and with superb spatial resolution. Commonly the characteristic vibrational modes of molecules/materials and their corresponding frequencies probed in the Raman spectra are the basis for identifying different materials. These frequencies are highly specific enabling one to distinguish among similar materials and even among different crystal phases of the same material such as in the case of minerals. The Raman technique has benefited enormously from the use of lasers, which deliver the power necessary to enhance the intensity of the low signals arising in the inherently weak Raman scattering process. In particular, the introduction of Raman microscopy in 1975, and advances in optical and detector technology have revolutionized the use of Raman spectroscopy leading to numerous materials analysis applications (Colomban 2012). Several powerful Raman microscopes are these days commercially available opening up opportunities for detailed studies of cultural heritage materials, though their cost remains rather high. In parallel, versatile, compact units offer the advantage of mobility, quite crucial in

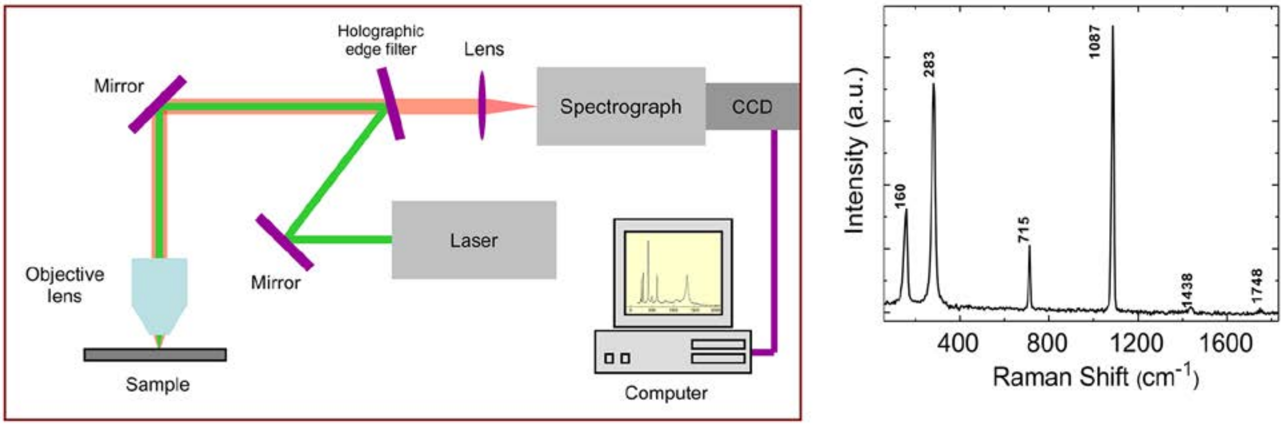

Figure 3. Schematic diagram for the Raman microspectrometer (left). Typical Raman spectrum collected from a sample of calcite, $CaCO_3$ (right).

the case of immovable object investigations or on-site campaigns.

Mobile Raman microspectrometer

The mobile Raman spectrometer (JY Horiba HE 785) used in this study comprises the following basic sub-units:

- Optical microscope probe with an integrated video camera viewing system for accurate pointing of the laser beam
- Diode laser operating at 786 nm with its power supply unit.
- Spectrometer – CCD Detector system covering the frequency range 200-3200 200-3200cm^{-1}.

The instrument is fully operated and controlled through a laptop computer via a standard spectroscopy software. A micrometer translation stage is used for accurate pointing and analysis while, in all cases, a tripod or appropriate scaffolding is used, depending on the specific location on a monument or object that needs to be reached for analysis.

