UNIVERSITY OF CALIFORNIA, MERCED

Redefining Digital Archaeology

New Methodologies for 3D Documentation and Preservation of Cultural Heritage

A Dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

World Cultures

by

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To Paola…constant presence in our never-ending
journey, and Edoardo…my little big world citizen

A Paola…presenza costante nel nostro viaggio senza fine,
e Edoardo…il mio piccolo grande cittadino del mondo

If on arriving at Trude I had not read the city's name
written in big letters, I would have thought I was landing at
the same airport from which I had taken off…Why come to
Trude? I asked myself. And I already wanted to leave.
"You can resume your flight whenever you like," they said
to me, "but you will arrive at another Trude, absolutely the
same, detail by detail. The world is covered by a sole Trude
which does not begin and does not end. Only the name of
the airport changes." (Italo Calvino)

Se toccando terra a Trude non avessi letto il nome della
città scritto a grandi lettere, avrei creduto d'essere arrivato
allo stesso aeroporto da cui ero partito...Perché venire a
Trude? mi chiedevo. E già volevo ripartire. "Puoi
riprendere il volo quando vuoi," mi dissero, "ma arriverai a
un'altra Trude, uguale punto per punto, il mondo è ricoperto
da un'unica Trude che non comincia e non finisce, cambia
solo il nome all'aereoporto." (Italo Calvino)

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geometric information can easily be integrated in the digital archaeological excavation plan (De Reu et al. 2012: fig. 4).

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Curriculum Vitae

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Acknowledgements

Abstract

Redefining Digital Archaeology
New Methodologies for 3D Documentation and Preservation of Cultural Heritage
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This research aims to investigate the potential use of 3D technologies for the analysis and interpretation of archaeological and heritage sites. The use of 3D laser scanners and dense stereo matching (DSM) techniques is well established in archaeology, since these techniques allow to digitally preserving information through time, giving the opportunity to multiple experts to revisit the information over the long-term. However, no convincing comparisons between those techniques (3D laser scanners and DSM) have been presented until now. This research fills the gap providing an accurate data assessment for the Las Cuevas site (Belize), and representing a concrete starting point for the definition of a sharable methodology.

Tests in different areas of Las Cuevas's site were conducted to compare both accuracy and density reliability of 3D models coming from laser scanning (triangulation light and time of flight laser scanner) and DSM. This study finds DSM as the most economical, portable, flexible, and widely used approach for the 3D documentation of archaeological sites today. In fact, DSM allows fastening the 3D documentation process, reducing both data acquisition and processing time. Nonetheless, the quantitative comparison presented in this research underscores the need to integrate this technique with laser scanner technologies when the data acquisition of micro-stratigraphy is required.

More broadly this research aims also to clarify if the use of new technology allows increasing the objectivity of the excavation process. Scholars are debating on the authenticity of 3D digital reproductions and simulation in heritage and archaeology. How should we consider these digital and virtual reproductions and simulations? Are they original digital representations of our cultural heritage or just virtual 'fakes'? Overall, the results of this research suggest that is not possible to define universal predetermined categories for the definition of 'authentic', since 3D digital reproductions and simulations of tangible heritage are influenced by subjective choices and interpretations of the creator of 3D contents.

Chapter 1

Introduction

Archaeology is becoming increasingly 'digital'. In the last ten years the use of new technologies for the 3D documentation and reconstruction of cultural heritage has changed the way to approach the archaeological survey. The use of 3D laser scanners and photogrammetric methods is well established now. One of the main reasons for this development is the possibilities that these techniques give to digitally preserve the information through time. In this way archaeology can be revisited over the long-term and, thanks to new discoveries, analyzed by multiple experts and subjected to new analytical techniques.

The interest in archaeological 3D documentation has greatly accelerated over the past decade (e.g. Addison 2008; Bobowski et al. 2008; Dell'Unto et al. 2008; Fröhlich and Mettenleiter 2004; Galeazzi et al. 2007; Koch and Kaehler 2009; Neubauer et al. 2005; Zubrow 2006). 3D technologies are being used more commonly in archaeology, but this can become problematic because researchers have yet to integrate these technologies to develop a complete and coherent methodology for 3D documentation of sites. This research seeks to remedy this through a complete documentation of an archeological site using different 3D survey technologies to find the most appropriate methods based on diverse environmental conditions and light exposures, and with varied surfaces. While the use of one of these technologies is well established for the documentation of archaeological sites (e.g., Abate et al. 2008; Dell'Unto et al. 2008; Craig et al. 2006; Neubauer et al. 2005; Galeazzi et al. 2007), there are only a handful of scholars who compared different techniques on site, and usually this evaluations considered just two technologies at a time (Dell'Unto et al. 2006; Koch and Kaehler 2009). The 3D documentation of the archaeological excavation process in real-time is one of the most challenging aspects of this research. The proposed work uses different 3D survey technologies to find the most appropriate methods to document different aspects of an archeological site.

One of the main goals of this research is to compare different 3D laser scanner technologies (triangulation, time of flight and phase-shift variation) with dense stereo matching technique. The analysis of all those techniques on site is fundamental to have a complete and comprehensive test of their potentialities, and to verify the possibilities to integrate them effectively in the 3D documentation process.

Even if time-of-flight and triangulation laser scanner technologies proved to be powerful tools for the 3D documentation of archaeological sites, they still present considerable limits in terms of cost ($40,000 to $100,000) and usability. For this reason, researchers have started to invest in more usable and less expensive techniques such as dense stereo matching. Dense stereo matching allows 3D data generation starting from a series of uncalibrated images. This technique is cheaper than laser scanner technologies— the acquisition of data is possible using a medium quality camera and post-processing software. Moreover, dense stereo reconstruction tools are more usable. The training required to acquire the basic knowledge for the use of this technique is considerably less than that necessary for data acquisition and post-processing using a laser scanner.

Software based on dense stereo matching is, currently, well established in archaeology and largely used for the 3D documentation of the archaeological stratigraphy (Dellepiane et al. 2012; Doneus et al. 2011; Fratus de Balestrini and Guerra 2011), but there are not examples of accuracy comparison between 3D models acquired with laser scanning and dense stereo matching techniques.

Whether the less costly and more portable dense stereo matching technique gives similar results, in terms of level of detail, to the more expensive laser scanner technologies is one of the most debated questions in archaeology and heritage studies today. The potential to record a monument/site in 3D just by taking pictures represents a revolutionary change in the discipline; the unprecedented dissemination of 3D representations of tangible heritage. However, scholars have not yet made quantitative comparison between the different techniques on site. For this reason, this dissertation research compared both accuracy and density reliability of 3D models coming from three techniques: triangulation light laser scanner (Minolta Vivid 910); phase shift variation laser scanners (Faro Focus 3D); and dense stereo matching (Photoscan, Agisoft). This on-site, comparative analysis is fundamental to

the goal of having a complete and comprehensive understanding of their technical abilities and research related potential, as well as the ability to verify their use and integrate these technologies effectively in the 3D documentation process.

Research questions informing this study are:

Research Question 1 – Do different environmental conditions, primarily different light exposures at the site, affect the choice of the technologies to be used during the data acquisition? Moreover, can different 3D survey technologies be chosen based upon the kinds of archaeological contexts to be examined?

Research Question 2 – Can dense stereo matching technique produce 3D data that have a geometric accuracy similar to that of laser scanner technologies?

Research Question 3 – What is the ontology of 3D metric replicas and simulation of tangible heritage? Should they be considered authentic digital reproductions of cultural heritage or just 'fake' representations?

Research Question 4 – To what extent does the creation of a 3D interactive application for archaeological 3D data sharing improve research? Can 3D technologies help create novel research questions? Can 3D technologies improve students' understanding of the archaeological record?

To answer questions number 1 and 2 data were collected at Çatalhöyük, Turkey, and Las Cuevas, located at the Las Cuevas Research Station in the Chiquibul Reserve in western Belize.

The 3D documentation campaign at Çatalhöyük took place in the summer of 2010 with a triangulation light laser scanner, the Konica Minolta VIVID910, which was used to scan the stratigraphic units of Building 86, a mud-brick house, in Çatalhöyük, Turkey. This

device can reach a level of detail of microns. Because this is a no-contact 3D scanning method, it does not interfere with the excavation process and the archaeological units. Moreover, it produces highly accurate 3D digital representations that are readily shared, indefinitely reproducible, and cheaply and efficiently stored, favoring the preservation and data storage of a very detailed 3D reproduction of the layers that would otherwise be impossible, considering the destructive nature of the archaeological excavation process.

The results of this data analysis confirmed the potential of time of flight laser scanner technology for the 3D documentation of archaeological context, and the limits of this technique for reaching sub-centimetric precision. Although, in fact, this technology delivers a point cloud with high density, the accuracy of individual points barely reaches one centimeter (Galeazzi et al 2010: 102; Koch and Kaehler 2009: 1).

Based on the findings from the Çatalhöyük project other techniques were compared in the Las Cuevas's site. This site, originally referred as "Awe Caves", is a medium-sized Maya ceremonial center located approximately 14 km east of Caracol. It is of particular interest because a large cave with an extensive dark zone tunnel system resides directly beneath the largest temple in the site core. This archaeological site is a perfect case study to test the different 3D documentation techniques and to integrate them in a precise working plan. The most interesting aspect of this site, from the standpoint of 3D documentation, is the heterogeneity in its parts. It consists of temples, range structures, a ballcourt, and what appear to be sacbes and causeways. These characteristics represent a perfect test to determine which 3D survey technologies are more appropriate for each structure category and how they can be integrated. Because of the complexity of the site, it has a wide range of environmental conditions – dark recesses of caves, areas in shaded sunlight under the jungle canopy, and areas of more direct sunlight in areas that have been cleared of brush or exposed by treefall. Thus, there is structure and lighting variability, and other kinds of features in close proximity.

The data collection done using integrated technologies highlighted the potentialities and performances of each technology and integrated them in a common working plan.

Thanks to their integration it was possible to transform the traditional archaeological documentation process, making it digital in all its parts. The possibility to completely survey Las Cuevas digitally in 3D using integrated technologies starting from a detailed comparison of the 3D models acquired using different documentation techniques represents a revolutionary change in the discipline.

The analysis of the accuracy and quality of the 3D models was possible thanks to a multidisciplinary collaboration with computer and cognitive scientists. These models, in fact, were verified in terms of resolution, perception and visualization.

Generally speaking, the results of this study strengthen the potential of dense stereo matching for 3D documentation of heritage sites, confirming the improvements, over the last few years, of this technique's ability to capture the level of detail needed for research purposes. This technique allows good reliability in the metric representation of the monument/site information, and more importantly, it is the most economical, portable, flexible, and widely used approach for the 3D documentation of archaeological and heritage sites to date. However laser scanner techniques seem more appropriate for the 3D reproduction of monuments/sites when the preservation of millimetric details is paramount. For now, the integration of laser scanner technologies with dense stereo matching seems like the optimal solution for the acquisition of all monument/site geometrical information.

This discovery can also increase the use of 3D documentation methods among scholars who want to understand the discipline and personally test these technologies. The extreme flexibility and portability of the photogrammetric method can promote teaching, training and learning, giving the possibility to students that lack access to the more expensive 3D laser scanner technologies, to experience some of the tools used during the documentation of an archaeological site. In this way they can understand the archeological documentation process from classes and be trained for real fieldwork (Di Giuseppantonio Di Franco et al. 2012).

Three dimensional metric replicas and simulation of archaeological sites/monuments are powerful tools for the analysis, understanding and interpretation of tangible heritage, since they give the opportunity to virtually revisit the archaeological context and excavation process by multiple experts without the limitations of space and time. In fact, today digital archives and the web allow preservation, sharing and accessibility of 3D data, favoring an unprecedented dissemination of information. For this reason scholars today are discussing the real value of 3D replicas and simulation of tangible heritage.

This research stresses the importance and value of 3D replicas and simulation of archaeological sites/monuments in the more broad discussion on authenticity in archaeology and heritage studies started in the 1960s with Walter Benjamin (1968), and continued by Baudlillard in the 1980s, who states that the need for simulation brings to the production of hyperreality of culture (Baudrillard 1986: 121).

To answer questions 3 and 4 different 3D real-time visualization systems were developed and tested thanks to a multidisciplinary collaboration between archaeologists, computer scientists and cognitive scientists at the University of California, Merced, to understand if the sense of spatiality and interactivity increase the understanding of the archaeological context. While the large use of 3D technology in archaeology over the last ten years has demonstrated the strong potential of this new tool for the communication and preservation of cultural heritage, its efficacy in research (data analysis and interpretation) and education is still not very clear and tested.

The 3D real-time systems were used by both specialists and students at UC Merced to understand if it is possible to reproduce the archaeological context and excavation process virtually. This opportunity is of extreme importance, especially considering the fact that the traditional interpretation phase of an archaeological excavation usually happens in labs after the dig is concluded. The integration of different technologies, in a precise working plan, could permit a complete 3D documentation of the site. What is needed, in fact, is to pass from a two-dimensional and transcribed way to approach the archaeological documentation process, to the three-dimensional and the digital. It is

essential, not just to preserve the data acquired, but also simulate in 3D the original shape and context of the cultural heritage that the archaeological site represents, in the attempt to understand its original nature. The interpretation made by the specialist allows the 3D reconstruction/simulation of the site. The term simulation is used here to intend the subjective nature of the reconstruction process. In the systems developed in this research, the 3D reconstructions were clearly distinguished from the reproduction of the excavation process and the actual site. In this sense the 'transparency' of the reconstructive process will permit new interpretation in the future.

The new methodology develop by the candidate can be a fundamental instrument to increase sharing and the accessibility of digital data in archaeology. Thanks to the creation of the interactive applications that can be widely consulted, this work will have a broader impact in the dissemination of archaeological research results. This can provide a new and innovative instrument for the data sharing, increasing the level of participation of scientists and students in archaeology and heritage studies.

My doctoral work comprises 7 chapters, including the present introduction.

The second chapter, *Archaeological excavation methods: state of the art*, provides an overview of the state of the art of the archaeological excavation method. Starting from the origin of archaeology, this first part of the dissertation wants to describe how the techniques of excavation and documentation have changed in the last forty years, and how new technologies can positively improve the documentation process on site.

The third chapter, *Digital Archaeology: status of existing research in 3D documentation and analysis of archaeological sites*, examines the development of digital archaeology over the last ten years, stressing the impact that the 'digital' had in archaeology and how this field of study is officially part of the *digital village* described by Zubrow (2006: 9). Moreover this section will examine the growth of information technology in 3D documentation tools in the last forty years. A process that started in the 1970s, when the advent of photogrammetry and early workstations allowed the first examples of digital documentation, and has concluded today with growing availability of 3D laser scanner. The effectiveness of digital technology in field archaeology and the impacts that this has

are illustrated in this section through examples illustrating the practical use of real time recording on site.

After the introduction of the case studies involved in this research in chapter four, *Case studies*, the fifth chapter, *Digging digitally using integrated technologies: data acquisition and comparison*, is the core of my research. This chapter details the research methodology used in the study and the results of the accuracy comparison conducted between the 3D models coming from laser scanning and dense stereo matching techniques.

The sixth chapter, *3D interactive systems for the spatial analysis, preservation and simulation of the archaeological record*, explores the potential of new technologies in the interpretation and virtual recreation of archaeological sites and monuments' original context. Digital technologies allows to preserve 3D metric replicas of the site/monument and simulate multiple virtual interpretations of the same archeological context that can be compared and analyzed by multiple experts.

This section stresses the importance of multidisciplinary research. Thanks to collaboration with cognitive scientists working at UC Merced, it was possible to design some cognitive experiments to determine if the use of 3D versus 2D tools, changing our space perception of the information, can improve the understanding of the archaeological records, supporting the analysis of the data.

The *Conclusions* summarizes the effectiveness and reliability of the methodology developed in this research, describing the impact this new method will have in understanding the real potential of the different 3D technologies for the documentation of archaeological sites and how new technologies can increase sharing and accessibility of digital data in archaeology through the creation of interactive real-time systems.

This last chapter also covers future improvements of this research, exploring the opportunity to develop a 3D real-time visualization system (3D viewer) that will allow the management, analysis and visualization of 3D realistic and metric reproduction of archaeological stratigraphy and contexts. The challenge of this future work will be the integration of the 3D viewer in online information aggregators for different resources (online data archives), giving users the possibility to access 3D archaeological data to ground-truth interpretations.

Up to now the efforts in the preservation of the archaeological record have produced a great number of digital data archives. Most of them focus on the preservation of the information over time without thinking about the fruition of this data on the part of the scientific community. In this sense the candidate's continuing research will improve new infrastructure for research and education through different activities with researchers and students in archaeology. The final product will be the creation of a 3D application that will be used for both scientific research and the creation of models and digital objects for heritage preservation and outreach activities.

This research is intended to be a starting point in the development of a new method for the 3D documentation, reconstruction and visualization of the archaeological excavation process and context. The results of this research will be disseminated in a number of different ways. They will be presented in papers at professional meetings and scientific articles in archaeological and scientific journals. Moreover the data will be also archived in the California Digital Library's Merritt repository (http://merritt.cdlib.org/) and accessible for future generations. This kind of infrastructure can participate in forming new generation of scientists, but also in diffusing knowledge to the general public.

Chapter 2

Archaeological excavation methods: state of the art

This chapter considers various methods of archaeological excavation and recording that not only affect how archaeologists carry out their work, but also potentially affect the possible interpretations of the archaeological context. These include the incorporation of stratigraphic information, vertical vs. horizontal excavations, and use of natural vs. arbitrary excavation levels. The first part of the chapter introduces the notion of stratigraphy and how the concept evolved in the last century. From the geological point of view of the 19th century, the concept of stratigraphy started to assume an archaeological meaning during the first half of the 20th century. Then the chapter concentrates on the different strategies used during the excavation process, such as vertical vs. horizontal excavation, arbitrary vs. stratigraphic excavation, and the importance of the interfaces in the understanding of the stratigraphic relations. In the last paragraphs the chapter discusses the evolution of the stratigraphic methods and Harris Matrix in the United Kingdom, and how different schools out of England contributed to the evolution of the archaeological practice.

2.1. The notion of stratigraphy: from geology to archaeology

Until the end of the 19th century, geology had a strong influence on the development of the knowledge in archaeological field (Daniel 1975: 25). According to Edward C. Harris, at the beginning of the 20th century stratigraphy in archaeology was conceived as starting from a geological point of view (Harris *et al.* 1993: 55).

On-site archaeological documentation acquired for the first time the third dimension in the 1880s, when Pitt-Rivers started to record objects in three measured dimensions—one for the absolute height of the find-spot and other two to site the object on a horizontal plane (Pitt-Rivers 1892: 90-95, Plate CLXXI). But this method presented some limits. Pitt-Rivers'

sections were not records of actual soil profiles as seen on the site, but were reconstructions. Moreover, the objects were not recorded in relation to a numbered archaeological layer.

The first attempts to stress the importance of archaeological stratigraphy were made by Max Uhle (1907), John Percival Droop (1915) and by Alfred Vincent Kidder (1924). Uhle's excavation at the Emeryville shellmound, the deepest site in the San Francisco Bay Area, was conducted in 1902 and is the first stratigraphic excavation in California. Ten strata with ten burials confined to the five middle strata were excavated on the west side of the mound. Uhle proposed three major periods for the development of the mound which correspond to the Early, Middle and late periods recognized today (Uhle 1907: 3). Droop's book *Archaeological Excavation* contains the first attempts to show through graphic drawings the nature of archaeological stratigraphy stressing the value and importance of the interface (the point of contact between two layers or features in an excavation) in archaeological practices (Droop 1915). While Kidder's *Introduction to the Study of Southwestern Archaeology* (Kidder 1924) was the first synthesis of North American prehistory based on professionally recovered empirical data. Kidder's research, through a systematic examination of stratigraphy and chronology in archaeological sites, contributed to lay the foundation for modern archaeological field method (Kidder 1924).

An important change in the archaeological documentation occurred with Mortimer Wheeler. He introduced the use of the actual soil section and the grid system: "From the outset, the strata are carefully observed, distinguished, and *labelled* as the work proceeds. It is, of course, as the work proceeds that 'finds' are isolated and recorded, and their record is necessarily integral with that of the strata from which they are derived" (Wheeler 1955: 54, italics in the original). These are the most important principles of the so-called Wheeler-Kenyon system of archaeological stratigraphy that introduced two important elements in the theory of archaeological stratigraphy—the value of the interface (i.e., the contact between two strata) and layer numbering. The latter indicates the systematic provenience of the artifacts from the deposits (Harris 1993: 55; Kenyon 1961: 69).

Since late 1970s very few efforts have been made in describing and creating methodologies for archaeological excavation. The lack of interest in this topic was clearly stressed by Kathleen Kenyon:

Excavation methods are a subject about which practically no mention is made in publications, and about which only people who have made prolonged visits to digs have any idea…in full scientific reports, the methods can often be deduced, but they are seldom described, as it is taken for granted that the reports will mainly be read by fellow excavators who will not require to be told about the methods [Kenyon 1939: 29].

A change in the contemporary archaeology occurred with the introduction of the *open-area excavation*. This strategy, in which more attention is given to the recording of the layers of soils and not just of structural features (a collection of one or more contexts representing some human non-portable activity that generally has a vertical characteristic to it in relation to site stratigraphy. Examples are features pits, walls, and ditches), was used at Glastonbury Lake Village excavation, reinterpreted in 1972 by David L. Clarke (1972), and standardized for the first time in 1975 by Philip Barker in his Wroxeter excavations. The plans produced during the dig are a clear example of this documentation method, which attempts to record the entire surface exposed by the excavation (Fig. 1).

Barker is credited with introducing the pre-printed recording sheets for the written descriptions of layers and features (Barker 1977: fig. 46). *Techniques of Archaeological Excavation* is the first published work that stresses the importance of the methodological aspect in the excavation and documentation of an archaeological site (Barker 1977). But according to Carandini, the real revolutionary change occurred with the phase that Carandini called "fase harrisiana," the Harris phase. He believes that this is the beginning of the contemporary fieldwork archaeology (Carandini 1981: 80). In 1973, Edward C. Harris invented an archaeological tool known as the "Harris Matrix" during the post-excavation analysis of site records compiled in the late 1960s at Winchester. The new method of stratigraphic analysis was published for the first time in June 1975 (Harris 1975). Before analyzing this revolutionary change in the archaeological documentation on site and during post-excavation analysis, it is important to describe the most common strategies and process used up to that moment for the archaeological dig.
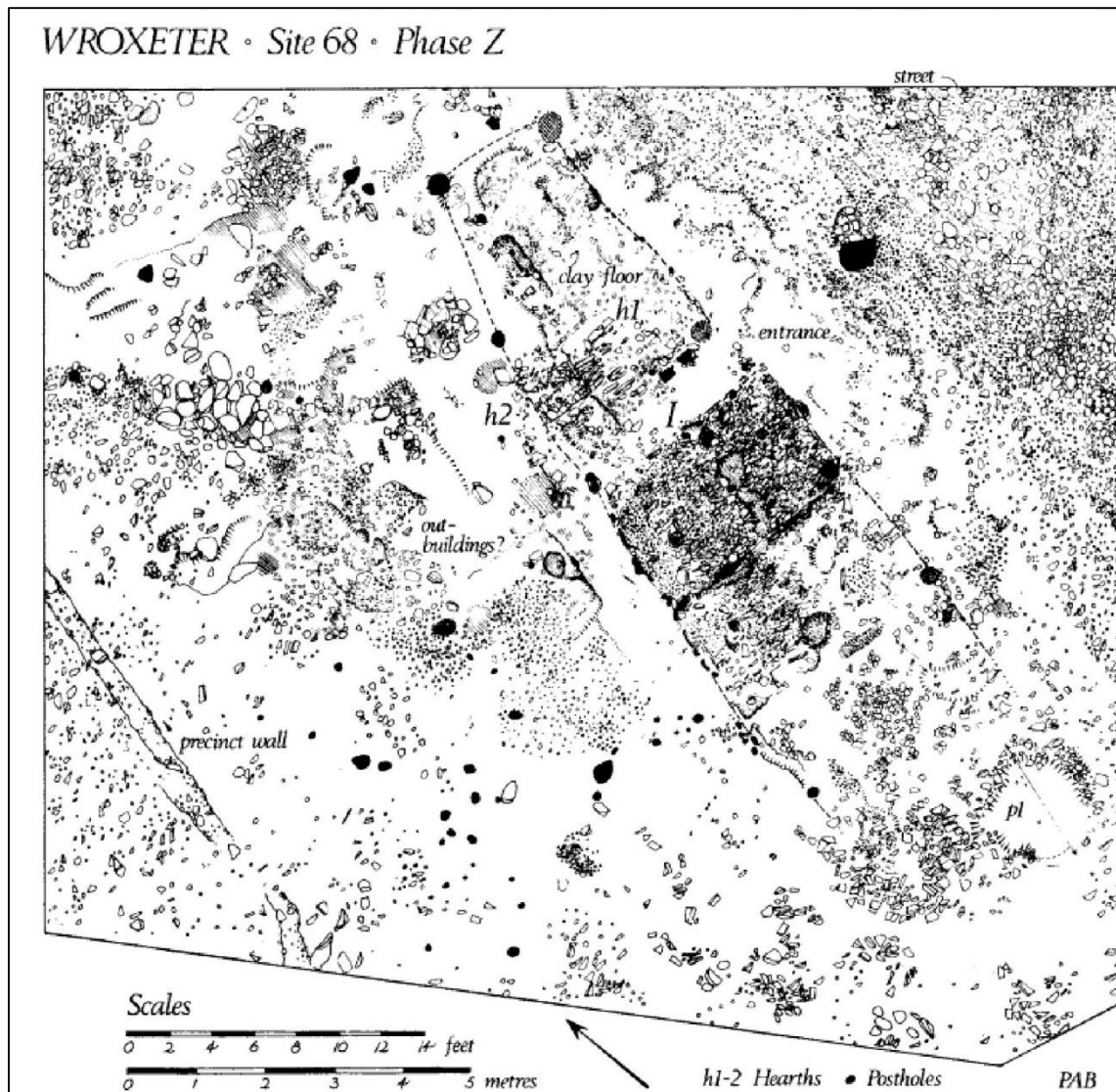
Figure 1. Example of *open-area excavation*, Baths Basilica at Wroxeter (Barker 1975: Fig. 3).

2.2. Strategy: vertical vs. horizontal excavation (Wheeler box-grid vs. Barker open-area excavation)

There are different methodological approaches to excavation, which Harris refers to as *strategies* (Harris 1975: 16) and Renfrew refers to as *techniques*. Renfrew and Bahn give in their introductory textbook on archaeology a simple, but very clear and effective,

definition of the two main excavation techniques, differentiating archaeologists who prefer to emphasize the vertical dimension −cutting into deep deposits to reveal stratification − from those who favor the horizontal dimension by opening up large areas of a particular layer to reveal the spatial relationships between artifacts and features in that layer (Renfrew and Bahn 1991: 92). The key element of both horizontal and vertical approaches is clearly space. The research that is presented in the next chapters of this dissertation stresses the importance of space in approaching excavation and documentation of an archaeological site. How and why do archaeologists decide to choose one method instead of the other? Does our personal perception of space, resulting from our personal experience, affect our decisions in this sense?

The horizontal and vertical approaches are mainly associated with two archaeologists who pioneered the methods. The Wheeler box-grid strategy seeks to satisfy both vertical and horizontal requirements; nonetheless, this is often associated with the vertical approach due to the importance given to the section retaining intact earth (i.e., baulks) between the squares of the grid. This type of archaeological profile is called *standing* sections. According to Harris, this method has some consequences:

1. The stratigraphic success of the excavations depends almost entirely upon the record of the section. Yet these must be drawn in an unhurried and unharried atmosphere at the end of the excavation when the required leisure is usually wanting.
2. Since the section is not recorded until last, it is likely to have eroded its face during the course of the excavation. It is possible therefore that there may be little correlation between the excavated deposits and the relationships far later observed in the once adjacent section face [Harris 1975: 54].

The *incidental* sections differ from standing sections, because they are revealed during archaeological excavation in areas subject to urban development (rescue archaeology). An appropriate method to record this kind of section is that described by Webster (1974: 66): "Any hurry at this stage is fatal to the whole enterprise, as the complete interpretation of main periods and relationship of all layers has to be established at this point.

As one draws each layer or feature, so its relationship to other layers is established." Finally, the *cumulative* section was introduced by Philip Barker as a consequence of open-area excavation. The open-area excavation method emphasizes the horizontal dimension, by opening large areas to reveal the spatial relationships artifacts and feature of each layer. According to Barker, if ten sites are to be destroyed it is better to dig two of sites totally and properly than to trench or partially excavate all ten: 'The fundamental principle of all excavations should be to remove and record each layer or feature in the reverse order from which it was deposited, over as extensive an area as possible' (1977: 54). However he recognized that there are some circumstances where the ideal must be modified; for example, when standing walls are present (Barker 1977: 54).

Barker's main critique of the Wheeler box-grid method is that the baulks prevent one from distinguishing of spatial patterning over large areas. Nonetheless, the open-area approach emphasizes the horizontal method and it also satisfies the vertical method, thanks to the introduction of the aforementioned cumulative sections: 'in this method, the excavation is carried up to a pre-determined [i.e., notational] line and the section drawn. The excavation then proceeds beyond this line. Each time the excavation reaches that line in the future the section will be drawn' (Barker 1977: 80). The considerable advantage of this method over the section cut on a notional line is that there is a direct correlation between the stratigraphic evidence recorded in section and that in the plans.

2.3. Arbitrary vs. stratigraphic excavation

The method of excavating arbitrary levels was of common use in archaeology up to the first quarter of the 20th century. According to Pitt-Rivers, the proper way to excavate perfectly defined this approach in digging an archaeological site. He suggests working down from the top in a sequence of spits, a unit of archaeological excavation with an arbitrarily assigned measurement of depth and extent without regard to the archaeological stratigraphy that may be identifiable at the archaeological site under investigation. The method of excavating in arbitrary spits (level for American archaeologists) is most

frequently used at site excavations which lack any visible or reconstructable stratigraphy in the archaeological context, or when excavating through intrusive or fill deposits (Roskams 2001: 112). Pitt-Rivers gave more importance to the recovery of artifacts and their position than to stratigraphic details (Pitt-Rivers 1892: 90-95, Plate CLXXI).

The first person to introduce the process of stratigraphic excavation was Mortimer Wheeler during his work at Maiden Castle in the 1930s, noting the "peeling off successive strata in conformity with their proper bed-lines, and thus ensuring the accurate isolation of structural phases and relevant artefacts" (Wheeler 1955: 53). The process of stratigraphic excavation is commonly recognized to be the best option when archaeological layers and features can be distinguished in the site's stratification (Barker 1977: 54; Carandini 1981: 31; Harris 1979: 19; Renfrew and Bahn 1991: 91; 33). In this method, the site's layers are excavated according to their natural shapes and dimensions and in the reverse order to that in which they were deposited. The main laws of archaeological stratigraphy are the law of original continuity, the law of original horizontality, the law of stratigraphical succession and the law of superposition.

Law of original continuity

"Any archaeological deposit, as originally laid down, will be bounded by a basin of deposit or will thin down to a feather-edge. Therefore, if any edge of a deposit is exposed in a vertical plane view, a part of its original extent must have been removed by excavation or erosion: its continuity must be sought, or its absence explained. Conversely, any feature interface, as originally created, will have had a continuous surface. If sides of the feature appear in section, a part of its original extent must have been destroyed, its continuity sought or absence explained" (Harris 1975: 124).

Law of original horizontality

"Any archaeological layer deposited in an unconsolidated form will tend towards a horizontal disposition. Strata which are found in a tilted form were so originally deposited, or lie in conformity with the contours of a pre-existing basin of deposition" (Harris 1975: 124-125).

Law of stratigraphical succession

"Any given unit of archaeological stratigraphy takes its place in the stratigraphic sequence of a site from its position between the undermost of all units which lie above it and the uppermost of all those units which lie below it and with which it has a physical contact, all other superpositional relationships being regarded as redundant" (Harris 1975: 125).

Law of superposition

"In a series of layers and interfaces, as originally created, the upper units of stratification are younger and the lower are older, for each must have been deposited on, or created by the removal of, a pre-existing mass of archaeological stratification" (Harris 1975: 124-125).

In 1993, Adrian Praetzellis published a very interesting comparison between the arbitrary and the stratigraphic methods, trying to underline the possible reasons for the still widespread use of arbitrary levels, especially in the United States (Praetzellis 1993: 69). European-trained excavators have been the most critical of what is known in US as "arbitrary" or "metrical" excavation and in Britain as the "planum" technique (Barker 1977; Carandini 1981; Harris 1975; Manacorda 1983; Wheeler 1955). James A. Ford and Raymond H. Thompson answered to this critique, insisting that European archaeologists did not understand the reasons and circumstances for the use of the arbitrary method (Ford 1962; Thompson 1955). The differences between these two methods can be understood just by analyzing the terms and terminology used. In North America, the terms "layer" and "level" are often synonymous and are applied to "demarcation of associated remains by natural (geological), cultural (for example, buildings), or arbitrary events (excavation techniques)" (Hole and Heizer 1969: 103). In Britain, since the arbitrary excavation is not considered a valid option and the term "level" has evolutionary implications, "layer" is associated with both human and geological strata (Barker 1977; Harris 1975).

One of the main reasons for the use of the arbitrary excavation—for example, in the arid western United States—is that most sites are not physically stratified. This site structure represents a constraint on the method (Praetzellis 1993: 72). Heizer's (1953: 44) description of most central California prehistoric sites seems to confirm this statement, as he described them as "…soft homogenous and unstratified dark midden deposit of

indefinite depth, often overlaid by a shallow layer of sterile topsoil and underlain by sterile subsoil which is usually gray, yellow, or red clay." In the western United States, layering seems to represent more natural than cultural processes. Alluvial, aeolian and other natural forces may form the deposit. For example, in a cave environment, material coming from the roof over many years may bury artifacts and features.

The method of arbitrary vertical excavation was first used in 1865 by William Pengelly in southern England (Wheeler 1955: 53), and was probably introduced in North America and applied to the site of Pueblo San Cristobal, in New Mexico, by Nels Nelson (1916). Nels Nelson initially worked with Alfred Kroeber and Max Uhle at the University of California at Berkeley. He probably acquired the method in the excavation of Castillo Cave during a visit in Spain in 1913 (Nelson 1915: 237).

In the late 1950s, the New Archaeology movement injected a sense of place into archaeological fieldwork, but only made minor changes in the excavation strategy. Arbitrary levels and excavation units were now measured in the metric system. The 1x1 m excavation unit and the 10 cm arbitrary level become a standard in North America for some years (Praetzellis 1993: 80). In the late 1960s and early 1970s an important evolution in the practice of North America archaeology occurred. Both federal and state cultural resource laws were passed and, thus, archaeological studies were required in advance of development projects (King et al. 1974).

European archaeologists agree on the fact that arbitrary excavation method can be used in those archaeological contexts where it is not possible to recognize physical layers and interfaces between the strata (Carandini 1981: 51; Harris 1975: 20). According to Carandini, in the presence of natural strata and in a other few cases where the homogeneity of the soil seems to have cancelled any visible interface it is convenient to dig using the arbitrary levels or "plana," to acquire the three dimensional position of artifacts and features. Also, a layer of anthropic origin that is of remarkable depth—and thus, is impossible to fully dug—can be removed in horizontal levels. However, it is not necessary to document such levels, since they are the result of a purely practical division (Carandini 1981: 51). But European archaeologists encourage using in all the other circumstances the stratigraphic method and open-area strategy, because it is the method that allows a more

complete understanding of archaeological context (Barker 1977; Carandini 1981; Harris 1975; Manacorda 1983).

Praetzellis (1993) states that the stratigraphic method is an archaeological practice appropriate just for historic period archaeological sites (1993: 83). This old-fashioned association of the stratigraphic method with historic period archaeological sites should be overcome, since this method is perfectly applicable in archaeological context of different periods, from Paleolithic to historic sites. This because, according to Carandini, the archaeological excavation (excluding the exception previously mentioned − presence of natural strata and where the homogeneity of the soil seems to have cancelled any visible interface) has always proceeded by strata and real surfaces rather than by pre-determined levels and in the inverse order of strata formation (1981: 51).

2.4. The contribution of Italian archaeology to the development of the archaeological excavation method

The contribution of Italian archaeology to the development of the archaeological excavation method is clear example of how archaeological practice was developed and improved by the different European schools. Italian archaeology was chosen as case study because was extremely important on developing new archaeological documentation methods and forms, such as the USM (*Scheda di unità stratigrafica muraria*/Masonry stratigraphic unit sheet) and the USR (*Scheda di unità stratigrafica di rivestimento*/Plastering stratigraphic unit sheet). This is just an example of how archaeological practice and methods were changed and improved based on specific and regional needs.

According to Manacorda, archaeology—in its aspect of scientific research more than in academic practice— is more established as an historical science in Italy than it is anywhere else in the world (Manacorda 1983: 30). This characteristic of the Italian archaeology is the result of the turbulent development of the discipline that Bianchi Bandinelli synthetized in three main periods: "19th century archaeology [was] essentially philological until the First World War (1914-18), exclusively art historical in the period between the two wars, and

essentially historical (particularly focused on prehistory and proto-history) after the Second World War" (Bianchi Bandinelli 1976: 4-5). Nevertheless, the archaeological discipline had to deal with historical problems. In its best expressions, Italian historical archaeological research was able to create an autonomous system of sources and methodologies. The most prolific expression of this consciousness raising as historical science took place in 1960s due to cultural stimulus that brought about the creation of the journal *Dialoghi di archeologia* (Dialogues of Archaeology). This radical turning point was at the origin of a period of prolific research, a modern point of view in the political aspect of the heritage protection, and improvements in the archaeological excavation methods (Bianchi Bandinelli 1976: 8).

Harris underlined the importance of the work of Italian archaeologists in adopting the new ideas related to fieldwork methodology, such as the introduction of the Harris Matrix. He considers Italian archaeologists as "one of the first large groups outside England to adopt the new ideas" (Harris et al. 1993: 1).

According to Carandini, Italian archaeologists can be divided in two main groups. The first includes people trained in the discipline between 1930 and 1960. This generation of excavators consists of those archaeologists who oversaw the development of the stratigraphy in Europe and produced the first "modern" fieldwork archaeologists in Italy, Nino Lamboglia and Bernabò Brea. The second group, dominant between 1970 and 1990, was brought to an end with the movement of renewal of the Italian archaeology, and in Carandini's words (Carandini 1981: 19).

The late renewal of the discipline in Italy was the cause of misunderstanding, especially out of Europe, about the value and importance of the Italian archaeology. Often ideas that non-Europeans have about Italian fieldwork methods is attached to the 1930-1960 generation of archaeologists and do not take in consideration of the great development of the discipline in the last 30 years. Until the 1960s, chronology was defined by a typology of building techniques and not through the artifacts and features discovered in archaeological deposits. Giuseppe Lugli, one of the most important archeologists in Italy to use the building techniques dating method, blames Lamboglia "doing [?] the history of the monument with two shards" (Lugli 1959: 322).

Carandini was the first archaeologist who tried to apply the British stratigraphic methods to an Italian site, Settefinestre, in 1976 (Carandini and Filippi 1985), but he used this approach before outside of Italy at Cartagine in 1973 (Carandini et al. 1983). Before the Cartagine experience, he used the best method available in 1960s in Italy, the "Lamboglia method." The excavation of Ventimiglia was the first dig of a classical period site in Italy that can be compared to Wheeler's experience. In fact, in this excavation Nino Lamboglia gives great importance to the stratigraphic sections, which were drawn using the same criteria as Wheeler (Lamboglia 1950: Fig. 2). Lamboglia was considered a "post-Wheeleriano *ante-litteram*" (Carandini 1981: 24). According to Manacorda, the method used by Lamboglia overcame the rigid geometry of the Wheeler's approach. Even if his method was based on the vertical stratigraphy —that is, the section— his excavation was not limited by the scheme of the spits and squares, but was instead adapted to the ground's topography.

Lamboglia was the first Italian archaeologist to work in the center of Rome, near the Curia, the Roman Forum, and the Forum of Cesare, after that area was knocked down during the 1930s. He tried to demonstrate that the stratigraphic method does not have temporal limitations and that can be applied to any archaeological context (Manacorda 1983: 25; Lamboglia 1950: 105). The use of stratigraphic methods in archaeological contexts of different periods confirms Lamboglia statement; for example, at Cartagine (Carandini 1983), Settefinestre (Carandini 1985), Scarlino (Francovich and Azzari 1985), and Rocca San Silvestro a Campiglia (Francovich et al 1987).

Andrea Carandini and Clementina Panella were the first excavators who had to defend the new British stratigraphic method from the critiques of those archaeologists still linked to the traditional methods. In fact, during the dig of the Swimmer Roman Baths (*Terme del Nuotatore*) in Ostia they were accused of being too accurate and too slow in the analysis of stratigraphy and artifacts (Carandini and Panella 1968). This example show the difficulties that these pioneers experienced defending the "culture of stratigraphy" so defined by Carandini (1981: 23). But as the years have passed, publications of the Swimmer Roman Baths excavation have become a datum point for Roman archaeology in the Mediterranean. In the same years, beginning of 1980s, Daniele Manacorda's introduction to the translation of one of the revolutionary publications in the contemporary archaeology, *Principles of*

archaeological stratigraphy (Harris 1975) shows the connection that the new Italian archaeology school created with the British school (Manacorda 1983: 7-36). The last important step in the development of Italian archaeology was the experience of excavations in urban contexts (Manacorda 1982, 1987; Carandini et al. 1985; Castagnoli et al. 1985; Visser-Travagli and Ward Perkins 1985; Panella 1987, 1990; Francovich and Parenti 1988).

2.5. The importance of interfaces in archaeological stratigraphy

According to Harris (1975: 36-37), the stratigraphic events on an archaeological sites are the deposit "which has a material mass which may contain artefacts," the surfaces or interfaces of deposits, and other interfaces "such as pits, which are stratigraphic units in their own right." Still, at beginning of the 1990s archaeologists and geoarchaeologists continued to debate the importance of the interface in the excavation process. Collcutt (1987: 11) and Farrand (1984: 5) consider Harris' approach to the excavation "separatist," and are firmly convinced that he has done a disservice to the profession. Collcutt (1987: 13) considers "the ideas concerning living floors of many researchers most simplistic. From my geoarchaeological point of view, man does not live on surfaces, he lives in a formerly superficial band of pre-existing sediments, nearly always 3-10 cm, and sometimes over a metre, thick" In his view, interfaces (living floors) are not an important part of stratigraphic interpretation; the crucial element is the sediment or deposit.

Stein (1983: 339) agrees with Farrand and Collcutt and believes that "in geology and archaeology, a bed or a deposit is an aggregate of sedimentary particles. Sediments are particulate matter that has been transported by some process from one location to another…all particles (including artifacts) found in archaeological deposits can be viewed as sediments." Stein stresses the importance of the laws of the universe in the interpretation of the past. According to Harris, however, Stein fails to understand that archaeological stratification produced by people cannot be included in the natural deposits category, but instead represents an entirely distinct phenomenon in the universe of knowledge with its own laws (Harris et al. 1993: 12). Moreover he believes that the principles of the archaeological

stratigraphy must also deal with "the non-historical attributes of stratification because it is they which are of universal application" (Harris et al. 1993: 13).

Harris believes that geoarchaeologists and other specialists may make a significant contribution to archaeological projects in geological settings, but he is also firmly convinced that the geological methods cannot "be extended to a majority of archaeological sites, which are those stratigraphically fabricated as a by-product of human society." He reaches this conclusion for two fundamental reasons. The first is because geoarchaeologists ignore the preeminent importance of the interface in archaeological stratigraphy. Harris et al. (1993: 15) argue that the significance of the interface comes from the fact that there are generally more interfaces than deposits on most archaeological sites. "Secondly, the specialty of geoarchaeology has produced no workable systems for the construction of stratigraphic sequences, as archaeology has in the Harris Matrix" (Harris et al. 1993: 15-16). According to Harris et al. (1993: 16), the Harris Matrix "system of stratigraphic interpretation has been proven to provide the necessary framework for meaningfully studying the specific contents of layers and features, whether they be the work of people, of nature, or a combination of the two."

2.6. Site recording sheet

In the 1970s Philip Barker and Edward Harris developed a methodology for the documenting archaeological excavations that, with minor changes, is still one of the most used today. Barker worked on the creation of the so-called index card, wherein the excavator could write down, during the immediate on-site recording, the minimum information required:

1. The abbreviated name of the site.
2. The area and grid numbers.
3. The feature number.
4. The position of the feature (as a grid reference).
5. The relation of the feature to features above, around and, eventually, below it.

6. A description of the feature, including its composition or fill.

7. Finds directly associated with the feature.

8. A sketch of the feature, if this would be helpful, and/or a polaroid photograph.

9. Cross-reference to measured drawings, sections and photographs.

10. Subsequent interpretive notes, e.g., post-hole, part of structure XIII, kitchen, Phase 2.

11. The considered reliability of this interpretation. [Barker 1977: 143]

This index card has been changed and adapted to different archaeological contexts over the last 40 years. For example, in Italy Carandini suggested some improvements to Barker's feature/ layer card. The new form, *scheda di unità stratigrafica* (stratigraphic unit sheet, US), included the following entries:

1. Stratigraphic unit (Positive or Negative).

2. Catalogue number.

3. Reference to other forms/unit sheets.

4. Location: 4.1. Space/Room, 4.2. Area, 4.3. Grid, 4.4. Feature.

5. Chronology: 5.1. Stratigraphic relations ("connected to," "cover/covered by," "cut/cut by," "fill/filled by"); 5.2. Relative chronology; 5.3. Absolute chronology; 5.4. Period or stratigraphic phase; 5.5. Dating elements.

6. Technical specifications: 6.1. Dimensions, 6.2. Altitude, 6.3. Preservation status, 6.4. Stratigraphic reliability.

7. Stratum description/analytical specifications: 7.1. Distinction criteria; 7.2. Formation; 7.3. Composition, 7.4. Consistency, 7.5. Color, 7.6. Description, 7.7. Interpretation, 7.8. Inclusions, 7.9. Samples, 7.10. Flotation, 7.11. Sieving, 7.12 Lab analyses, 7.13 Comments.

8. Documentation: 8.1. Photographic documentation, 8.2. Graphic documentation, 8.3. Video, 8.4. Related references, 8.5. Reference to old stratigraphic unit forms, 8.6. Compiler, 8.7. Area or Field Director, 8.8. Revision, 8.9. Registration data, 8.10. Update. [Carandini 1981: 90].