In brief, the excitation source is a cw diode laser, emitting at 786 nm (maximum power at the sample: 50 mW), fiber optically coupled to an optical head that enables focusing of the beam by means of a number of objective lenses (10x, 20x, 50x) which provide a variable focus of the beam (magnification of the work area) down to a few microns on the sample surface. A white light illumination system and a high resolution colour camera (video microscope) are also part of the optical head and offer a very clear view of the area under investigation, necessary for positioning the beam on individual pigment particles or particle aggregates. The scattered Raman radiation is collected through the focussing objective and sent through an optical fibre to a compact spectrograph, equipped with a concave grating, which provides spectral coverage up to 3200cm^{-1} at a spectral resolution of about 10-15 cm^{-1}. The detector, a Synapse™ CCD (1024 x 256 pixels), is air-cooled and has a high sensitivity. For transportation, the whole instrument is packaged in two carrying cases, a medium-sized one housing the optical probe and the micro-positioning stage (dimensions: 46x33x17 cm^3, weight 7.5 kg) and a larger one (dimensions: 61x48x30 cm^3, weight 28 kg) containing

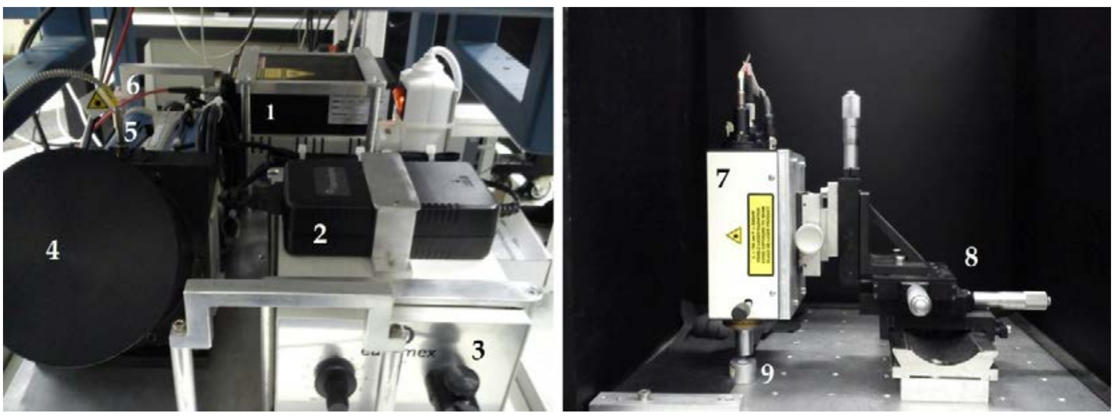

Figure 4. Main parts of the Raman microspectrometer. Laser and power supply (1,2), Sample illumination source (3), Spectrograph (4), Detector (5), Optical fiber (6), Optical probe (7), Micro-positioning stage (8), Sample (9).

the laser and its power supply unit, the sample illumination source, the spectrograph and the detector, all attached firmly to a light-weight aluminum frame (Fig. 4).

In a typical measurement, the object/sample is placed under the microscope objective and with the help of the XYZ micro-positioner and the video microscope, the area to be analyzed is selected. Analysis is therefore performed in situ, namely on the sample itself, with no need for any sampling. A potential limitation exists when rough surfaces are examined, which prevent the high magnification objective focusing on features located in 'deep valleys'. The beam power on the sample was, depending on the material investigated, in the range of 0.05-5.5 mW. Typical exposure time of the CCD was 20 s per scan, while normally 10 to 20 scans were averaged.

The main features of Raman analysis and the mobile spectrometer, as an analysis and documentation tool, include the following:

- Direct molecular information is obtained.
- The technique does not require sampling, so analysis can be performed directly on the object or monument.
- The analysis is completely non-invasive.
- The instrument permits clear observation of the object, selection and accurate aiming of spots for analysis through the viewing camera.
- The system is supplied with a user friendly interface and can be operated by non-technical personnel following basic training.
- The software includes a reference library and provides an option aiding spectra interpretation. It also provides the option of overlaying the acquired spectra with reference ones. The reference library can be continuously updated with relevant data.
- It allows the photographic documentation of spots during all stages of analysis. Documentation images are stored along with the spectral data.