This form was developed by the *Istituto Centrale per il Catalogo e la Documentazione ICCD, Ministero per i Beni e le Attività Culturali,* (Central Institute for the Cataloguing and Documentation, Department for Cultural Heritage and Activities). ICCD also created other forms that were conceived in the following order (ICCD 1984a; www.iccd.beniculturali.it/getFile.php?id=215):

1. *Scheda di Sito,* SI (Site documentation sheet; ICCD 1984b; www.iccd.beni culturali.it/getFile.php?id=1172).
2. *Scheda di Complesso topografico*, CA (Topographic context sheet; ICCD 1984c; www.iccd.beniculturali.it/getFile.php?id=1171).
3. *Scheda di Monumento archaeologico*, MA (Archaeological monument sheet; ICCD 1984c).
4. *Scheda di Saggio archeologico*, SAS (Archaeological sample sheet; ICCD 1984a: 15-16).
5. *Scheda di Unità stratigrafica*, US (Stratigraphic unit sheet; ICCD 1984a: 26-27; fig. 2).
6. *Scheda di Unità muraria*, USM (Masonry stratigraphic unit sheet; ICCD 1984d; www.iccd.beniculturali.it/getFile.php?id=218).
7. *Tabella dei materiali*, TMA (Material table; ICCD 1984: 47-53, 99-107, 118-121).
8. *Scheda di Reperto archeologico*, RA (Archaeological find sheet; ICCD 1984e; www.iccd.beniculturali.it/getFile.php?id=1170).
9. *Scheda per la Numismatica*, N (Numismatics sheet; ICCD 1984e).

Carandini criticized the ICCD for omitting some forms already present in the *Archaeological Site Manual* developed by the Department of Urban Archaeology of the London Museum (1981: 87; Museum of London, Department of Urban Archaeology 1994), including the *Scheda di unità stratigrafica lignea*, USL (Timber recording sheet; 1994: 75), *Scheda di unità stratigrafica di deposizione funeraria*, USD (Skeleton and Coffin recording sheets; 1994: 91,98) and *Scheda delle campionature paleoambientali*, SCP (Environmental archaeological sampling sheet; 1994: 50, 53).

US	N. CATALOGO GENERALE	N. CATALOGO INTERNAZIONALE	MINISTERO PER I BENI CULTURALI E AMBIENTALI ISTITUTO CENTRALE PER IL CATALOGO E LA DOCUMENTAZIONE

SOPRINTENDENZA

LOCALITA'	ANNO	AREA	SAGGIO	SETTORE /I	QUADRATO/I	QUOTE	UNITA' STRATIGR.
				AMBIENTE			NAT. / ART.

PIANTE	SEZIONI	PROSPETTI	FOTO	TABELLE MATERIALI
				RA
				N

DEFINIZIONE E POSIZIONE

CRITERI DI DISTINZIONE

MODO DI FORMAZIONE

COMPONENTI	INORGANICI	ORGANICI

CONSISTENZA	COLORE	MISURE

STATO DI CONSERVAZIONE

DESCRIZIONE

		SEQUENZA STRATIGRAFICA	
UGUALE A	SI LEGA A		POSTERIORE A
GLI SI APPOGGIA	SI APPOGGIA A		
COPERTO DA	COPRE		
TAGLIATO DA	TAGLIA		ANTERIORE A
RIEMPITO DA	RIEMPIE		

OSSERVAZIONI		

INTERPRETAZIONE		

ELEMENTI DATANTI		

DATAZIONE	PERIODO O FASE	

DATI QUANTITATIVI DEI REPERTI		

CAMPIONATURE	FLOTTAZIONE	SETACCIATURA
AFFIDABILITA' STRATIGRAFICA	DIRETTORE	RESPONSABILE

Figure 2. US (*Scheda di Unità stratigrafica*/Stratigraphic unit sheet; ICCD 1984a: 26-27).

Italian archaeologists introduced new forms in the documentation process because the Stratigraphic Unit form (US) was not entirely sufficient to describe internal microstratigraphy of walls and plastering. To fill this gap, they developed the USM (*Scheda di unità stratigrafica muraria*/Masonry stratigraphic unit sheet) and the USR (*Scheda di unità stratigrafica di rivestimento*/Plastering stratigraphic unit sheet). This was possible due to the efforts of some in convincing the ICCD to adopt and standardize such forms (Carandini 1981: 325; Brogiolo et al 1988; Francovich and Parenti 1988: 253).

USM (*Scheda di unità stratigrafica muraria*/Masonry stratigraphic unit sheet; ICCD 1984d) entries are as follows:

1. Masonry stratigraphic unit.
2. Cataloguing number.
3. Reference to other sheets/US.
4. Location: 4.1. Space/Room, 4.2. Area, 4.3. Grid.
5. Object.
6. Chronology: 5.1. Stratigraphic relations; 5.2. Relative chronology; 5.3. Absolute chronology; 5.4. Period or stratigraphic phase; 5.5. Dating elements.
7. Technical specifications: 6.1. Dimensions, 6.2. Altitude, 6.3. Orientation, 6.4. Preservation status, 6.5. Modern restorations, 6.6. Stratigraphic reliability.
8. Stratum description/analytical specifications: 8.1. Typology of the wall, 8.2. Building techniques, 8.3. Structural Building material (e.g., bricks), 8.4. Binder building material, 8.5. Configuration of the wall, 8.6. Laying of the wall's, 8.7. Quarry and Industry's Marks, 8.8. Manufacturing traces, 8.9. Decorative elements of the wall façade, 8.10. Description, 8.11. Inscriptions, 8.12. Symbols, Emblems, 8.13. Interpretation, 8.14. Samples, 8.15. Lab analysis, 8.16. Comments.
9. Documentation: 8.1. Photographic documentation, 8.2. Graphic documentation, 8.3. Video, 8.4. Related references, 8.5. Typological comparison references, 8.6. Reference to old forms, 8.7. Compiler, 8.8. Area or Field Director, 8.8. Revision 8.9. Registration data, 8.10. Update.

The *Site Manual* developed by the Department of Urban Archaeology of the London Museum presented its own Masonry recording sheet, which was more generic and had fewer entries. Moreover, this form does not include a single description for each entry; rather, the compiler has to include all the entries in a common part of the sheet (Fig. 3).

Entries for the USR (*Scheda di unità stratigrafica di rivestimento* - Plastering stratigraphic unit form; ICCD 1984a: 32-33; fig. 4) are:

1. Plastering stratigraphic unit sheet number.
2. Cataloguing number.
3. Structure compound: 3.1. Vertical reference.
4. Reference to other sheets.
5. Location: 5.1. Geographic location, 5.2. Specific location, 5.3. Museum or Department inventory, 5.4. Geographic location (finding), 5.5. Finding specifications, 5.6. Space/Room, 5.7. Area, 5.8. Grid, 5.9. Excavation data/information.
6. Object: 6.1. Definition (6.1.1. Wall, 6.1.2. Floor, 6.1.3. Ceiling).
7. Chronology: 7.1. Stratigraphic relations; 7.2. Relative chronology; 7.3. Absolute chronology; 7.4. Stylistic phase, 7.5. Period or stratigraphic phase; 7.6. Dating elements.
8. Technical specifications: 8.1. Dimensions, 8.2. Profiles/Corners, 8.3. Preservation status, 8.5. Modern restorations, 8.6. Stratigraphic reliability.
9. Stratum description/analytical specifications: 9.1. Preparatory strata (9.1.1. Strata number, 9.1.2. Thickness, 9.1.3. Color, 9.1.4. Inorganic components, 9.1.5. Organic components, 9.1.6. Preparatory layout, 9.1.7. Manufacturing footprints), 9.2. Surface, 9.3. Relations between plastering and architectonical structure, 9.4. Description and/or decorative pattern, 9.5. Inscriptions, 9.6. Interpretation/historical-critical information, 9.7. Drawings, 9.8. Samples, 9.9. Lab analysis, 9.10. Comments.

MASONRY RECORDING SHEET

MUSEUM OF LONDON

MASONRY

Grid Square(s)	Area/Section	MASONRY	Site Code	Context
115 / 210 - 215	B		XYZ | 89	148

1. Materials
2. Size of materials (brick : BTL in mm)
3. Finish of stones
4. Coursing / bond
5. Form
6. Direction of face(s)
7. Bonding material (brick : Height of 4 courses & 4 bed joints in m)
8. Dimensions of masonry as found
9. Other comments

1) RAGSTONE AND FLINT NODULES
2) RAGSTONE VARIES FROM 310mm x 230mm x 330mm TO 200mm x 210mm x 300mm (INFILL 290mm x 220mm x 420mm) - FLINT NODULES VARY FROM 100mm x 70mm x 200mm TO 130mm x 100mm x 190mm AND ARE SLIGHTLY MORE UNIFORM IN SIZE THAN THE RAGSTONE. 3) ROUGHLY HEWN
4) RANDOM COURSED 5) WALL FOUNDATION
6) N/A 7) CREAMY PINK MORTAR, VERY HARD, INCLUSIONS OF MODERATE SMALL ANGULAR PEBBLES + OYSTER SHELL FRAGMENTS; SMALL FRAGMENTS AND FLECKS OF TILE AND CHARCOAL; OCCASIONAL LUMPS OF CHALK AND LIMESTONE. 8) N-S AXIS = 4·85M E-W AXIS = 480mm, THICKNESS : 420mm 9) N/A
PTO

Stratigraphic matrix

138	140	88							

This context is | 148 |

166									

Your interpretation : Internal (External)

LARGE BLOCKS OF UNWORKED RAGSTONE LAID IN CUT [166] WITH FLINT NODULES LAID IN TWO PARALLEL LINES AND SET IN MORTAR. TOP OF FOUNDATION REMOVED WHEN WALL ABOVE WAS ROBBED (?) NORTHERN END OF WALL TRUNCATED BY WELL CUT [88]

Associated contexts   POSSIBLY FOUNDATION FRAGMENT [101] TO NORTH (?)

Context same as   ——

Worked stones   NONE   PTO

Plan nos- P 148	(X)	Site book refs		Initials & date NH. 29/8/89
Other drawings S/E	(X)	Matrix location :	C3	
Photographs ✓	Card nos			Checked by & date SF 14-9-89

Levels on reverse

Tick when reduced and transferred to plans : ✓

Highest :		Lowest :	

Samples

Petrological : 12+13 4 Regular bricks : ——
Mortar : 15   Special bricks : ——

Checked interpretation :

PTO

Provisional period	Group	Structure no	Initials & date	

Figure 3. Masonry Recording Sheet (Museum of London, Department of Urban Archaeology *1994*; 57).

30

USR	N. CATALOGO GENERALE		N. CATALOGO INTERNAZIONALE		MINISTERO PER I BENI CULTURALI E AMBIENTALI
					ISTITUTO CENTRALE PER IL CATALOGO E LA DOCUMENTAZIONE
CODICI			ITA:		SOPRINTENDENZA

LOCALITA'	ANNO	AREA	SAGGIO	SETTORE/I QUADRATO/I	AMBIENTE	QUOTE	UNITA' STRATIGRAFICA DI RIFERIMENTO

PIANTE	SEZIONI	PROSPETTI	FOTO	TABELLE MATERIALI PROVENIENTI DA ALTRE US

DEFINIZIONE E POSIZIONE	TABELLE MATERIALI
	RA
	N

TECNICA DI RIVESTIMENTO	MATERIALE/I

SEQUENZA FISICA / SEQUENZA STRATIGRAFICA

	UGUALE A	SI LEGA A		POSTERIORE A
	GLI SI APPOGGIA	SI APPOGGIA		ANTERIORE A
	COPERTO DA	COPRE		

STRATI PREPARATORI

STRATO	1°	2°	3°	4°
SPESSORE mm Minimo, massimo				
COLORE				
COMPONENTI INORGANICHE (sabbia, calce, calcite, pozzolana, cocciopesto, altro)				
COMPONENTI ORGANICHE (paglia, "cannucce", altro)				
SINOPIA, BATTUTO DI CORDA, GRAFFITO				

RETRO, impronte

SUPERFICE (liscia, impronte di pennellate, altro)

COLORI

SOVRAPPOSIZIONI di colori

OSSERVAZIONI

DESCRIZIONE E / O SCHEMA DECORATIVO

DATI EPIGRAFICI

		PROFILI, ANGOLI			

		COLORI	BIANCO	NERO	
ALTRI mattoni lastre		MATERIALI (lapideo, vetroso, fittile)			
OPUS SECTILE piastrelle		FORMA (superfice)			
		MISURA SUPERF. Min. Mass. Media ALTEZZA O SPESSORE			
		N° PER 100 cmq			
MOSAICO tessere		ORDITO			

RAPPORTO TRA RIVESTIMENTO E STRUTTURA ARCHITETTONICA

ELEMENTI DATANTI

DATAZIONE

FASE STILISTICA	PERIODO	FASE (STRATIGRAFICA)

BIBLIOGRAFIA

CONFRONTI

	'DEPOSITI' DI SUPERFICE	INCROSTAZIONI RESISTENTI
STATI DI CONSERVAZIONE	DIFETTI DI ADESIONE	DIFETTI DI COESIONE
	LACUNE	
	USURA	
	ALTRO	

	CONSOLIDAMENTO	INCOLLAGGIO
INTERVENTI DI CONSERVAZIONE	VELATURA	DISTACCO
	IMBALLAGGIO	COPERTURE TEMPORANEE
	CAMPIONE/I PER ANALISI	INDIRIZZO LABORATORIO

DATA	IL RESPONSABILE

Figure 4. USR (*Scheda di unità stratigrafica di rivestimento*/

Plastering stratigraphic unit form; ICCD 1984a: 32-33).

10. *Documentation*: 10.1. Photographic documentation, 10.2. Graphic documentation, 10.3. Video, 10.4. Manuscript, 10.5. Related references, 10.6. Typological comparison references, 10.7. Exhibitions, 10.8. Reference to old forms, 10.9. Compiler, 10.10. Area or Field Director, 10.11. Revision 10.12. Registration data, 10.13. Update.

As this discussion highlights, early simple forms developed for the first time in England (Barker 1977: 143), were changed and adapted to different archaeological context over the last 40 years. For example in Italy the Barker's feature/layer card was improved with new entries (Carandini 1981: 90). Moreover additional forms (USM – *Scheda di unità stratigrafica muraria*/Masonry stratigraphic unit sheet, USR –*Scheda di unità stratigrafica di rivestimento*/Plastering stratigraphic unit sheet) have been added to address particular needs in those areas, such as Italy, where sites are traditionally very complex.

The types of information recorded range from simple *Scheda di Sito,* SI (Site documentation sheet) to more detailed forms such as: *Scheda di Unità stratigrafica*, US (Stratigraphic unit sheet); *Scheda di Unità muraria*, USM (Masonry stratigraphic unit sheet); *Scheda di Reperto archeologico*, RA (Archaeological find sheet); etc.

2.7. The Harris Matrix

Edward Harris developed the Harris Matrix in response to the extreme complexity of the records of the Lower Brook Street archaeological site at Winchester, England. This complexity was an incentive to overcome the obsolete "phasing notes" method for recording the site's stratigraphic sequence (Fig. 5).

This method presents two main limits: (1) since the order of notebook entries rarely respects that of the stratigraphic sequence, it had to be re-written in the order of the phases and periods; and (2) it is impossible to recollect from page to page many stratigraphic relationships between the numerous layers and features. Thus, Harris believed that the possibility to see the sequence in a single drawing would accelerate the correct understanding

of the different phases contained in the sequence. The result of his efforts was the Lower Brook Street's Harris Matrix (Fig. 6). This method "assumes that any two units of stratification have either no stratigraphic connections, or they lie in superposition or may be correlated as parts of an originally single deposit. These assumptions are of course the essence of the notions of relative time" (Harris 1979:page #). The diagrams represented in matrix drawings were initially referred to as "layer charts" and later, as "layer complexes."

Final Periods	Working Periods		P.1	P.2	P.3	P.4 (Not shown on diagram)
IIIb	A	Plough Fill of Pit B	1 2 3 4	1 2 3		
IIIa	B	Pit B, cut through Period III hut floor				
III		Floor of Period III hut, overlying Period II hut and Pit A			2 3	
		Upper fill in Pit A	6a 7			3 4
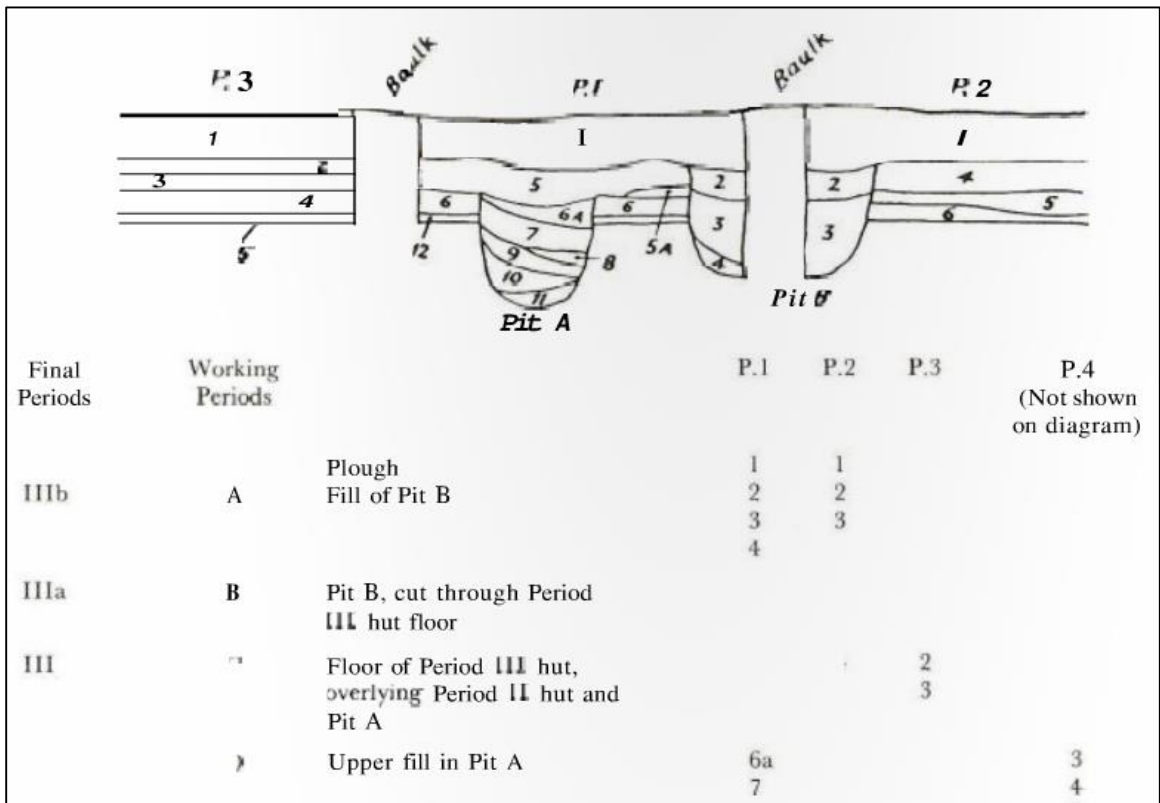
Figure 5. First published illustration of the method of correlation and periodization in British archaeology, based on the analysis of sections and the stratigraphic sequence in a written tabulated form (Kenyon 1961: Fig.13).

Another development made by Harris concerned the stratigraphic value of plans, as opposed sections. Harris stated that it could be possible to avoid many stratigraphic problems in the first instance by the use of the single-layer plan or such problems could be solved to some extent by the use of this plan in post-excavation work. Working on the individual planning of stratification, Harris developed the notion of "units" of stratification. He believed that the terms "layers," "pits." and "walls," used in past practices, describe just the functional

aspects of stratification that he considers of secondary importance in recording stratification. By using the term "unit," he stressed the physical relationships between the elements, creating a system everywhere recognizable as stratigraphic entities (Harris 1979: 120).
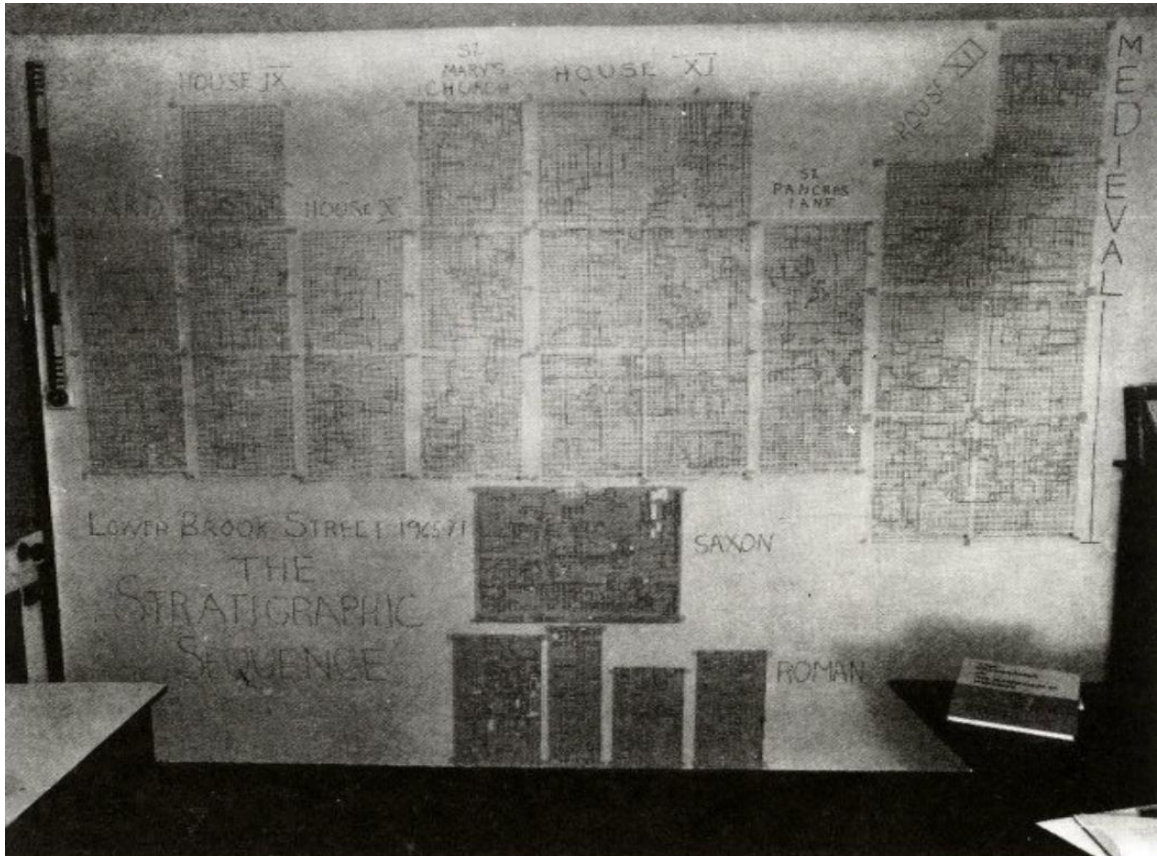
Figure 6. The stratigraphic sequence of the Lower Brook Site, Winchester, as illustarted in the Harris Matrix (Harris 1979: Plate I).