Case studies

On the basis of the two instruments, a versatile methodology that enables analysis of materials in situ has been worked out. The focus in the present study lies on the identification of pigments on painted stone sculpture. Pigments, typically inorganic minerals, can be identified on the basis of their characteristic Raman spectra (Burgio and Clark 2001) as well as through elemental analysis by LIBS. In a typical investigation, Raman analysis is carried out first, given it is a totally non-invasive method. Given that Raman signals can be weak or masked by fluorescence emission, arising from the paint materials or impurities, it is not uncommon that Raman analysis may be not fully conclusive concerning the identity of the pigment or pigments used in painting. In this case complementary analysis is carried out by LIBS, which typically affords strong emission signals that provide information about the elemental composition of the sample. Then, combining LIBS with Raman data and using background information from historical sources and standard knowledge concerning common pigment materials one can obtain proof or strong evidence about the type of pigments employed (Burgio *et al.* 2000, Castillejo *et al.* 2000). In several cases the findings can be complex and ambiguous, however, it should be stated here that even simple optical inspection under magnification (for example through the viewing systems in either instrument) can provide supporting evidence for the type of pigments used and even their stratigraphy. Finally it is noted that LIBS is most appropriate for the analysis of metal materials, for instance thin silver or gold foils often used in paintings.

Study of painted sculpture at the Historical museum of Crete, Heraklion

A campaign has been performed for the in-situ identification of pigments or traces of pigments on Venetian and Ottoman sculptures, hosted in the Historical Museum of Crete (Fig. 5). The basic aim of this campaign is to uncover similarities and differences in painting materials and trace the evolution of painting techniques from the Venetian (13th -17th century CE) to Ottoman (17th -19th century CE) periods.

For instance, regarding the analysis of an Ottoman stone inscription (late 19th century CE, code AI 244), micro-Raman spectroscopy revealed traces of red lead (Pb_3O_4) and chrome yellow ($PbCrO_4$) (Fig. 6a). Confirming these findings, lead (Pb) and chromium (Cr) have been detected in the LIBS analysis. But furthermore, the elemental analysis performed by LIBS determined also the presence of gold (Au) and copper (Cu). This is strong evidence for the use of a gold-silver-copper alloy (Au-Ag-Cu) (Fig. 6b) possibly as a decoration on the stone.

In another Ottoman decorative colored stone sculpture, showing a double axe (early19th century CE, code AI 0176), Raman analysis confirmed the presence of two different blue pigments, ultramarine blue ($Na_{6-8}(AlSiO_4)_6S_{2-4}$) at the blue area and Prussian blue ($Fe_4[Fe(CN)_6]_3$) at the green area. Moreover, LIBS analysis contributed with the detection of lead (Pb) and chromium (Cr) at the green area implying the presence of chrome yellow ($PbCrO_4$). The complementary information of the two techniques reveals that the green colour is most likely produced by mixing yellow and blue pigments.

Pigment analysis at the church of St George, Kamariotis, Heraklion

Taking analysis beyond the museum environment, a number of campaigns have been carried out on-site, investigating paint on stone sculpture at selected small churches situated in rural locations in the greater Heraklion area. These field campaigns are in practice performed outdoors, leading to several technical challenges including the need for steady power supply or handling the instrument at unusual temperatures or not easily accessible locations. Indicative results are presented from the use of the Raman-

Figure 5. Painted sculpture study at the Historical Museum of Crete. a) The LIBS and Raman probes mounted on a rail permitting parallel work over the sculpture surface. b) The Raman microspectrometer supported by a pair of tripods and mounted on a custom-made platform working directly in front of the surface of the sculpture.