The method developed by Harris allows an excavator to quickly and efficiently record all the "vertical feature interfaces" and the "horizontal feature interfaces" (Fig. 7). "Vertical feature interface" is usually referred to as a feature; this unit marks a distinct event like the digging of a pit and results in the destruction of pre-existing stratification (Harris 1979: 127). "Horizontal feature interface" is associated with upstanding strata and marks the levels at which they have been partly destroyed (Harris 1979: 124).
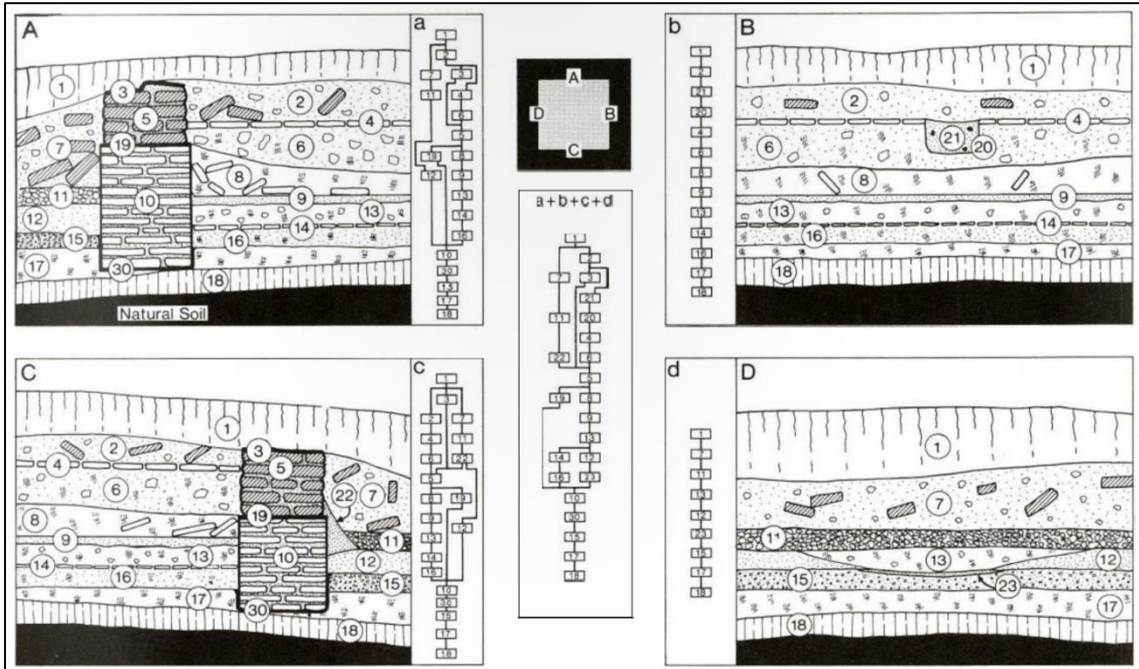
Figure 7. This illustration shows the gradual construction of a stratigraphic sequence for the single section represented by profiles A-D. By the Law of Stratigraphic Succession, the four profiles are merged into a single sequence (a+b+c+d) and superfluous relationships are deleted (Harris 1979: Fig. 32).

Chapter 3

Digital Archaeology: status of existing research in
3D documentation and analysis of archaeological sites

Digital archaeology explores the use of Information and Communication Technology (ICT) and digital technology in archaeology and the impact that such digital "tools" have had in the data recording and interpretation of archaeological sites. According to Patrick Daly and Thomas L. Evans (2006: 7), "digital archaeology should exist to assist us in performance of archaeology as a whole. It should not be a secret knowledge, nor a distinct school of thought, but rather simply seen as archaeology done well, using all of the tools available to aid in better recovering, understanding and presenting the past".

ICT and digital techniques in archaeology are no longer secret knowledge for ICT specialists. The development of user-friendly tools in the documentation and analysis of archaeological data makes ICT and digital techniques more accessible to non-dedicated ICT specialists. But before considering the importance and the role that technologies have today in the archaeological analysis, it is fundamental to analyze the beginning of this process.

3.1. Overview on Digital Archaeology

At the beginning of the 1960s archaeologists started to apply calculation-intensive tests such as factor analysis to archaeological data. This was possible due to the development of large mainframe computers. For the first time, end users were able to use more sophisticated large-scale statistical analysis. This technology allowed for a concrete, substantive method to make archaeological analysis more "scientific" and "analytical", as envisioned by Taylor (1967).

A revolutionary change in the analysis of the archaeological data occurred with the introduction of GIS (Geographical Information System) platforms. For the first time, they

allowed modeling and simulation of contexts favoring spatial thinking in archaeology. Mark Aldenderfer describes GIS as a "sophisticated database management system designed for the acquisition, manipulation, visualization, management, and display of spatially referenced (or geographic) data" (Aldenderfer 1996: 4). GIS originated with the computer-assisted mapping software developed during the 1970s, and is widely used in archaeology today.

Kvamme identifies five broad themes of GIS use in archaeology: regional data management, management of remotely sensed data, regional environmental analysis, simulation, and locational modeling (Kvamme 1989: 162).

Richards describes the single largest growth areas of GIS in computer application in archaeology during the 1990s (Richards 1998: 336). The early development of GIS took place in North American archaeology. In the 1990s, the imbalance in early applications in favor of the United States is evident in the volume edited by Allen et al. (1990) that discusses the use of GIS application in archaeology. Only the paper of Harris and Lock (1990: 33-53) looked at European archaeological contexts. The situation started to change at the middle of 1990s, when in the 1995 Leiden CAA (Computer Applications and Quantitative Methods in Archaeology) proceedings 18 papers focused on GIS (Kamermans and Fennemans 1999: XI-XIII). At the beginning of 1990s a great number of GIS projects were landscape oriented, and only a few were intra-site analyses (Richards 1998: 338).

The growth of information technology in 3D documentation tools, including electronic surveying instruments, laser scanners, photogrammetric cameras, and even CAD (Computer-Aided Design) modeling approaches, has brought an exponential increase of digital data. The process started in the 1970s, when the advent of photogrammetry and early workstations allowed the first examples of digital documentation, such as the extrusion of stones in a façade outline. The growth of the early computer-aided design (CAD) tools in the 1980s, and of geographic information systems (GIS) in the 1990s, increased the possibility of linking data with largely 2- or 2.5-D maps and contours. But the revolutionary change in the digital documentation has been possible only in the last decade, due to the growing availability of 3D laser scanners (Addison 2008: 28). This

technology permits a very detailed 3D capture of archaeological objects of all kinds in the form of point clouds and meshes.

The use of 'real-time' survey software and hardware, such as Total Station Theodolite, Global Positioning Systems (GPS), and laser scanners, has had a remarkable impact on archaeological recording and important implications for archaeological survey. The use of these techniques, improving the accuracy, detail and precision of the documentation process, is considerably changing the nature and implications of the word "digital" in archaeology. Digital archaeology, in fact, is adding a new dimension to the debate about the subjective versus objective nature of field recording. Matt Bradley (2006) recognizes the importance and benefits of the use of digital techniques in archaeology, but at the same time he points out the potentially subjective elements for such techniques. He believes that there are basic common principles and issues of field survey, regardless of the techniques used. Basic issues such as resolution and definition are, in fact, "determined by a combination of time pressure, resources available, and personal decision and preferences. This does not change when using even the most sophisticated of 'digital' techniques" (Bradley 2006: 29).

The existence of subjective elements in the archaeological documentation process is evident also when the acquisition is made through the most innovative digital techniques. The challenging theme in this debate is not the existence of subjectivity in the archaeological documentation process, but understanding if the use of new technologies may reduce archaeological survey subjectivity, making the acquisition process more objective.

The analysis of the objective and subjective nature of the excavation process is one of the most debated aspects in the archaeological process. Barker advocated the separation between the objective description and the subjective interpretation, affirming that, in archaeology, subjectivity and speculation become central only at higher levels of interpretation (Barker 1977: 147). But is it really possible to collect archaeological data in an objective way?

The two most important post-processual theoretical schools of archaeology, the descriptive and the interpretative, debate the essence of the new archaeology. Renfrew and

the cognitive archaeologists argue that it is impossible to interpret the past; we can just describe the phenomena that bring forth the creation of artifacts and features (Renfrew 1994: 3-12). The interpretative archaeologists (e.g., Hodder 1986; Shanks and Tilley 1987), on the other hand, argue that it is not enough to understand how something happened. We need to work on the understanding of the reasons behind it as well.

An aspect that this dissertation research wants to explore is not where, according to Zubrow, one sits on the post-processual/cognitive fence (2006: 19), but which role technology plays in archaeology and where we should locate "Digital Archaeology" in this theoretical discussion. Cognitive archaeologists were always more open to the introduction of the digital in archaeology (Zubrow 2006: 9). According to Ezra Zubrow, in fact, digital technologies:

1. "offer a way to represent the real world in a compact and efficient package;
2. allow one to count, do statistics, manipulate and evaluate measurements in a variety of summary and analytical forms;
3. allow one to efficiently model and simulate real world processes in order to understand complex interacting processes of humans in their environments;
4. make possible the creation of virtual worlds that are independent of actuality;
5. allow one to transmit all of these manipulations, representations, and words around the earth at almost the speed of light to an increasingly worldwide audience" (Zubrow 2006: 12).

It is not possible to say the same for post-processual archaeology. The first impact of this school with the use of digital innovations was unfavorable. Whitley (1998) highlighted the incompatibility between digital technologies and post-processual theory. The first representative of this school, Ian Hodder, highlighted the distance that exist between digital and post-processual archaeologies:

1. post-processual is interpretative, digital is analytic;
2. post-processual is deconstructive, digital is reconstructive;

3. post-processual is narrative, digital is measured (Hodder 2001).

Ten years after Hodder's consideration of the digital, the approach that part of the post-processual school has regarding technologies is changing. In the summer 2010 new technologies entered in one of the most important post-processual excavations, Çatalhöyük (Turkey). The director of the excavation, Ian Hodder, permitted a team of researchers from the University of California, Merced, directed by Maurizio Forte, to use different kinds of laser scanners on site.

The use of technologies in archaeology is starting to be more widespread on both the sides of the post-processual/cognitive fence. This is because the key point of the discussion is no longer if new technologies are employed or not on site, but how they are used in the creation of new theories and schools of thinking. According to Zubrow, in fact, there are two contradictory views. The first one considers the digital developments in archaeology just for this methodological aspect. In this sense, new technologies have to be considered simply a new set of tools in the archaeological tool kit for solving theoretical and narrative concerns. Therefore, these techniques are considered "as being «a-theoretical» or even «anti-theoretical»" (Zubrow 2006: 9). The second view believes that digital developments take an important part in the creation of theory, or at least influence this process.

Starting from the Zubrow's dualistic vision of the digital component's importance in archaeology, the role that new technologies are playing in creating new categories and schools of thoughts is perceptible. Digital developments are, in fact, impacting all the different parts of the archaeological field. Archaeologists coming from different theoretical schools and backgrounds, cultural historians, processual, post-processual, and post-post-processual, are involved in this digital transformation process.

Archaeologists have to deal with the extremely fast advance of technologies. Technology not only has methodological relevance, but it also determines some aspects of theory. Zubrow clearly stresses the relation that exists between computing and archaeological theory development in the twentieth century (Table. 1).

Date	Archaeological school	Types of theories and problems	Computing machines– hardware and software	Subjects of use
Pre-1930	Natural observation	Descriptive	Calculating machines	Statistical analysis
1930–65	Cultural history	Temporal and geographic gapsmanship as well as reconstructive	Mainframes, Fortran, Cobol	Statistical analysis, data storage and manipulation
1965–80	Processual	Systemic, hypothetical, nomethetic, behavioural, group oriented	Mini's Vaxs, PC, Pascal, C, Basic	Causation, modelling, simulation, GIS
1980–95	Post-processual	Individual, interpretative	PCs, C++, Prolog	Expert systems, non-causative, AI, field use, GIS
1990–	Cognitive	Individual, experimental and hypothetical, reconstructive	Work stations, PCs, parallel processing, super computing, visual basic, numerous specialized languages	AI, GIS, individual modelling, visualization, webography

Table 1. History of computing and archaeological theory (Zubrow 2006: Table 1).

The complexity of digital applications in archaeology is constantly increasing (from numbers, to text, to sound, to multi-dimensional motion, to reconstructive video technology). As a consequence, archaeologists have to deal more with problems of implementation. For this reason, archaeologists are less independent in developing their research; "the day of autonomous researchers, the archaeological Livingstone or the 'Indiana Jones' of the world is gone" (Zubrow 2006: 21). The more archaeological studies are linked to the use of new technologies, the more archaeologists are forced into collaborative and multidisciplinary research.

This research is not interested in ascribing 'Digital Archaeology' to one of these theoretical schools. Instead, it aims to analyze this new digital phenomenon and understand if, due to the use of new technology, it is really possible to increase objectivity in the excavation process, leaving the subjective level to the final interpretation of material data.

Digital archaeology is a broad field that includes different aspects of 2D and 3D documentation, analysis, and visualization of the archaeological record. It explores the

relationships that archaeologists have with ICT and digital techniques to understand the impact that such innovations have had on the archaeological field. This dissertation research will focus on one aspect that is incorporated into the comprehensive field of digital archaeology—the last advancements in the use of 3D integrated technologies for the documentation of archaeological sites.

3.2. 3D spatial and descriptive data acquisition

In the past ten years the use of new technologies for the 3D documentation and reconstruction of cultural heritage has changed how we approach archaeological research. Archaeology, becoming even more "digital", is officially part of the *digital village* described by Zubrow (2006: 12). The use of 3D laser scanners and photogrammetric techniques is now well established in the field, because archaeological investigations require detailed, high-resolution registration and documentation of the excavation area to digitally preserve information through time in order to maximize the opportunities for future interpretation and simulation. The preservation of very accurate 3D reproductions in archaeology is especially critical for the documentation of soil features removed during the excavation process and for the virtual preservation of sites at risks of destruction due to conflict, decay, lack of financial resources, etc. In these specific circumstances, 3D reproduction can facilitate the interpretation of the features within the excavation area and their relationships in space. This is because 3D realistic replicas allow archaeologists to analyze the stratigraphic sequence after the excavation process.

The framework of contemporary archaeological management requires fast and accurate methods, but also easily accessible and manageable data for contemporary and future researchers and the general public. Moreover, the documentation should preferably proceed to more than 2D techniques. According to De Reu et al. (2012: 1109), in fact, "multi-dimensional recording and reproduction of excavated structures could potentially bridge the gap between in and ex-situ preservation. It could enhance the quality of the archived heritage for future perception and study by offering a better visualization and

allowing the personal participation of the present and future data-viewers in the manipulation of the images of the excavated structures".

The application of 3D laser scanning techniques is becoming more and more prevalent in archaeological survey and excavation data collection. The time of flight/terrestrial laser scanner (TLS) technology is the most widely used technique adopted for the documentation of archaeological sites. This technique is particularly used for the documentation of large contexts, since it allows for fast acquisition of large areas (Dell'Unto et al. 2008: 121-122; Galeazzi 2008: 129-133; Doneus et al 2005: 226-2231; Neubauer et al. 2005: 470-475; Zimmermann and Eßer 2008: 58-64). However, this technology is less appropriate for rich sub-centimetric precision (Galeazzi et al 2010: 102; Koch and Kaehler 2009: 1). For this reason, the use of structured light scanners seems more appropriate to obtain sub-centimetric accuracy of all the features within the excavation unit. Using this technique it is possible to obtain sub-millimeter accuracy in 3D representation with color information. Structured light scanners are commonly used to scan artifacts, human remains, and faunal remains (Bayle et al. 2011: 29-46; Güth 2012: 3105-3114; Niven et al. 2009: 2018-2023). The use of this technique can often support archaeological data analysis and interpretation. To this end, Karasik and Smilansky developed a method for the 3D documentation and reconstruction of potsherds. Using 3D scanning technologies, they acquired approximately 1000 potsherds from several sites and periods. Newly developed software allowed them to identify the rotation axis of wheel-produced ceramics and reproduce the profile of the fragments with a high rate of success (Karasik and Smilansky 2008: 1148-1168). This is just one example of the different research groups in the last decade that have worked, on computerized 3D scanning applications for pottery analysis in the attempt to render this 3D technology a practical tool in archaeology (Adler et al. 2001; Leymarie et al. 2001; Razdan et al. 2001; Schurmans et al. 2001). A structured light scanner was also used by Lin et al. to scan lithic artifacts and calculate the proportion of cortex, a proxy measure of artifact transport on assemblage formation (Lin et al. 2010: 694-702).

While the aforementioned projects seem to confirm a well-established use of structured light scanners for the documentation of artifacts, human remains, and faunal remains in archaeology, the use of this technology for scanning surfaces and *in situ* objects

is not so widespread yet. There are, in fact, several examples of cave art reproductions (Díaz-Andreu et al. 2006; Freitas et al. 2007; Robson Brown et al. 2011), but very few of stratigraphy and *in situ* objects documentation (Doneus and Neubauer 2004; McPherron et al. 2009: 19-24). The 3D data acquisition of two Middle Paleolithic sites in southwest France, Jonzac and Roc de Marsal, is a successful example of the use of structured light scanners for the data acquisition of archaeological features (McPherron et al. 2009: 19-24). This research demonstrated that the use of this technology in the field is possible, and the results in term of accuracy are impressive. But to obtain such results it was necessary to solve some logistic issues concerning lighting and camera positioning. Structure light scanners do not work with direct ambient light, so it was necessary, to improve the acquisition, to cover the area to be scanned with a black tarp. The acquisition of a surface of approximately 2.5 m^2 required one full day of field. The aim of McPherron et al. research was not the analysis and comparison of different technologies on the same surface, since objective measures of the resulting data were not available. However, according to McPherron and his colleagues, the results were quite satisfying. "Structured light scanners are one more tool that archaeologists can use to document their finds alongside total stations, laser scanners, digital photogrammetry and similar technologies" (McPherron et al. 2009: 23). However this technology is not optimal for many excavation settings since allows only the acquisition of small areas increasing the data acquisition and processing time of the overall documentation process.

The application of 3D laser scanner techniques was shown to be a very powerful tool for archaeological site data recording, but at the same time this technique shows some logistical limits connected to fieldwork, especially when this technology has to work in remote locations and under extreme environmental conditions. For this reason, archaeologists have started to test different acquisition techniques that do not require the use of heavy instruments on site, such as photogrammetry and dense stereo matching.

The use of photogrammetric techniques for the 3D documentation of archaeological sites was tested in different digital archaeology projects (Galeazzi et al. 2007; Pierrot-Deseilligny et al. 2011: 291-299; Remondino et al. 2006: 269-291; Sanz et al. 2010: 3158-3169). These techniques, used to create simplified 3D metric models with a photorealistic

aspect, provide image-based modeling. Using photogrammetry, it is possible to calculate measurements and build 3D models through digital pictures. 3D image-based methods are widely used for recording archaeological sites (McPherron et al. 2009), cultural heritage at risk (Barazzetti et al. 2011; Remondino and El-Hakim 2006), rock art (Sanz et al. 2010: 3158-3169; Ogleby 1999), and statues and artifacts (Guidi et al. 2004; Pierrot-Deseilligny et al. 2011: 291-299).

3D image-based techniques that combine close-range photogrammetry and digital image correlation (DIC) have been employed in the analysis of rock art (Fryer et al. 2005; Chandler et al. 2007), buildings (Desmond and Bryan 2003; Remondino and Campana 2008) and microtography (Abd Elbasit et al. 2009). DIC technique allows the 3D structure of a scene to be obtained from two different viewpoints through a pair of oriented images, assuming that two points of those images are matched (Orteu 2008: 285). This measurement can be performed through manual, semi-automated, or automated procedures (Remondino et al. 2006: 273-275). Manual and semi-automated approaches were found to be accurate but time-consuming for two main reasons: first, because the camera calibration has to be done several time before the on-site acquisition since the field environmental issues effect the stability of technologies during the data collection of archaeological sites. Second, the data post-processing has to be done manually, totally or partially, through the selection of control points (Remondino et al. 2006: 284).

Until recently, 3D registration in archaeological and cultural heritage studies has been obtained through various techniques that are based on image-based modeling, including photogrammetry (e.g. Guidi et al., 2004; Hendrickx et al., 2011; Koutsoudis et al., 2007), range-based modeling (e.g. Entwistle et al., 2009; Fowles et al., 2003; Lerones et al., 2010; Lin et al., 2010; Stojakovic and Tepavcevic, 2011), or a combination of image-based and range-based modeling (e.g. Al-kheder et al., 2009; Lambers et al., 2007; Lerma et al., 2010; Yastikli, 2007). Remondino and El-Hakim (2006) explain in detail the main difference between these techniques:

1. *Image-based modeling*. "IBM methods (including photogrammetry) use 2D image measurements (correspondences) to recover 3D object information through a

mathematical model or they obtain 3D data using methods such as shape from shading, shape from texture, shape from specularity, shape from contour and shape from 2D edge gradients. IBM methods use projective geometry or a perspective camera model. They are very portable and the sensors are often low-cost" (Remondino and El-Hakim2006: 271).

2. *Range-based modeling.* "This method directly captures the 3D geometric information of an object. It is based on costly (at least for now) active sensors and can provide a highly detailed and accurate representation of most shapes. Nowadays many commercial solutions are available (including Breuckmann, Cyberware, Cyrax, Leica, Optech, ShapeGrabber, Riegl and Z + F), based on triangulation (with laser light or stripe projection), time-of-flight, continuous wave, interferometry or reflectivity measurement principles. They are becoming a very common tool for the scientific community but also for non-expert users such as cultural heritage professionals" (Remondino and El-Hakim2006: 271-272).

3. *Combination of image- and range-based modelling.* "In many applications, a single modelling method that satisfies all the project requirements is still not available. Photogrammetry and laser scanning have been combined in particular for complex or large architectural objects, where no technique by itself can efficiently and quickly provide a complete and detailed model. Usually the basic shapes such as planar surfaces are determined by image-based methods while the fine details such as reliefs employ range sensors" (Remondino and El-Hakim2006: 272).

All three methods present some limits. First of all they require a certain level of expertise, and are not straightforward and implementable during archaeological fieldwork for people that are not trained. Second, they are not cost-effective. These techniques, in fact, are often time consuming and can be quite expensive.

Looking to more cost-effective methods, in the last decade several computer vision techniques such as structure for motion (SfM) and dense stereo reconstruction algorithms in low-cost or open source computer vision based packages were implemented and are available for the public use: Autodesk 123D Catch (Autodesk Inc., 2012); Automatic

Reconstruction Conduit (ARC 3D), (VISICS, 2011); Bundler (Snavely, 2010); PhotoModeler Scanner (Eos Systems Inc., 2012); PhotoScan (AgiSoft LLC, 2011); Photosynth (Microsoft Corporation, 2011); or VisualSFM (Wu, 2012).

Software based on SfM and dense stereo matching algorithms is currently well established in archaeology and largely used for the 3D documentation of the archaeological stratigraphy (Dellepiane et al. 2012; Doneus et al. 2011; Fratus de Balestrini and Guerra 2011). With this technique, the camera calibration that was mandatory with photogrammetric software (PhotoModeler) is not necessary anymore. Dense stereo reconstruction tools, in fact, allow 3D data generation starting from a series of uncalibrated images. The different steps of the process of 3D reconstruction are image matching, camera parameter estimation, and density matching; the results of this computation may be similar to a series of range maps associated to each input image. The processing of image sets usually takes many hours. This technique is cheaper than laser scanner technologies—data acquisition is possible using a medium-quality camera and post-processing software. Moreover, dense stereo reconstruction tools are more usable— the training required to acquire the basic knowledge for use of this technique is considerably less compared to the training necessary for data acquisition and post-processing using a laser scanner. The main problem in the use of this technique is the lack of scale information.