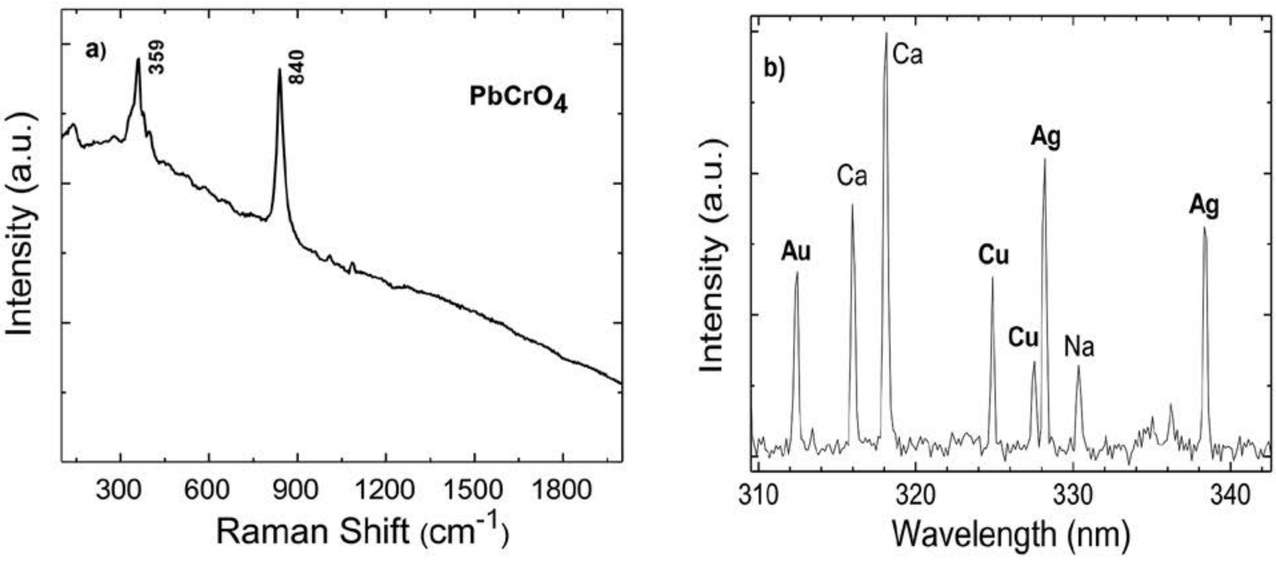

Figure 6 a) Raman spectrum of chrome yellow ($PbCrO_4$) collected from traces of yellow paint, and b) LIBS spectrum of the gold-silver-copper alloy (Au-Ag-Cu), both detected on sculpture AI 244.

LIBS analytical strategy for the integrated investigation of a sculpted door frame of the 15th century, colored in different periods, at the church of St George in the village of Kamariotis (Gratziou 2010). Both instruments were used in-situ, directly on the artwork with the use of appropriate scaffolding (Fig.7).

Micro-Raman spectroscopy detected the presence of ultramarine ($Na_{6-8}(AlSiO_4)_6S_{2-4}$) at the light blue areas of the columns; carbon black was the pigment identified by the same technique at the dark blue areas and anhydrous ferric oxide (Fe_2O_3) was determined as the red pigment found on the red column (Fig.8a). These data are in accordance

FIGURE 7.IMAGES TAKEN DURING THE CAMPAIGN AT THE CHURCH OF ST GEORGE IN THE VILLAGE OF KAMARIOTIS.

with the dominant presence of iron (Fe) on the red column and CN (indicative of carbon) molecular emission at the dark blue areas as detected by LIBS. The analysis by LIBS shows the prominent presence of iron (Fe) at the light blue areas, which could be interpreted as deriving from the presence of Prussian blue ($Fe_4[Fe(CN)_6]_3$) in mixture with ultramarine blue. Moreover, the detection of chromium (Cr) and lead (Pb) on the yellow column indicates strongly the presence of chrome yellow ($PbCrO_4$) in mixture with possibly hydrous ferric oxide ($Fe_2O_3 \cdot nH_2O$), as it can be appreciated by the concurrent detection of iron. Furthermore, the existence of manganese (Mn) can be interpreted as evidence of manganese black (MnO_2) on the brown column (Fig.8b). The presence of titanium (Ti) at the red, yellow and brown areas is ascribed to titanium white (TiO_2), and the simultaneous detection of barium (Ba) and zinc (Zn) at the red, yellow and light blue areas may imply an indirect identification of the extender lithopone ($BaSO_4 \cdot ZnS$). Both of these materials may be coming from later conservation interventions known to have taken place at this church.

Conclusions - outlook

As outlined in this paper, the proposed analytical strategy based on the combined use of Raman and LIBS mobile instrumentation is a versatile one, which combines key analytical features and holds potential for becoming a useful tool in support of analytical survey and conservation campaigns. Both techniques provide within seconds or minutes valuable results, essential for assessing a broad spectrum of materials ranging from pigments, minerals and pottery to glass, stone and metals. Future tests and practical applications of these instruments will undoubtedly lead to further technological and methodological improvements with less expensive systems becoming available to a broader user community. But more importantly a close collaboration and interaction of scientists and engineers with conservators, historians and archaeologists, will help develop instruments, methods and strategies tailored to the needs of the actual users enabling them to make routine use of these techniques for addressing day-to-day problems as well as important analytical challenges in archaeological science and conservation.

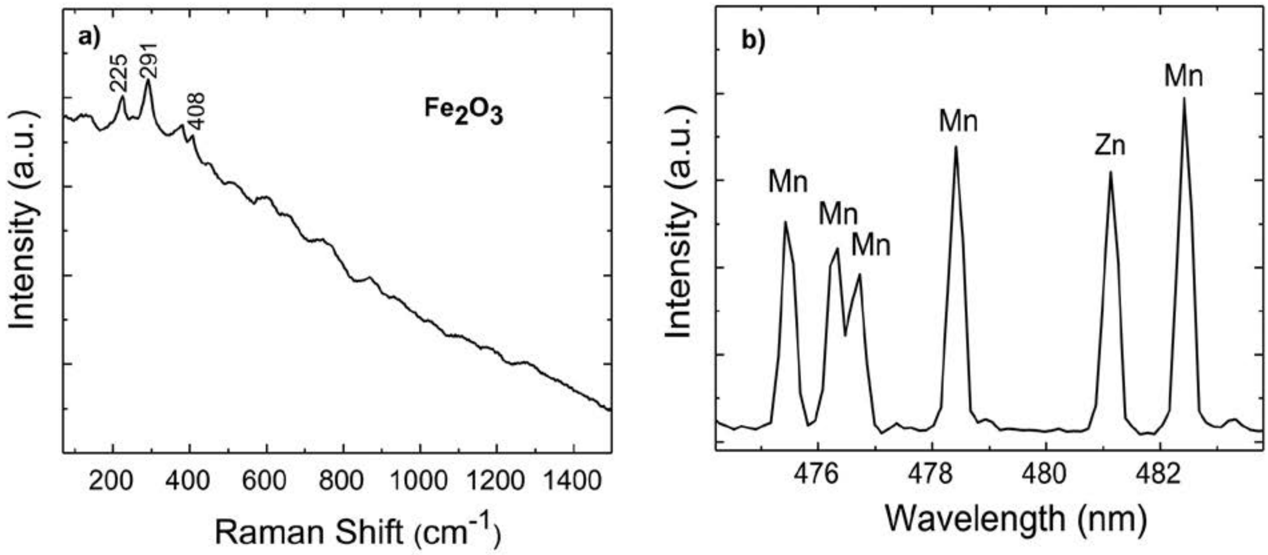

Figure 8 a) Raman spectrum of red ochre (Fe_2O_3) collected from the red column, and b) LIBS spectrum recorded on the brown column, of the colored door frame.

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