In 2011 Doneus et al. (2011: 81-88) compared 3D models reproducing archeological stratigraphy of a Late Neolithic pit found on the open settlement site of Platt in Lower Austria acquired through terrestrial laser scanner (TLS) and dense stereo matching techniques (DSM). TLS measurements were the basis for the spatial accuracy and precision assessment of the DSM. Several metrics were extracted from this dataset: a maximum positive and negative altitude difference; the mean difference; the mean of all altitude differences; the standard deviation; and the Root-Mean-Square Error (RMSE). He noted that "95% of all the computed 3D points have an error with respect to the true ground position that is smaller or equal to the stated accuracy metric. Regarding the fact that both the TLS and PhotoScan georeferencing is accurate to within about 1 cm and, additionally, the TLS data is characterized by a noise of ± 1-2 cm in the < 10 m range, the calculated RMSE is more or less falling in the typical random error range. Therefore, this test allows one to assume that

the PhotoScan result has more or less the same overall accuracy as the TLS data set" (Doneus et al. 2011: 84). The visual assessment of both vertical and horizontal positional accuracy displays the TLS versus PhotoScan difference grid (Fig. 8).
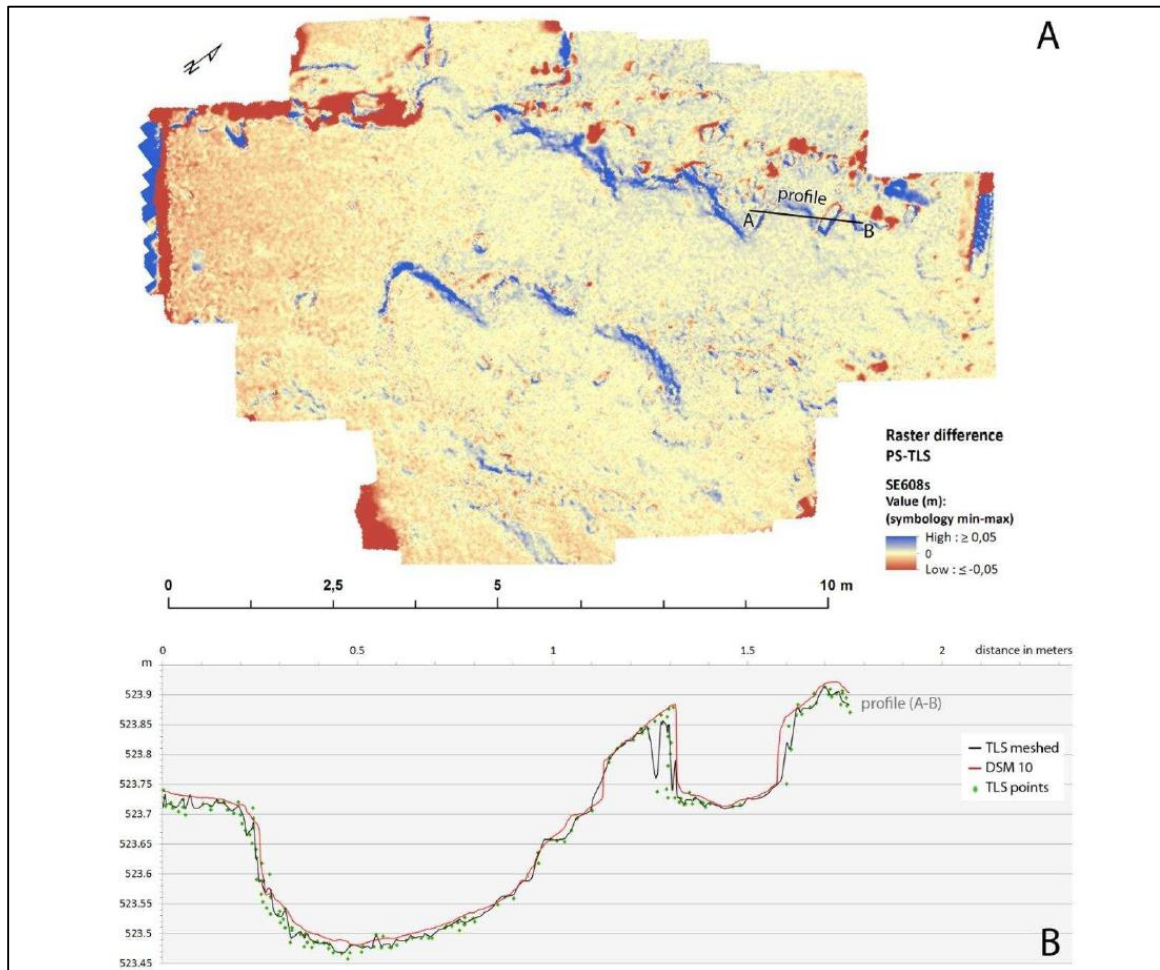
Figure 8. a. Difference grid between PhotoScan DSM 10 and the TLS data that were processed by Doneus et al. standard workflow; b. The profile A-B indicated in (A) shows the differences between the original point cloud, the Photoscan DSM and the DSM extracted by our standard workflow from the TLS data (Doneus et al. 2011: fig. 2).

In 2012 PhotoScan DSM was used to acquire data on the foundation of an outbuilding at the abbey site of Boudelo (De Reu et al. 2012: 1111). The georeferencing of the relative model was performed with 30 GCPs (Ground Control Points) and achieved a total RMSE of 0.015 m and 0.008 m, 0.009 m and 0.010 m for the RMSE on the x-, y- and

z-coordinates respectively (De Reu et al. 2012: 1112). The high accuracy of the results and the possibility to export the 3D models as a 2D orthophoto allow easily integration of the geometric information in the digital excavation plan (Fig. 9).
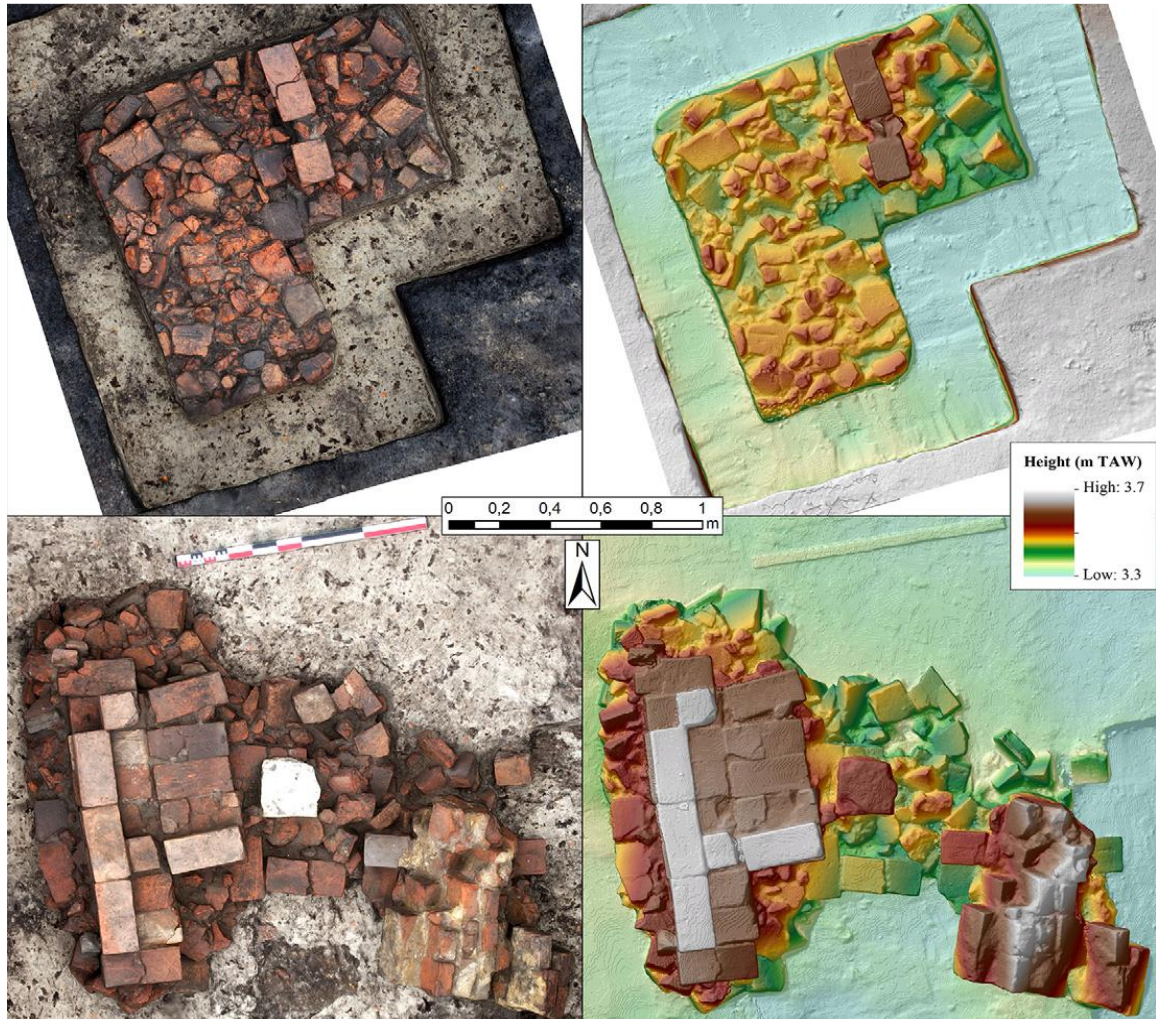
Figure 9. Orthophoto (left) and DTM (right) generated from the 3D surface model of the two documented dadoes on the excavation of the abbey of Boudelo. The accurate geometric information can easily be integrated in the digital archaeological excavation plan (De Reu et al. 2012: fig. 4).

The replicability of DSM was evaluated in 2012 by Dellepiane et al. (2012: 1-10). One of the most important aspects in the 3D documentation of archaeological stratigraphy is the potential to use a system that is able to produce reconstructions with the minimal amount of accuracy's modification between 3D models representing different stages of the

excavation. Starting from different photographic datasets of the same object—an area of the Uppakra site—Dellepiane and his colleagues were able to evaluate the replicability of DSM. The geometrical deviation between the two models indicated that more than 90% of the surface had a deviation of less than 1 cm, and 50% of the surface deviated less than 0.5 cm (Fig. 10).
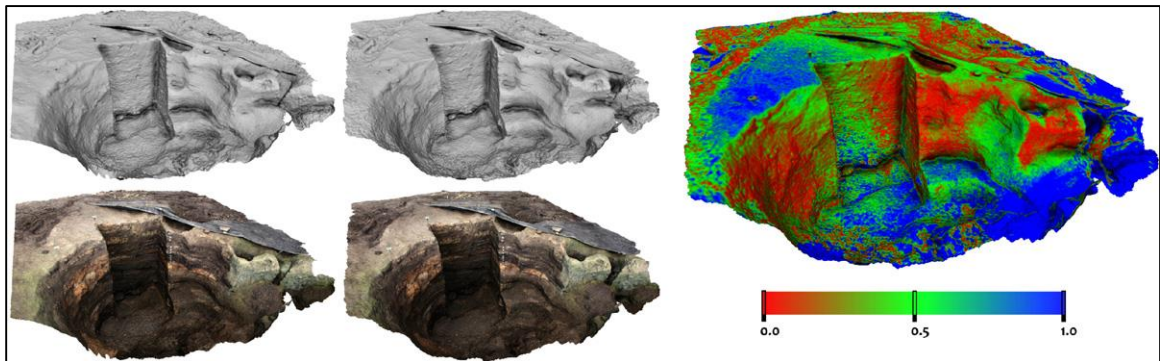
Figure 10. Replicability Test. Left: the two datasets of the same object (pure geometry above and with mapped color below). Right: the color-coded deviation between the two models; 90% of the model is below 1 cm deviation. Reference color scale is shown below the model (Dellepiane et al. 2012: fig. 3).

While some attempts have been made to compare DSM and laser scanner techniques (De Reu et al. 2012; Dellepiane et al. 2012; Doneus et al. 2011: 81-88; Fratus de Balestrini and Guerra 2011; Verhoeven et al. 2012), the definition of a coherent methodology is still far in the future. According to Doneus et al. (2011: 87)., in fact, "investigations under different controlled conditions are necessary to assess the image-based modelling more thoroughly and quantify whether and under which conditions SfM approaches are a reliable documentation technique for archaeological excavations".

The combination of image- and range-based modeling seems to respond better to archaeological needs. Archaeological sites are usually heterogeneous in their parts (e.g. stratigraphy, buildings, etc.). Moreover, complex sites can present a wide range of environmental conditions. For this reason, the use of different technologies seems to be the best solution to completely record a site in 3D.

The combination of laser scanners and close range photogrammetry has started to be common in archaeology. The combination of which methods to use depends on the nature of

the area being investigated and available budget and time. In 2007 Yastikli (2007: 423-427) combined methods in digital photogrammetry and terrestrial laser scanning for the documentation of the Fatih Mosque located in the Fatih district in Istanbul. The author was able to assign the RGB value of a set of stereo digital images to the scanned 3D points (Yastikli 2007: 427). A similar process was used by Al-kheder et al. (2009). For the 3D documentation of the Umayyad desert palaces in the Jordan desert, they were able to transform each 3D point into a corresponding pixel in the color image (Al-kheder et al. 2009: 543). Similarly, a high-resolution calibrated digital camera was firmly mounted to the scanning head of a terrestrial laser scanner (Riegl LMS Z420i) to record the entire site of Pinchango Alto on the south coast of Peru (Lambers et al. 2007: 1702-1712). Terrestrial laser scanning and close range photogrammetry techniques were also tested in cave environment by Lerma et al. (2010: 499-507). The Cave of Parpalló, one of the most important Paleolithic sites located in the Mediterranean area of the Iberian Peninsula, was documented (Lerma et al. 2010: 499-507). The interior part and the entrance of the cave were scanned using a terrestrial laser scanner. Moreover, detail of one parietal engraving was documented by merging together 3D scan and images taken with a digital camera, following a photogrammetric approach (Lerma et al. 2010: 506).

The studies discussed above illustrate the strong interest in the use of integrated technologies in archaeology, but do not stress advantages and specific limitations of the integrated techniques during the acquisition process in terms of accuracy. Various examples of accuracy assessment are coming from other disciplines (Georgantas et al. 2012: 23-28; Skarlatos et al. 2012: 209-304; Gumus et al. 2011: 6529-6536) and cultural heritage building studies (Grussenmeyer et al. 2008: 213-218; Héno et al. 2012: 559-564).

Koch and Kaelher combined TLS (LMS-Z420i) and photogrammetry for the 3D data acquisition of the Apadana Palace in Persepolis, Iran (Kock and Kaelher 2009: 1-7). The test was challenging for walls of the stairways of the eastern entrance, decorated with relief showing representatives of all 23 nations of the Persian Empire. After examinations of different areas of the relief, it was possible to estimate a deviation in the 3D models accuracy of max. ± 3 mm. One of the most interesting aspects of this project consists of the discovery that the accuracy of a particular point depends on the position of this point

in the image. "Details evaluated in the center of an image reach a higher accuracy (± 1 mm) than details located on the margins (± 3 mm)" (Kock and Kaelher 2009: 6).

While there are various examples of the integration technologies for the documentation of cultural heritage buildings, it is not possible to state the same for the data capture of archaeological stratigraphy. A few research projects have brought 3D technologies on site with the goal of integrating them for the documentation of archaeological stratigraphy (Doneus et al. 2011: 81-88; Forte et al. 2012: 350-378), but a precise test of the accuracy of the 3D models coming from the different techniques is still years away. Today, the use of technology for the 3D documentation of archaeological sites is well established. For this reason it is crucial to understand the real efficacy and reliability of these new tools for improving the accuracy and objectivity of the excavation process. In this sense, the definition of a new methodologies able to take stock of the current knowledge of 3D documentation of archaeological sites and give a more scientific basis to the entire 3D documentation process. A timely geometrical comparison of the models, is central for the creation of a new and effective tool for archaeologists.

3.3. Visualization systems for the analysis of the archaeological record

The creation of digital data archives in archaeology has started to be spread in the last decade (Richards 1998: 333-335; Shaw et al. 2009), but the potential to visualize these data in an interactive and simple way for inexperienced users is not as common.

In the last 30 years significant progress has been made in computer applications used in archaeological work (Barceló 2003). GIS-based photomapping has permitted the development of multivariate visualization and analytical methodologies for the spatial analysis of artifact distributions in archaeological sites (Craig et al. 2006: 1626). The situation is different if we consider only programs used for 3D stratigraphic analysis of archaeological position. In fact, while a good number of 2D applications for stratigraphic data presentation were developed starting at the end of 1980s (Alvey 1989; Boast and Chapman 1991; Herzog and Scollar 1991), it is not simple to find 3D examples.

Interest in the development of a visualization system that could facilitate the creation, exploration and presentation of stratigraphic relationships, started in 1975 with Wilcock's STRATA program (1975). This program demonstrated that a computer program could be used to derive the logical sequence between stratigraphic layer relationships.

A decade later, Ryan prepared the foundation for several subsequent developments (Ryan 1985a: 126-132). Working on the related problems of drawing genealogical diagrams and graphical representations of computer stored file, he used core algorithms of existing system software, the UNIX "topological sorting" program *tsort*, to develop *gtree*, a generalized program for drawing and manipulating tree-like data structures. The result was an interactive system called the *gnet* system, which allowed interaction with and exploration of the stratigraphic diagram (Fig. 11).
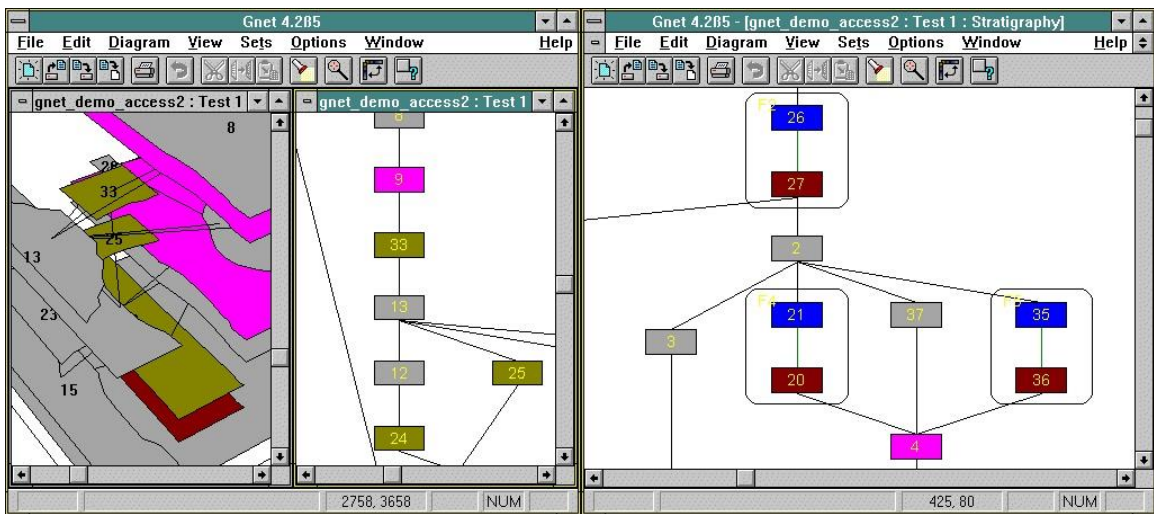
Figure 11. Gnet showing the stratigraphic diagram (Ryan 1985b: 404-414).

In 1991 Boast and Chapman (1991: 29-37) presented an approach based on SQL (Standard Query Language). In the same period, Herzog and Schollar developed and presented the "Harris" system, an automated application devoted to the production of stratigraphic diagrams (Herzog and Schollar 1991: 53-59). With this system it was possible to change and interact with the Harris diagram, working on the layers and their time relationships. This program followed the earlier approach developed by Wilcock of producing a solution as the output of a batch run. In 2002 the Harris program was improved

by the Herzog with a data entry form for units and a more complex interface for the user (Herzog 2002: 1-11).

The Integrated Archaeological Database (IADB) is one of the first examples of a complex and integrated database for post-excavation analysis. IADB is a web application that uses modern AJAX programming techniques that is, a group of interrelated web development techniques used on the client-side to create asynchronous (a form of input/output processing that permits other processing to continue before the transmission has finished) web applications (Garrett 2005). The access to the database is possible through a web browser from any Internet-connected computer without installing software on the user's computer. The development of this database started in the late 1980s, when an early version of the system ran under MS-DOS and was written in Clipper and C using the dBase database format. In 1997 through Visual Basic, IADB was moved to Windows using an MS Access database. In 1999 IADB was converted to a web application using MySQL and PHP (IADB). The hierarchical structure of the database consists of finds, contexts, sets, groups, and phases. The find and context record only contains data fields applicable to all finds and contexts (Fig. 12). Data applicable only to a specific class of finds and contexts is recorded through Specialized Recording Sheets (SRSs). SRSs are used in the database for pottery, skeletons (burials; fig. 13), and timber. AEGIS is integrated into IADB, allowing the digitization of all single-context plans (Fig. 14a), and group plans (Fig. 14b) to be generated automatically, manually, or by using a combination of the two methods.

A matrix compiler and editor, CONSORT, is integrated in IADB, allowing analysis of all the stratigraphic relationships. Single and/or complex interrogations of all data tables are possible due to SQL. IADB gives archaeologists a complete digital recording solution for 2D analysis and data collection of archaeological stratigraphy (IADB). A pioneer of net solutions and the introduction of a 3D visualization to charts is N. Ryan with his project *jnet* (Ryan 2001). *Jnet* system was developed to recast "the capabilities of the earlier *gnet* program in a form that is more appropriate to modern networked and distributed computing environments" (Ryan 2001: 11).

Figure 12. Context data input in IADB (http://www.iadb.org.uk/).

Figure 13. Skeleton SRS recording window in IADB (http://www.iadb.org.uk/).
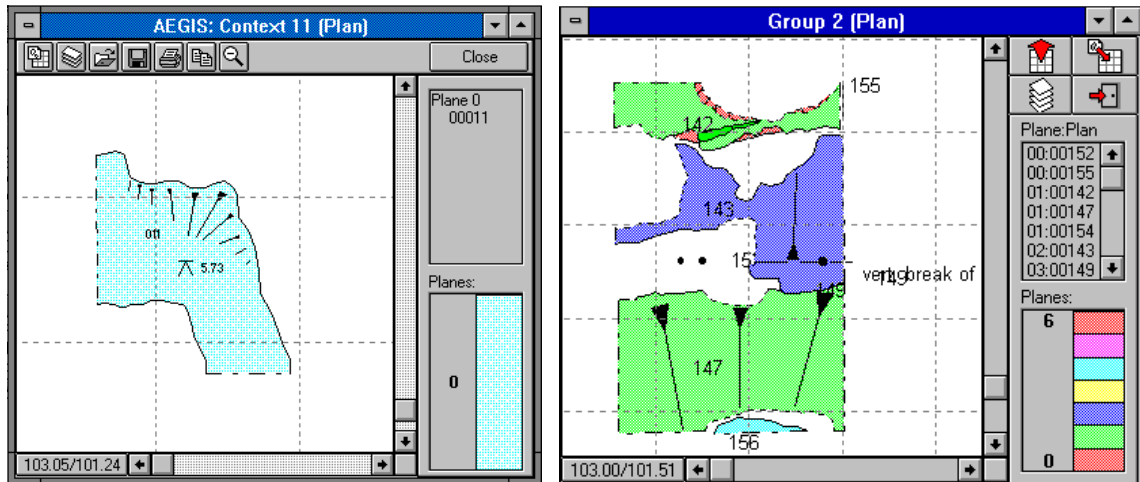
Figure 14. AEGIS in IADB: left. Single plan window; right. Composite group plan
(http://www.iadb.org.uk/).

Researchers of Brunel University working at the *3D Murale* project developed the *Strat* tool (*Strat* Tool 2001), a tool for the 3D visualization of archaeological sites, This tool was developed using API – MFC (Application Program Interface – Microsoft Foundation Class library). This free software allowed the development of a Windows application using OpenGL. Another version of the database was developed using Linux.

The database allows creation of different site projects and uploading the 3D stratigraphic models in each project based on the date of the stratum excavation (Fig. 15).

Figure 15. *Strat*: left. Creating a new site; right. Defining a new excavation unit (*Strat* Tool 2001).

Depth information is recorded using the four heights of the corners of the stratum recorded by the archaeologist or by specifying only an average (Fig. 16).
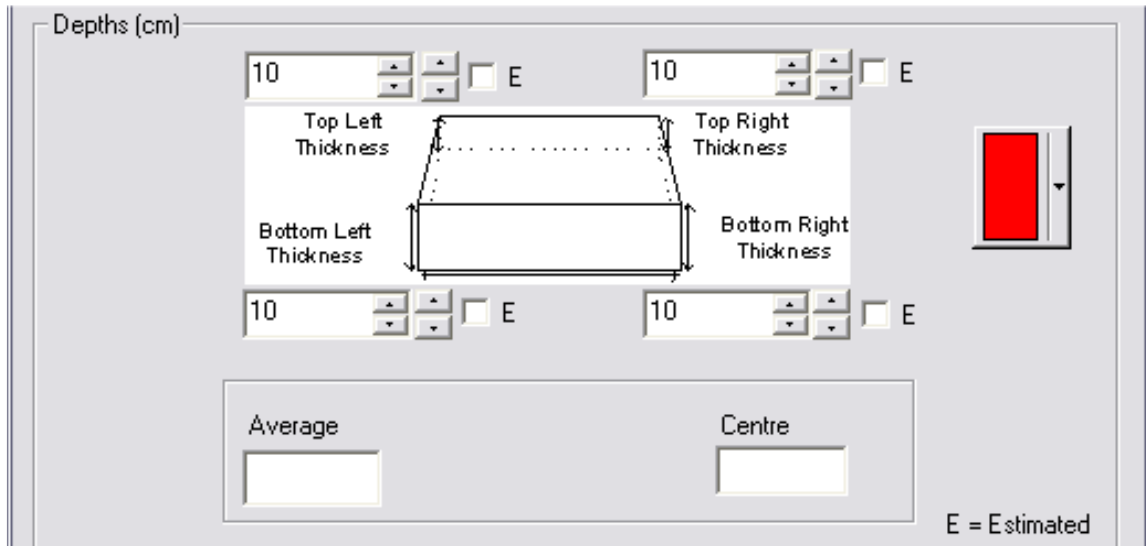
Figure 16. Depth information in *Strat* (*Strat* Tool 2001).

In this project, the archaeological artifacts, structures, and buildings were reconstructed in 3D using a photogrammetric technique while the stratigraphic layers were represented through very simple 3D volumes, obtained only from the measurement of the depth of the four corners of the trench (Fig. 17). All the 3D models used in *Strat* (photogrammetric 3D models and simplified stratigraphy) do not reproduce and preserve the strata information in three dimensions. They are basic and low resolution representation of the stratigraphic sequence.

In 2004, researchers from the Department of Computer Science of the Columbia University developed VITA (Visual Interaction Tool for Archaeology; Benko et al. 2004: 132-140), a collaborative mixed reality system for off-site visualization of an archaeological dig. The system allows "multiple users to walk around the virtual site, and explore it using multimodal interaction to inquire about interesting finds in situ. VITA also includes a collaborative table surface, augmented with a world in miniature model of the environment and high-resolution screens, to allow for simultaneous viewing of all available 2D and 3D site data" (Fig. 18 left; Benko et al. 2004: 132).
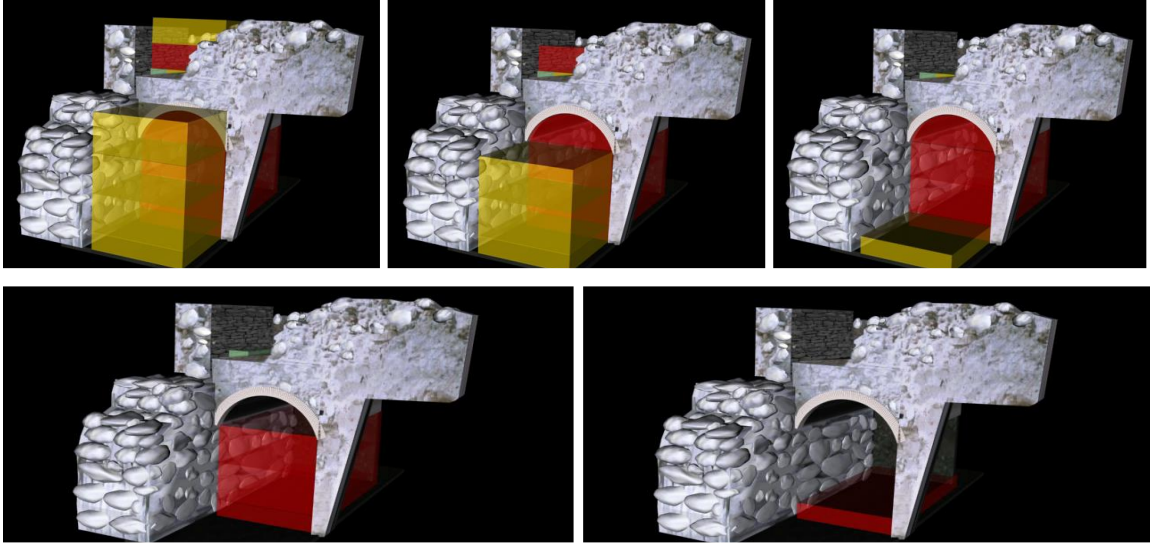
Figure 17. Stratigraphic sequence in *Strat* (*Strat* Tool 2001).

The system allows for interaction of multiple users with the 3D replica of the archaeological site, giving information about artifact location in the space. VITA has a variety of modalities that stress the interaction and engagement of users with the 3D models: *tablet interaction* allows 2D navigation of all objects and their relations to the various layers of the site; *handheld widget* creates a movable high-resolution portal within the tabletop (Fig. 18 right); *hybrid gestures* permit the manipulation of objects' 3D models (Fig. 19); *multimodal interaction* give users the potential to point and select objects; *virtual-tray widget* allows users to save the selected objects in a "tray" that surround the user (Fig. 20). This offline system has great potential in terms of visualization, interaction and engagement, but the system lacks a well-designed and solid database.
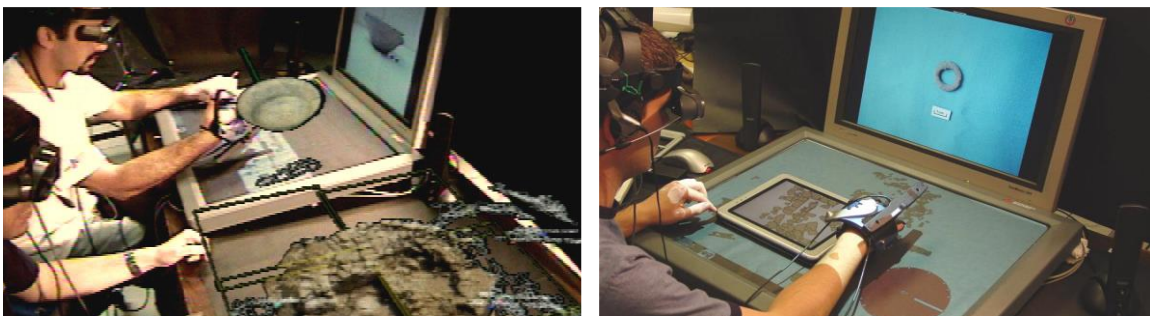
Figure 18. VITA (Visual Interaction Tool for Archaeology; Benko et al. 2004: 132):
left. VITA; right. tablet interaction and handheld widget.

Figure 19. Hybrid gestures in VITA (Benko et al. 2004: 132).

Figure 20. User inspecting objects in the VirtualTray (Benko et al. 2004: 132).

In 2007 VERA, a project funded by the JISC (Joint Information Systems Committee), developed three main software components aimed at improving IADB: *Recycle Bridge*, an infrastructure tool used to assist in the development of legacy web applications within a portal environment; *XDB*, a cross-database search; and Arch3D a visualization tool that allows accessing and viewing the excavation data in a different way (Mills and Baker 2009: 1-10). Arch3D allows the integration and investigation of the multi-dimensional datasets obtained from an excavation, and the examination of the logical and spatial stratigraphy of the site. Nonetheless, the use of the third dimension is partial in this tool, since "Arch3D shows contexts as flat 'plates,' representing the outline of the context in plan. The third dimension is used [just] to indicate the position within the stratigraphy of the site" (Mills and Baker 2009: 6).

According to Bobowski and his colleagues, the combination of *jnet* and *Strat* tools could "enable archaeologists to visualize archaeological stratigraphy data and all information from an excavation" (Bobowski et al. 2008: 2). To this end, during the International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA) 2007 they presented a Dynamic 3D Visualizations of Harris matrix Data (Bobowski et al. 2008). This tool is simple in terms of visualization, but it is challenging in its attempt to combine 3D visualization and analysis. Using X-VR technology and X-VRML language, in fact, they created a virtual reality active application based on databases. The visualization of the 3D Harris Matrix, integrating vertical stratigraphy with horizontal topographical presentation, was created by data stored on the database server. The system consists of two components: a *data management system*, responsible for controlling data from excavations in the database, enabling inspection and editing of database content and data loading from external sources; and a *data visualization sub-system*, a spatial visualization subsystem realized using the Cortona Virtual Player plugin (Bobowski et al. 2008: 3).

The discussed projects had the merit of developing 3D visualization system for the stratigraphic analysis. With these programs archeologists were able to analyze archaeological units with their real spatial relations. Still, these researchers either created visualization systems characterized by well-made and solid database but 3D schematic graphic representation of the layers (Ryan 2001; *Strat* Toll 2001; Bobowski et al. 2008; Mills and Baker 2009), or very powerful visualization system that lacked a solid database (Benko et al. 2004). None of the analyzed research was able to create a solid database linked to a visualization system that was able to display realistic 3D representations of the archaeological stratigraphy.

In this sense, Losier et al. (2007) believe that field archaeologists would greatly benefit from the integration of Computer-Aided Design (CAD) and Geographical Information System (GIS), because they offer valuable tools for capturing, modeling, storing, sharing, analyzing, and depicting geographically referenced data. Losier and his colleagues note how these systems would allow archaeologists "to model 3D excavation units in realistic 3D representations, at the same time as managing their relationships," and

they also argue that in this way it could be possible to create "an asset for field archaeologists because it would allow them to carry out topological analysis and visualize the results in a more realistic manner" (Losier et al. 2007: 237).

The use of GIS for the data analysis of archaeological sites is very common in archaeology (Aldenderfer 1996; Allen et al. 1990; Gillings et al. 2000; Zubrow 2007: 252-280). In 2003 Nathan Craig and Mark Aldenderfer developed a real-time digital data recording system for archaeological excavation units using the Arcview GIS database (Craig and Aldenderfer 2003: 12-22; Craig et al. 2006: 1617-1627). GIS- based photomapping allowed for integration of experimental data into the interpretation process of the Jiskairumoko site in Peru. The application of additive color multivariate visualization allowed archaeologists to see relationships between distributions of interest. This project produced a very solid methodology for the analysis of archaeological sites though multivariate visualization, spatial analysis, and integration of experimental results that are possible with GIS-based photomapping. Likewise, the use of CAD software has become common for the 3D reproduction and analysis of the archaeological stratigraphy (Cattani et al. 2004: 299-303; Uotila and Tulkki 2002:427-430; Zhukovsky 2002: 431-438).

The challenging aspect of Losier at al. work is the idea of integrating the two elements (CAD and GIS). Using the Gocad 3D modeling tool, they were able to transform GPS points representing upper surfaces of excavation units of the Tell 'Acharneh site (Syria) in 3D voxel models and publish them with VRML. Moreover, the software allowed them to assign qualitative and quantitative properties to every excavation unit in order to do attributes querying. These properties were assigned to a region of voxels, since in the voxel model the concept of object does not exist. This research seems to move in the right direction, promoting the integration of realistic and metric 3D models and solid software for the analysis and management of data, such as GIS. However, how it is possible to see in figure 21, the graphic representations of the excavation units are not very accurate and detailed, but only a simplified representation of the general volumes of the units without color information. These kinds of visualization systems need to be tested with 3D models characterized by high density of taken points. Losier and his colleagues underline the

necessity to test the system with 3D reproductions of excavation units described by millions of points coming from 3D laser scanners (Losier et al. 2007: 287).

The aim of this chapter was to introduce the state of the art in the use of 3D digital technologies for the documentation, preservation and visualization of the archaeological record. The main goal of this dissertation research is to develop a coherent and complete methodology that will be instrumental for the definition of new practices in the use of 3D technologies in archaeology. The first step of this research is the intra-site 3D data recording using different technologies.
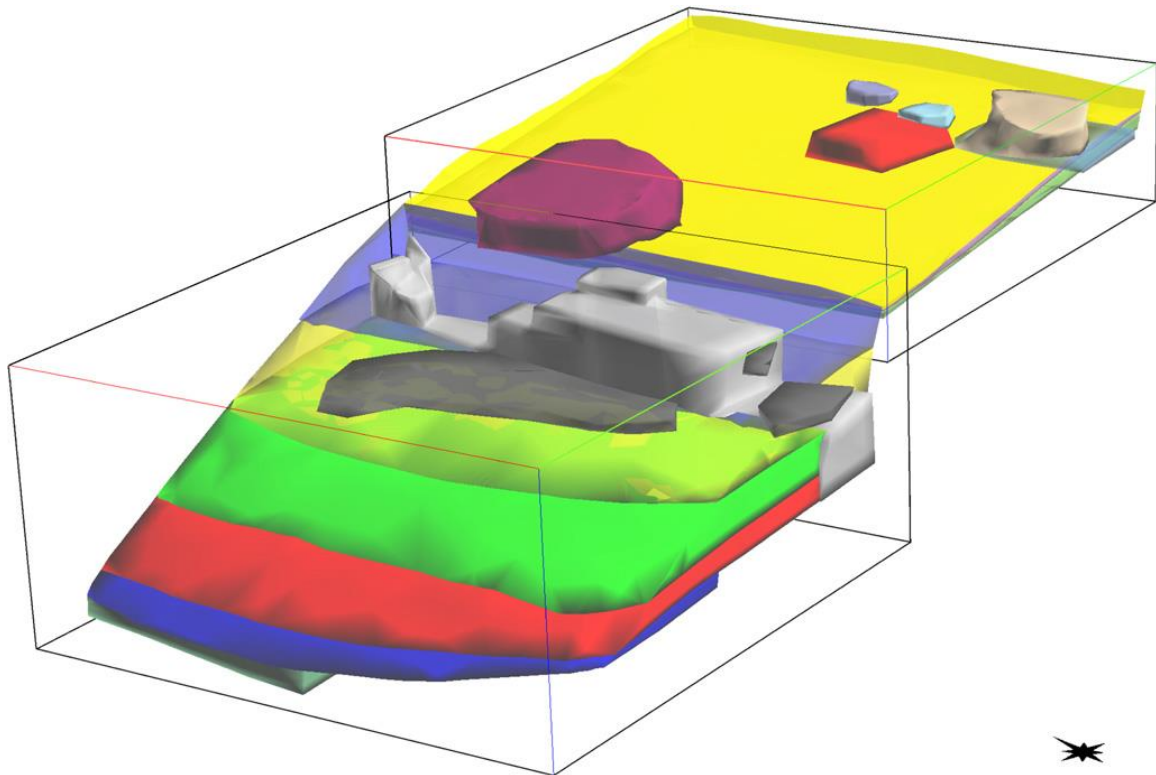
Figure 21. Surface lots of TEW 1 and 2 at Tell 'Acharneh (Losier et al. 2007: fig. 14).

The following chapter presents the comparison of different 3D acquisition techniques for the documentation of three archaeological contexts (Xi'an – China; Çatalhöyük – Turkey; and Las Cuevas – Belize). The excavation process of the two sites was recorder using laser scanning and dense stereo matching techniques. The accuracy comparison of the 3D models

acquired using the different techniques were performed using commercial and open source software. The chapter presents the final results of this comparison stressing pros and cons in the use of the different technologies, and suggesting possible solutions for their integration in the data collection of the excavation process.

Chapter 4

Case studies

This chapter provides a description of the three case studies used for this research: Xi'an (ancient Chang'an), China; Çatalhöyük Site, Turkey; Las Cuevas Site, Chiquibul Reserve, Belize. Chapter 4 provides general information of the three sites, while the following chapters 5 and 6 will provide more technical information of the technologies used to record these sites in 3D, which was helpful to define the methodology of this study and discuss research results (chapter 5), and the value of 3D metric replicas and simulations of heritage sites in research and education (chapter 6).

4.1. Xi'an (ancient Chang'an), China

The project "The Virtual Museum of the Western Han Dynasty" started in 2008, thanks to the collaboration between the Xi'an Jiaotong University and the University of California, Merced, School of Social Sciences, Humanities and Arts. Later this collaboration was extended to the Xi'an Municipal Cultural Relics Conservation and Archaeological Research Institute (China), and CNR-ITABC, Italian National Research Council (Italy). The scope of the project was the creation of different virtual museums in China and California, based on the 3D documentation and reconstruction of sites, landscapes, and main artifacts of *Chang'an*, the ancient capital of the Western Han Dynasty. One of the most challenging part of this research was the 3D documentation and reconstruction of two mural tombs: the Xi'an University of Technologies (M27) (Fig. 22 left) and the Cuizhuyuan, also known as Green Bamboo Garden (M1) (Fig. 22 right).

Figure 22. Three dimensional models of the mural tombs: left. Xi'an University of Technologies Mural Tomb (M27);

right. Green Bamboo Garden Mural Tomb (M1).

4.1.1. Xi'an University of Technologies mural tomb (M27)

Xi'an University of Technology mural tomb is located on Leyou Plane, northwest of Yue Jiazhai Village in the south suburb of Xi'an. Originally it had to be covered by an earth mound, that was cut during the 1950s and 60s. The mural tomb was excavated between January and March 2004. During the excavation, robbery holes were found in the north wall of the tomb chamber, and on the brick wall closing the main chamber entrance (all the information on this tomb comes from the excavation report of the tomb: VV.AA. 2006, later translated in an English unedited version by Lizhi Zhang, Jaotong University of Xi'an).

The monument is characterized by the following elements: a tunnel excavated directly in the ground; two side rooms, where grave goods were preserved; the main chamber. The orientation is south-north. Through the tunnel is possible to have access to the three underground chambers that are all made of bricks.

The side rooms are located at the end of the tunnel, before the main chamber gate. In the eastern side room four seals and one pottery basin were discovered. In the western room two lacquer wooden chariots were placed in the front and back position. Both were rectangular in plane and had double shafts and single horse. Of these chariots only the lacquer pieces and the bronze ornaments remain, while the wooden part has deteriorated into wooden powder.

The main chamber has a rectangular shape (4.6 meters long from the south to north and 2.08 meters wide from the east to west). The chamber wall is 1.25 meters high, and the chamber itself is 2.10 meters high. It was completely covered of frescos. Inside the main chamber, the coffin of the deceased was found located in the northeast corner (2.10 meters long and 0.60 meters wide). Next to the coffin there were two jade eye masks, a jade object outlining in the mouth of the deceased, two jade nose elements, and a jade necklace ornament. Moreover 200 Wuzhu coins and a bronze seal were found in the chamber.

The tomb was dated at the end of the Western Han Dynasty (206 BC-9AD) thanks to a typological comparison with similar structures that were dated, and to the bronze Wuzhu coins discovered inside the tomb. The identity and status of the tomb owner have been assumed based on the size of the tomb, the importance of the burial objects, and the paintings. He was probably a governmental official during the Western Han Dynasty (Loewe 2006; Ch'ü T'ung-tsu 1972).

Mural paintings description
The mural paintings inside the main chamber of M27 are realized on a thin white clay layer applied on the walls and ceiling. Because of the nature of the murals, there are important conservation issues that need to be addressed. Even though the mural tomb is closed to the public, and anti-molding and anti-germ processing have been frequently executed, the conservation of these paintings is still at risk. They cannot even be detached from the bricks and collocated into a museum, because of the way they have been realized. All the paintings are characterized by a black ink contour line, filled up with natural colors. The main colors are green, white, yellow, red and black, and they have a symbolic meaning linked to the universal elements of Chinese philosophy.

Entering in the main chamber, the first subjects that appear in the eastern and western sides of the gate are the two tomb animal guardians, the dragon and the tiger (Fig. 23). They are both in the standing position between clouds, holding a long narrow flag; the dragon body traces an "S" and it is characterized by a sharp mouth, round eyes, double horns, and golden scales; the tiger is winged with black stripes on the back, and the face is not recognizable.

A second representation of a dragon and a tiger is on the ceiling, respectively in the south-east and in the northwest angle. The green dragon is connected with the sun in front of it –inside which there is a golden crow– and symbolically associated, in the Chinese philosophy, to the East and the day. In the opposite angle the white tiger stands linked to the moon –in which there are a toad and a jade rabbit– representing the West and the night.

In association with these two mythical animals in the middle of the south part of the ceiling is the red bird of the South (zhuque), which seems to fly in the south direction (Fig. 24a). The zhuque, or red bird, is sometimes mistaken for the fenghuang, but they should be two separate entities. Fenghuang is a fantastic animal made up of the beak of a rooster, the face of a swallow, the forehead of a fowl, the neck of a snake, the breast of a goose, the back of a tortoise, the hindquarters of a stag and the tale of a fish (Chang 1983: 56). It represents both male and female entities as other symbols in Chinese culture.
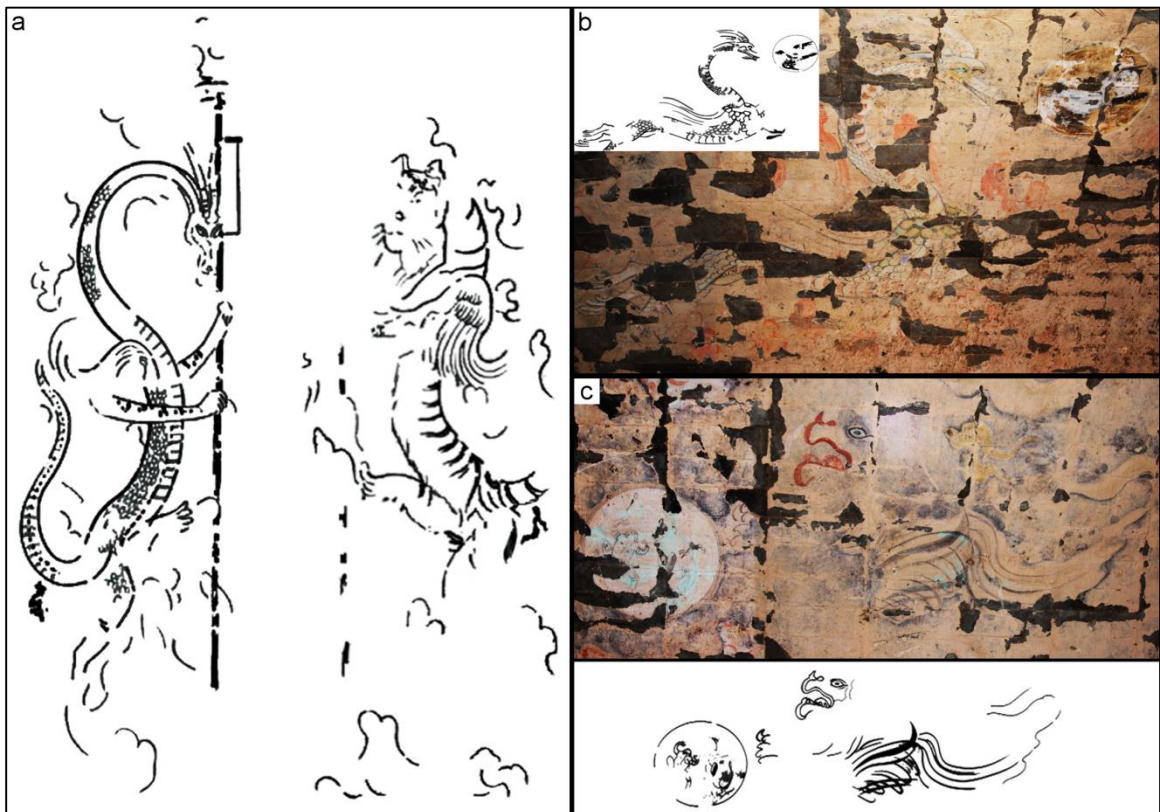
Figure 23. Xi'an University of Technologies (M27) mural tomb: a. Tomb guardians (side walls of the chamber gate, drawing); b. Green dragon symbol of the East (ceiling; picture and drawing); c. White tiger symbol of the West (ceiling; picture and drawing).

南方朱雀, Nán Fāng Zhū Què literally means 'the South red bird'. It appeared in association with the other three animals during China's Warring States period (476 BC - 221 BC), and they were frequently painted on the walls of early Chinese tombs (Loewe 1970: 72). In M27 the bird predominant color is red, but it is not the only one; the body in fact is yellow, the peacock tail is multicolored, the long neck is blue.

The last cosmic symbol is represented by a snake or a tortoise (Fig. 24c-d). Strangely neither symbol is depicted on the ceiling, but we can recognize two snakes on the northern wall, where there is the symbolic representation of ascension to heaven for immortal life.

On the ceiling it is also possible to recognize three celestial cranes among clouds (Fig. 24 b-e). All the celestial birds and auspicious animals are flying to the south. In conclusion it can be said that the ceiling reveals the heaven in which the soul of the tomb owner lives.

On the side walls murals are featured by scenes of daily life, which underline the social status of the deceased:

- On the eastern wall scenes of horse hunting are represented (Fig. 25a). On the top of the south end of the wall there are chariot outgoing scenes: the master seems to be represented sitting in the two-horse leading chariot escorted by two riders with running horses opening the way, followed by one rider in the middle. On the middle and the northern part hunting scenes are represented; all the figures seem in movement to the north. We can recognize nine groups of characters: a red-clad hunter riding a white horse and holding a bow in his left hand and pulling an arrow in the right hand to shoot two fleeing deer in the front; two riders riding shoulder by shoulder; a hunter in red riding a black horse, and pulling his bow to shoot a deer; a red-faced hunter in grey riding a dark brown horse; a hunter in green off the horseback to pick up the prey; a hunter riding a white horse, holding the rein in the left hand, and keeping the lash, to whip the horse forward at fast speed; a hunter in red running after a wild boar; a white-clad ride hunter holding a spear on the back on a white horse; a hunter dressed in yellow, riding a red horse, and shooting the prey over his back; other figures are mutilated and unrecognizable. In the lower part,

the most damaged, the scenes are difficult to be understood and described. The only recognizable is another scene of chariot outgoing.
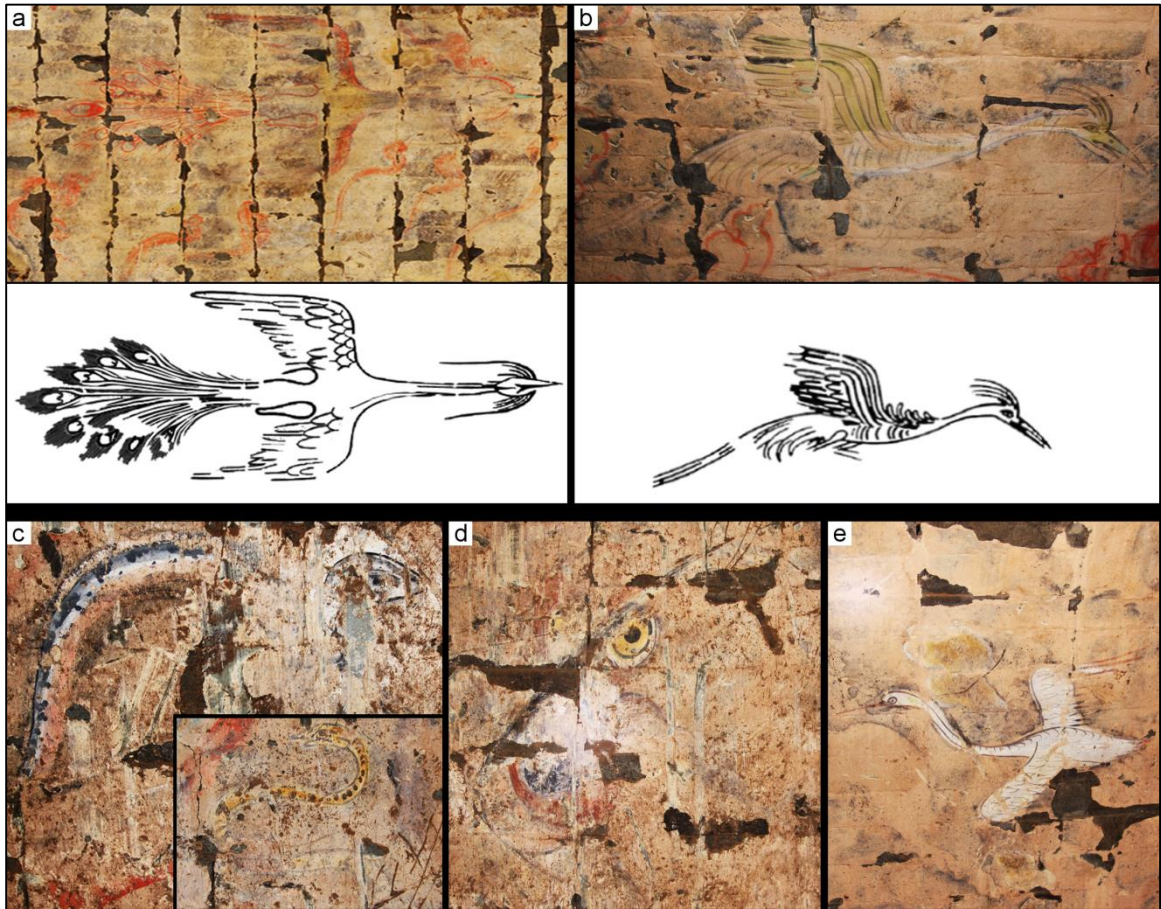
Figure 24. Xi'an University of Technologies (M27) mural tomb: a. Red bird of the South (ceiling; picture and drawing); b. Celestial crane (ceiling; picture and drawing); c. Snakes (northern wall; pictures); d. Unrecognizable animal (northern wall; picture); e. Celestial crane (ceiling; picture).

- On the western wall, paintings in the north are stripped off seriously. It is assumed that those paintings should be the scenes of musical and dancing performance (Fig. 25b). In the middle of the wall is the scene of rooster fighting. In the south of the wall is the banquet scene with dances; some characters are sitting on a wooden couch with a screen on the back; others are enjoying the show sitting on the floor; at the center of the scene there are two dancers. The screen is a very important element during the Western Han

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period, but more generally in Chinese culture. It represents a division between the private part of rich houses and the representative space.

Figure 25. Xi'an University of Technologies (M27) mural tomb, scenes of daily life: a. Horse hunting − hunter pulling his bow to shot a deer (east wall; picture and drawing); b. Banquet – banquet scene with dances (western wall; picture and drawing).

On the northern wall is a Yuren –the celestial being who leads the dead to ascend to heaven for immortal life (Fig 26). He faces a dragon and the west, and his arms are stretching forward in the steady position, as if to hold the dragon snout. He has red face, huge animal ears, round eyes, high nose, protruded lip, curly and fluttering hair, and wings on the shoulder. The dragon is red in belly and green in the back, the head of which has been severely mutilated due to the robbery hole. Below the dragon are a yellow and a green snake. In addition, there is another animal, which has striking eyes but unidentifiable trunk. Among those images clouds are painted.

Figure 26. Xi'an University of Technologies (M27) mural tomb: Yuren − the celestial being who leads the dead to ascend to heaven for immortal life (northern wall; picture and drawing).

Tomb historical context

In the iconography of the tomb M 27 we can recognize the symbolic expressions of the Western Han culture. The Han period marks the beginning of an imperial bureaucratic state, where the social status rests on a rudimentary examination system and the growth of a land based aristocracy (Ch'ü 1972).

During this period there was the first operation of imperial unity, in the sense of the continuity of a single dynastic house. Government was now more effective than it had ever been; cultural life was richer, with more frequent contacts with non-Chinese people, a more sophisticated view of literature, and the embellishment of many of China's arts and crafts. In this period the religion had formed an integral element in society and politics.

The religious belief and practices of Han China are based on three major principles: that of the Five Phases, which regulated the cycles of growth, change and decay; that of the complementary forces of Yin and Yang; and that of the single overwriting presence of *tao*.

Five Phases - The term *wu hsing* is variously rendered as the "Five Phases" or "Five Elements" or "Five Agents" (Loewe 2005: 38). In a 100 B.C. source it is said that the so

called 'Yellow Emperor', Huang ti, who examined the movements of the stars, worked out their cycles and initiated the concept of the five phases that comprehend universal activity. The powers of the five elements became associated with materials (wood, metal, fire, water, earth) and other sets of objects or qualities that could be numbered in five, such as the colors (red, black, white, green and yellow) or the directions (south, north, west, east and center). The number five assumed a strong symbolism: there were five sacred mountains, five senses of human perception and five musical notes. Wu hsing were associated also with different animal symbols (green dragon at east, red bird at south, white tiger at west, serpent and turtle at north, no symbol at the center). These animals marked the four seasons and four cardinal directions: the green dragon of the east (spring), the red bird of the south (summer), the white tiger of the west (autumn), and the black snake or tortoise of the north (winter). The fifth direction was the center linked with no animal symbols (Loewe 1970: 118-121).

The four symbols appeared frequently as a decorative motif on the backs of mirrors, on porcelains and of roof tiles. It is important to notice that, from the middle of the first century before Christ, the Five Phases affected iconography. The four animals sometimes may be accompanied by what may be a fifth symbol, a mound.

Yin-Yang - According to one theory which was evolved at about 300 B.C., the creation of the world and the continued processes of nature were to be attributed to the complementary powers of two major forces of Yin and Yang. The different impact of these two forces could be recognized in the everyday phenomena of the world. Yin was associated with female, dark and cold, Yang with male, light and heat; and the rhythmical procession of natural phenomena depended on which of the two forces happened to be in the ascendant. Yin and Yang were manifested in types of energy or qualities, or the material elements of fire, water, metal, wood and earth, whose creation they had contrived but which were themselves powerful enough to ordain the form of the material world.

Tao - Tao is known in writings as the Tao-te ching and the Chuang-tzu as the rule that underlines the universe. Tao is also defined as the *way*, "is majestic, and brings into question the value of human assumptions, judgments and aspirations" (Loewe 1982: 38-41; Loewe 2005: 43). Tao theories had to be well known during Han Dynasty. According

to Loewe, in a Daoist school of thought the movements of nature had to be seen as advance and decline of Yang, followed by that of Yin, in a total of five phases.

To those who thought in terms of Five Phases and Yin and Yang, Tao was the order of nature within which those rhythms operated. Dynastic governments identified themselves to a color and to an element as representative of its power. Han sovereignty was explained as representing the dominant element of water-black, or later earth-yellow, and the appropriate colors were chosen for ceremonial use and display. The yellow color became increasingly popular, so much so some emperors started to be named "Yellow Emperor" (Khon 2005: 136-137).

During the Han Dynasty the cult of immortality was also important and it influenced religious practices. The world of the immortals is sometimes depicted in the fresco paintings of Han tombs. The Yuren, a celestial being partly human partly animal, was considered the spirit who leads the dead to ascend to heaven for immortal life. The desire to prolong life was not just linked to an individualistic conception of life, but to the desire of ensuring lineage and community continuity or survival. There were both the desire of a physical immortality and the conviction that it was possible to obtain the bliss in a non-worldly immortality; the latter was proper of ascetics and hermits (Loewe 1970: 114). Both the definition of this complex political and social system and the diffusion of Confucianism in the Western Han Dynasty could have brought about the introduction of scenes of daily life in the tombs. They could be interpreted representing the social status of the tomb master.

4.1.2. Green Bamboo Garden mural tomb (M1)

M1 was discovered and excavated in November of 2008, in the course of construction of the Cuizhuyuan housing estate, together with other three Western Han tombs in the southern suburbs of Xi'an City, Shaanxi Province (Xi'an Municipal Institute of Archaeology and Preservation of Cultural Relics 2010). M1 is a vertical pit tomb very similar to M27, with a long sloping passage and brick chambers: a tomb tunnel, a coffin chamber, a paved path, and two side chambers with accesses from the coffin chamber.

Differently from M27 the orientation is south-north. The tomb structure and burial objects suggest that the tomb was built in the late Han Dynasty as well. In M1 all the recognizable legacies from the past disappear in favor of newer motives: besides the introduction of human figures, for instance, constellations take the place of the four symbols of the cardinal points on the ceiling (Fig. 27a); the symbolic animal-guardians are substituted by male figures (Fig. 27b); the opposition night-day remains just on the ceiling; in the lateral walls, in fact, the clear dichotomy between day/night, male/female, yin/yang, disappears in favor of a parade of people converging on the eastern wall, where a screen stands at the center.

Figure 27. Mural tombs: a. Constellations (ceiling; M1); b. Tombs guardians − green dragon of the east (side walls of the chamber gate, M27), human figure (side walls of the chamber gate, M1).

The screen is a very important piece of furniture in a traditional Chinese house, because it divides the public space, where the owner receives guests, from the private part

of the house. Clouds decorate the M1 screen, and they seem to symbolically recall the trip to the immortal life. The mural tombs coffin chambers show a very rich repertoire of subjects, such as scenes of daily life, rituals and the ascension to heaven (He Xilin 2005).

The diffusion of Confucianism influenced the iconographic representation of this period and brought about the introduction of human figures (Chang 1983). The aim of Confucianism was the creation of a complex system of social and moral laws to end the Chinese spiritual decay. Confucianism focuses on the human experience and never on supernatural and metaphysic aspects. However scenes of daily life are still fused with pre-Han iconographic motives, as the soul journeys after death. This fusion of elements underlines an important moment of cultural transition in the Han period.

After the establishment of PRC (People's Republic of China), with the economic development of China, building works have increased and archaeologists have found a significant number of Han Dynasty Mural Tombs. Over sixty of them have been reported through media, but mostly they are dated back from the period of Xin Wang Mang (9 AD - 25 AD) to the end of Eastern Han Dynasty (25AD - 220 AD).

Few Western Han Dynasty Tombs have been excavated so far and, according to incomplete statistics, one is dated at the beginning of the dynasty and eight at the end. Only four are discovered in the region of Chang'an, ancient capital of Han Dynasty, partially corresponding to the modern Xi'an. Their typology and size are similar, but they differ for style, layout and contents of mural paintings. The paintings in the Xi'an University of Technology Mural Tomb are very innovative. They are richer from an iconographic point of view, and more structured and elegant. The innovation consists in the introduction of scenes of daily life, which become very popular during the Eastern Han Dynasty. In this latter period, in fact, there is a shift from the absolute depiction of celestial figures to the expression of ordinary people, considered the switch from visionary romanticism to rational realism (He Xilin 2001). According to Chinese scholars, this tomb together with the XJTU Mural Tomb, has bridged the gap concerning the Western Han Mural Tombs in the central plain of Shaanxi Province, gaining significant academic values in offering valuable references for the study on Western Han mural paintings.

4. 2. Çatalhöyük Site, Turkey

The large Neolithic settlement of Çatalhöyük, located in central Turkey, existed from approximately 7400 BC to 6000 BC (Cessford 2005). This site was first discovered in the late 1950s and excavated by James Mellart between 1961 and 1965 (1967). Mellart's reconstructions of elaborate shrines with complex paintings, installations and sculptures was the beginning of a long season of archaeological investigation that made of Çatalhöyük one of the most important Neolithic sites in the world. The notoriety of this site is mainly due to some characteristics that make of this settlement a unique example for the Neolithic of Anatolia and Middle East: the large size and dense occupation of the settlement; spectacular wall paintings and other art discovered inside the houses; the nature of the houses with no doors to the outside, but accessed through ladders from the roof; the practice to buried the dead under the floors of the houses' platforms (Hodder 1996).

The complexity of the site stratigraphic sequence is related to the fact that each house at Çatalhöyük was built and rebuilt several time. These houses are built with one main room containing oven or hearth and internal platforms with associated side rooms. Few of them were constructed in tandem with or connected to other houses, but they are relatively rare (Hodder 2013: 16).

The hearts' and houses' shapes change from round to rectangular through time. The change to rectangular was interpreted in terms of the packing of houses into increasingly dense settlements and a more careful ordering and compartmentalization of space as more and more activities took places in the houses. Individual houses seemed relatively self-sufficient but in times of failure or hardship individual houses were tied together into larger buildings centered on a history house in which 'house' members were preferentially buried. As the population increased the links between people and houses groups proliferated, favoring the houses' society-based links around symbols such as bear and leopard. As shown by the increase of rooms and storage areas in houses, history houses invested less in the neighborhoods focusing more on independent production and the build-up of their own surplus. The need of more durable materials for the bigger and more complex houses

increased pressures on the individual houses, leading to specialize more so that not all houses of groups of houses had to do all tasks (Hodder 2013: 25).

Since the 1960s, the understanding of Çatalhöyük and of the Neolithic of the Middle has changed as a result of new finds and excavations started by Hodder in 1993 (Balter 2005; Hodder 1996, 2000, 2005, 2006, 2007). It is clear today that the symbolism of Çatalhöyük is part of domestic cults and that the female imagery, the mother goddess described by Mellaart as prominent in this site, is only a small part of a diverse set in which mother and goddess characteristics are hard to find (Hodder 2007: 206).

Space 344 and Building 86

Space 344 is defined as an open space of multiple midden deposition that formed after the closure of Building 86, largely characterized by levelling and midden dumping, perhaps reflecting the need to remodel the area (or landscape it) after the fire that destroyed the earlier buildings (B.79 and B.80).

Even though the presence of pottery and worked clay was not substantial within the layers excavated, it is important to take note of the occurrence of clusters of articulated pottery shards, (19125), (19127), in the layers closest to Building 86 in-fill. One of the clusters (19125) was comprised of burnt shards, and the datum reinforces the idea that numerous activities, mainly associated with fire spots, were taking place within the midden. There is more evidence of activities in the earlier layers.

Many of the midden layers were disturbed by post-depositional features, such as insects and plant activities, as well as a number of animal burrows. Moreover, the north-western limits of Space 329 had been exposed since the Mellaart excavation. In general it was evident that there was a depression at the centre of the midden area with laminated deposits conveying in the middle and with a concave profile. This is confirmed by the two sections on the Eastern and Western edge of the trench (Çatalhöyük 2010 Archive Report: 20-23. http://www.catalhoyuk.com /downloads/Archive_Report_ 2010.pdf).

4. 3. Las Cuevas Site, Chiquibul Reserve, Belize

The Las Cuevas Archaeological Reconnaissance (LCAR) investigation started in 2011 under the direction of Holley Moyes, principal investigator of the project. This research investigates the ancient Mayan archaeological site of Las Cuevas, located in the Chiquibul Reserve in western Belize, Central America (Fig. 28).

The only notable investigation conducted at Las Cuevas's site, originally referred as "Awe Caves," was conducted in 1957 by Adrian Digby for the British Museum (1958), who wrote a brief article for the *London News* with the description of the site and the report of his excavation. In 1962 A. H. Anderson, Commissioner of the Belize Department of Archaeology, in a paper presented for the Americanists' Congress mentioned a visit to Las Cuevas in 1938 when he produced a sketch map of the site.
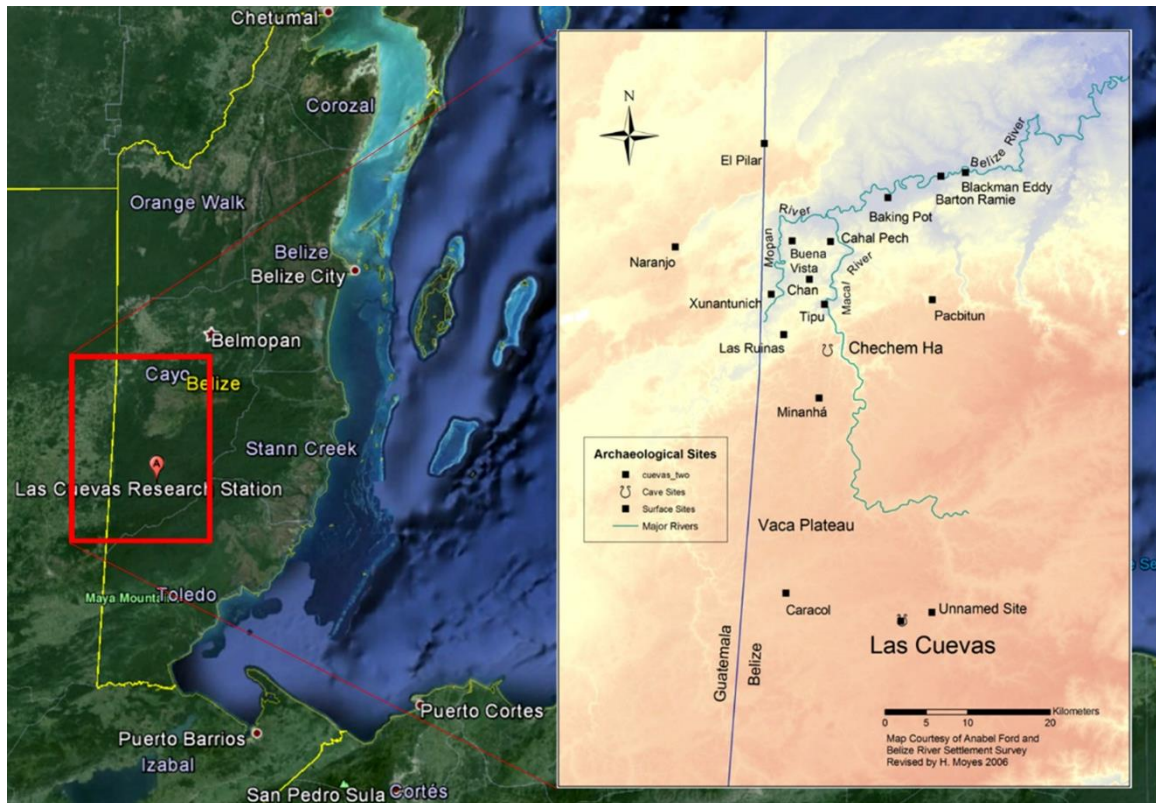
Figure 28. DEM of Belize showing location of Las Cuevas (Courtesy of the Las Cuevas Archaeological Reconnaissance).

The conventional use of terms such as "collapse" and/or "fall" was considered misleading by recent studies (Moyes 2012; Aimers 2007; Demarest et al. 2004:546). Demarest et al. (2004) redefine the "collapse" of the late 9th century as the decline of the elite class and the abandonment of the institution of kinship in the Mayan Lowlands, instead of a total failure of an entire civilization.

However most Mayanists identify in this period a major change in the political systems and ideologies which conditioned both social organization and population until the abandonment of many sites between mid and late 9th century (Moyes 2012; Aimers 2007; Demarest et al. 2004).

According to Holley Moyes, "Las Cuevas offers an excellent venue for exploring this issue. It is a medium-sized Maya administrative/ceremonial center that appears to date primarily to the later part of the 9th century A.D." (Moyes 2012: 4). The site is located 14km southeast of the larger polity of Caracol.

In the Late Classic period, Caracol's settlement had an unprecedented expansion in the northeast direction to the site of Mountain Cow (Morris 2004) where it is attested that the construction of a road existed connecting the two sites. According to Moyes,

> …although Las Cuevas is an obvious contender to be incorporated into Caracol's expansion, there is no evidence to date that suggests that Cuevas was under its authority. Data collected thus far indicate that there were no roads leading from Caracol to Cuevas, no epigraphic or iconographic indications of apical elite use of the cave such as glyphs or cave drawing like those at Naj Tunich, and no carved stela depicting the Caracol emblem glyph (Moyes 2012: 12).

Moyes states that the proximity of Cuevas to the Caracol site core may be an evidence of either the weakening of the traditional kingship at Caracol, or the political disorder and fragmentation during this period, opening up "an opportunity for lesser nobility or political upstarts to break from Caracol, or possibly even an aspiring elite from further afield to create the ritual complex at Cuevas" (Moyes 2012: 14).

The aspect of the superficial site of Las Cuevas appears similar to many Late Classic Belizean sites, such as Baking Pot, Floral Park, Blackman Eddy or Minanha (Iannone 2004).

The originality of this site when compared to the others resides in a large cave system located directly beneath Structure 1, and runs beneath Plaza A. The cave entrance is located below the eastern pyramid or "shrine," that was described as the foci of ancestral burials not only at Las Cuevas (Moyes 2012: 4), but also at both Caracol and Tikal, (Chase 2004:53, Becker 2003:258-262). The cave presents a massive, cathedral-like, entrance and an architecture that was probably modified for large public performances. Moreover inside the cave's entrance is a cenote with a natural spring at its base (Fig. 29).
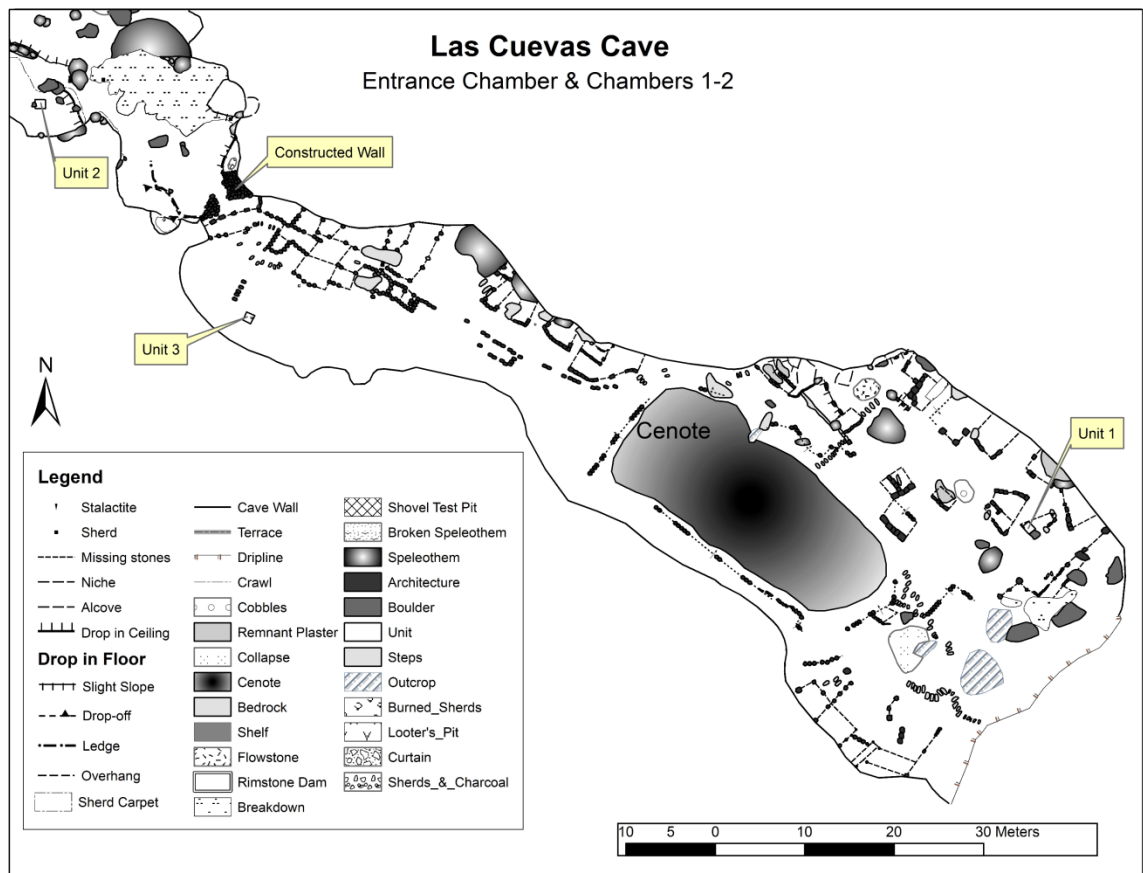
Figure 29. Map of Las Cuevas illustrating placement of units 1, 2, and 3 in the cave (Courtesy of the Las Cuevas Archaeological Reconnaissance).

The aim of LCAR is to combine evidences coming from the structures in the cave with those of the surface site to describe and clarify how the community used the different spaces of the site for ritual practices, and how those practices relate to the sociopolitical and

natural environments (Moyes 2012: 4). According to Moyes and Brady, "while it is not unusual for Mayan sites to be associated with caves, we rarely see such a direct connection or such an extensive tunnel system beneath a site core" (Moyes and Brady 2012).

Test excavations, both in surface contexts and within the cave, were conducted to begin to establish the site's chronology. The plan of the principal investigator of the project, Holley Moyes, and her team is to investigate connectivity between Las Cuevas and Caracol by comparing architectural layouts, ceramic assemblages, chronology, ritual practices and settlement patterning between the sites (Moyes 2011; Moyes 2013).

Chapter 5

Digging digitally using integrated technologies: data acquisition and comparison

The use of 3D technologies for the documentation of archaeological and cultural heritage sites is well established today. Laser scanning and, recently, dense stereo matching techniques have shown to be very powerful tools for the 3D documentation of the archaeological excavation and context. However, no convincing comparison and accurate data assessment of the different technologies has been presented so far. The research described in this chapter aims to be a starting point in the creation of a coherent and overall methodology that, through the comparison of 3D technologies in different archaeological contexts, will contribute to defining best 3D practices for the documentation of archaeological sites.

This chapter compares different 3D documentation technologies used to record the archaeological contexts described in chapter 4. The first section of this chapter (5.1) shows the comparison between time of flight and triangulation light laser scanning techniques, highlighting pro and cons in the use of the two technologies on site. The second and third sections (5.2. and 5.3) detail the results of the accuracy comparison conducted between 3D models of the archaeological stratigraphy coming from two laser scanning technologies (triangulation light and phase shift variation) and dense stereo matching techniques. The last section (5.4) describes the results of these tests through a detailed comparison of both data acquisition and processing time, and accuracy evaluation of the different techniques. The 3D data collection at both Çatalhöyük (Turkey) and Las Cuevas (Belize) was possible thanks to the courtesy of the *Çatalhöyük 3D Dig Project* and the *Las Cuevas Archaeological Reconnaissance*.

5.1. Comparison of time of flight and triangulation light laser scanning techniques

In the past ten years, time of flight laser scanner technology has proven itself to be very powerful in the 3D documentation of general archaeological contexts. In 2008, the University of California Merced, School of Social Sciences, Humanities and Arts launched a multidisciplinary project in Xi'an (China), aimed at studying the Western Han Dynasty (206 BC-8 AD) in the light of the new archaeological discoveries. One of the main goals of the project was the 3D digital preservation of two Western Han Dynasty mural tombs.

The candidate was responsible for the 3D reconstruction of two mural tombs: the Xi'an University of Technologies (M27) (Fig. 30) and the Cuizhuyuan, also known as Green Bamboo Garden (M1) (Fig. 31). They are two of the few Western Han mural tombs discovered in the city (Galeazzi et al 2010).

Figure 30. Cuizhuyuan (M1) mural tomb: 3D model with high-resolution texture applied.

Figure 31. Xi'an University of Technologies (M27) mural tomb: 3D model with high-resolution texture applied.

M 27 was acquired in 2008, two years after the conclusion of the archaeological excavation (VV.AA. 2006). The comparison between the images documented immediately after the excavation of the tomb (2006) and the images as they appeared in 2008, showed considerable deterioration of the frescos. 3D technologies allowed the creation of different 3D models with both 2006 and 2008 images. These data stress the importance of 3D technologies for assessing the status of degradation of archaeological monuments over time. Differently, M1 was digitally documented by the VHLabs in summer of 2009, immediately after the Chinese archaeological campaign ended (Fig. 32).

These examples of mural paintings contain a very complex interpretation code explaining the relationship between life and death during the Western Han dynasty (for a more detailed description of the tombs iconographic representations and architecture see Galeazzi et al. 2010; Di Giuseppantonio and Galeazzi 2013).
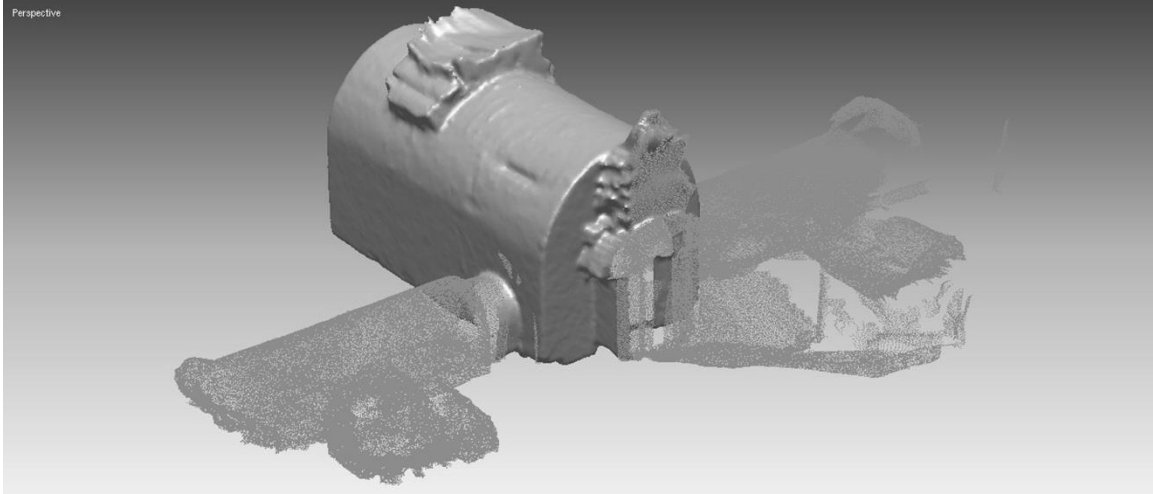
Figure 32. Green Bamboo Garden (M1) mural tomb: point cloud obtained through scanner laser technique.

The 3D data collection of the two mural tombs was obtained using a Riegl LMS Z390i laser scanner. This time of flight laser scanner allows setting the accuracy of the acquisition at 6 mm for an acquisition range of 1-400 m. The two monuments were scanned selecting a very high level of detail (8 mm). Very detailed point-clouds were obtained and are of incredible value from a preservation standpoint because high-resolution reproductions are fundamental for the preservation of at risk heritage. The issue of preservation is particularly important in Xi'an, with its rapid urban development. Every year archaeologists discover hundreds of monuments during emergency surveys in construction sites.

During the post-processing phase, point cloud data were filtered using filter noise, filter redundancy, smooth points, and sample points, without losing sight of the metric accuracy of the final 3D model. In other words, the final model preserved the accuracy of 8 mm. In a second phase two different triangulated point clouds were obtained for the tombs: one at high-resolution for preservation purposes, and one optimized for its display in an immersive virtual environment. In the latter model the number of polygons was reduced, and the virtual reality engine performance increased.

The acquisition of M1 was complicated by the fact that the vault of the tomb is supported by retaining structures that considerably increased scanning time. In fact, more point clouds were needed to scan the entire surface of the monument, slowing down the post-processing phase.

The tests conducted during the Xi'an fieldwork campaigns on the two mural tombs showed the limits of time of flight laser scanner technology in reproducing 3D models characterized by sub-centimeter precision, which is often required for high quality site documentation (Galeazzi et al. 2010: 102; Di Giuseppantonio Di Franco and Galeazzi 2013; Koch and Kaehler 2009: 1). For this reason, in the summer of 2010, a triangulation light laser scanner (optical measurements system), the Konica Minolta VIVID 910, was used to scan the stratigraphic units of Building 86, a mud-brick house, in Çatalhöyük, Turkey. The use of optical measurements systems is well established today, demonstrating one of the best solutions for the acquisition of millimetric and sub-millimetric archaeological features (Güth 2010: 3105-3114; Mc Pherron et al. 2009: 19-24). During the fieldwork it was possible to scan 27 stratigraphic layers (Fig. 33). This first test represents a very good starting point in the analysis of the effectiveness of this new methodology.
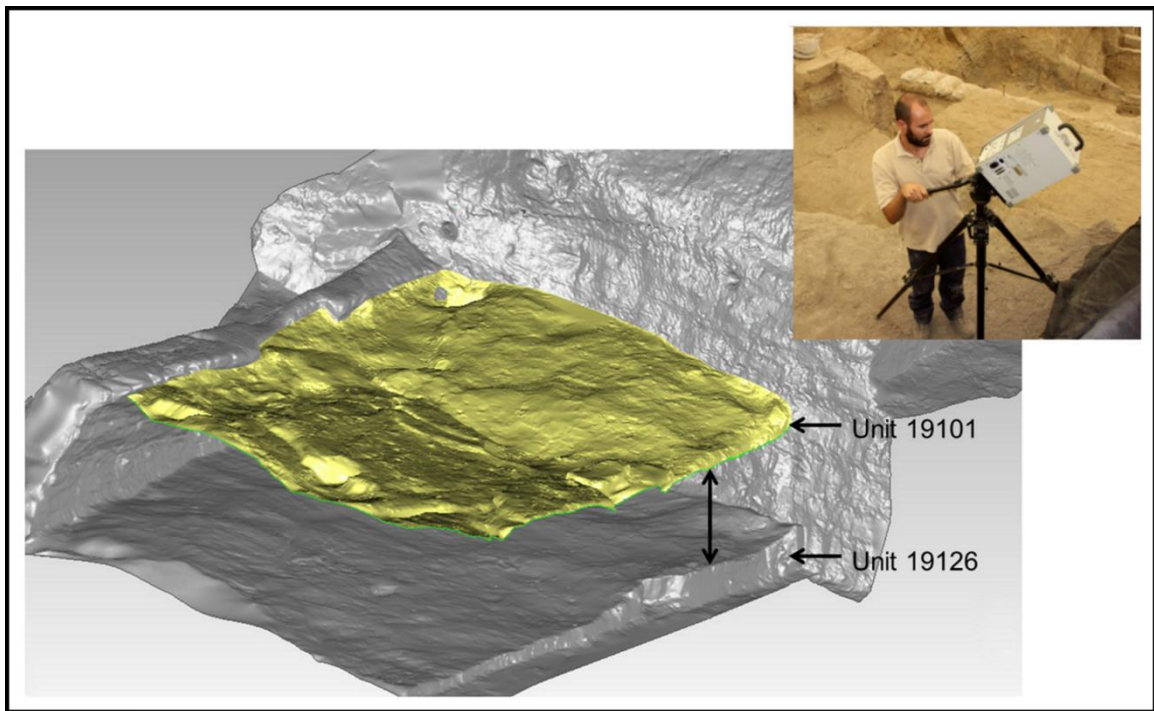
Figure 33. Three dimensional stratigraphic units of the settlement's houses, B. 86, Çatalhöyük, Turkey (Konica Minolta Vivid 910 Laser Scanner).

The stratigraphy was acquired using two different laser scanners: the Konica Minolta Vivid 910 and the Trimble CX. The first is a triangulation light laser scanner able to reach a level of detail within a millimeter (TELE X: ± 0.22 mm, Y: ± 0.16 mm, Z: ± 0.10 mm), with a scan range of 0.6 to 2.5 m. The second is a time of flight laser scanner that can reach levels of detail between 8 mm and 1 cm (considering the post-processing phase), with a scan range of 0.5-350 m.

Both scanners have positive and negative attributes. The Minolta's data recording time is not as fast as that obtained by the Trimble, which can acquire large areas in a few minutes of work. However, the Trimble's data post-processing is faster. Conversely, the Minolta is able to acquire textures (under good light conditions) and surfaces, while the Trimble does not have this capability. The Trimble can only acquire point clouds that have to be triangulated and texturized in the post-processing phase. Unfortunately, the Minolta cannot work in direct light conditions (Vivid 910/VI-910. Instruction Manual: http://sensing.konicaminolta.us/wp-content/uploads/2011/05/VIVID910_VI-910.pdf). For this reason the excavation area was shielded from light, prior to scanning the layers. Since the team was not prepared for this kind of situation it was not possible to have perfect light distribution with the cover. Unfortunately, the textures acquired by the scanner were not homogeneous enough to be used in the 3D models of the layers. The textures of the layers were acquired through a high-resolution digital camera in the attempt to georeference them to the 3D surfaces of the layers during post-processing. There are two negative aspects associated with this kind of texturing procedure: 1) the alignment of the map to the 3D model is made manually through control points, and the accuracy of their matching is not always guaranteed, and 2) manual matching is extremely time-consuming.

The fieldwork proved that when using the Minolta it is possible to obtain very detailed 3D meshes in the acquisition of stratigraphic layers, and confirmed that the time of flight laser scanner cannot produce sub-centimeter precision, which is often required for high quality site documentation (Koch and Kaehler 2009: 1).

5.2. Comparison of triangulation light laser scanning and dense stereo matching techniques

The Xi'an and Çatalhöyük fieldwork campaigns, described in the previous paragraph, demonstrated the limits of time of flight laser scanner technology in generating sub-centimeter 3D reproductions for archaeological purposes.

Starting from these results, different 3D documentation techniques were tested in 2011 at the Las Cuevas site, Belize: triangulation laser scanning (Minolta Vivid 910) and Dense Stereo Matching (Photoscan, Agisoft). The tests were conducted in four different areas of the site, characterized by diverse environmental conditions and light exposures, and with varied surfaces:

Test 1 – Caves Chamber 2 (no natural light/compact and muddy soil; Fig. 34a). The test in the second chamber of the cave allowed testing the data acquisition techniques (dense stereo matching or triangulation laser scanner) in an area characterized by the total absence of natural light. Moreover testing this part of the cave was of extreme importance to put in evidence the performance of different documentation technologies in high level of humidity and compact and muddy soil conditions.

Test 2 – Caves Entrance Chamber (medium natural light/compact and medium wet soil; Fig. 34b). The first chamber is at the entrance of the cave and for this reason it presents a medium exposure to natural light. The soil is less compact and less muddy compared to Chamber 2.

Test 3 – Ballcourt (areas in shaded sunlight under the jungle canopy/wet soil; Fig. 34c). The test in this part of the site showed the limits and potential applications of the different methods in no direct natural light conditions. The jungle canopy, in fact, permits a homogeneous distribution of the sunlight all day long.

Test 4 - Open area of the research station (direct sunlight in areas that have been cleared of brush or exposed by treefall; Fig. 34d). The test in this area was, probably, the most challenging because of exposure to direct sunlight.
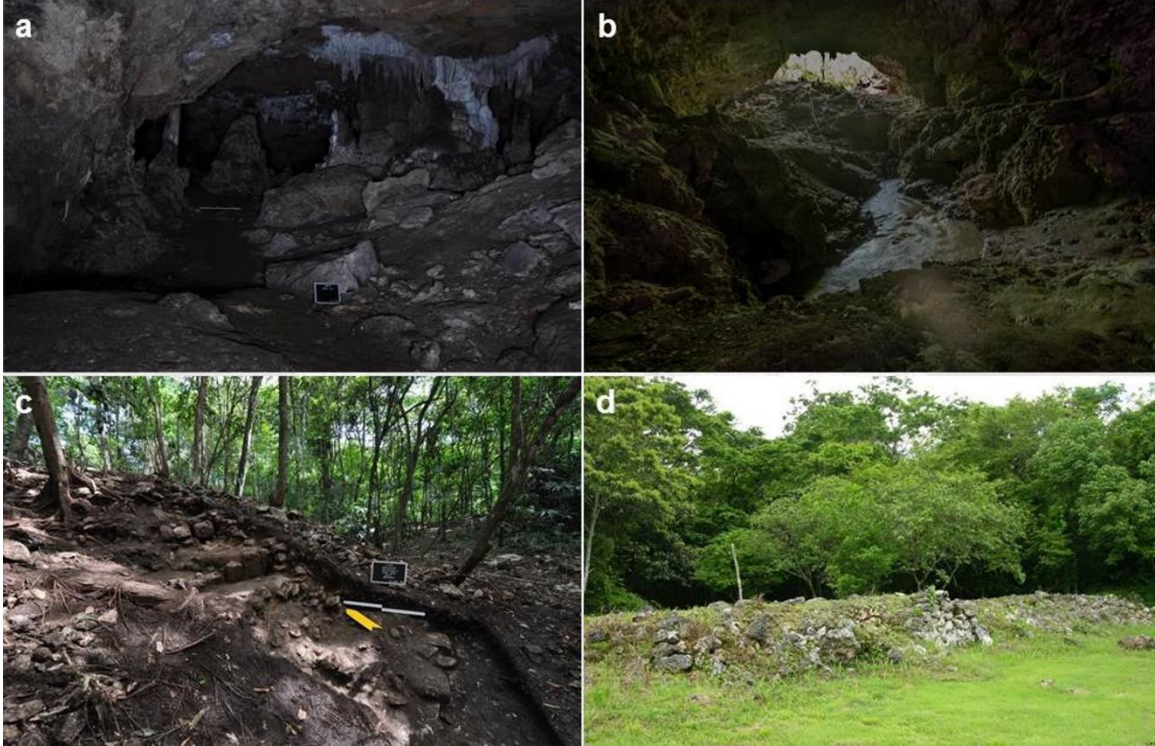
Figure 34. Las Cuevas: a. Chamber 2; b. Entrance chamber; c. Ballcourt; d. Open area (Courtesy of the Las Cuevas Archaeological Reconnaissance).

The tests conducted in the ballcourt (3) and in the open area of the research station (4), showed the limits of the triangulation laser scanner technique in these environmental conditions. Test 4 confirmed the results obtained in the Çatalhöyük project, the triangulation laser scanner (Konica Minolta Vivid 910) cannot work in a direct light condition. Test 3 gave the same result. In fact, even when the canopy partially filters the direct sunlight, it is still very difficult to obtain satisfactory results in these lighting conditions. Acquisition in these kinds of environments (3 and 4) can be made possible by covering the area that will be scanned. Unfortunately, this covering procedure is not always possible during archaeological fieldwork; moreover the textures acquired by the scanner are not homogeneous enough to be used in the 3D models of the layers.

The triangulation laser scanner techniques showed its limits in the outdoor environment of the site (tests 3 and 4). The result was totally different in cave environment (tests 1 and 2, fig. 5). Two areas of the cave were dug and surveyed using two different approaches, the triangulation laser scanner (Minolta Vivid 910) and dense stereo matching.

Two units have been excavated inside the cave, one in the entrance chamber, another in chamber one. The entire excavation process was acquired (9 strata in the entrance chamber and 8 strata in chamber one).

Methodology

Two test units were placed in the cave. Barbara Voorhies supervised the cave investigations. Laura Kosakowsky analyzed the ceramics for chronology using standard type: variety designations largely in line with the Belize Valley (Gifford 1976). All of the units contained datable material and all contained ceramics dating to the Late Classic Spanish Lookout/Tepeu II complex (Moyes et al. 2011).

The site was, also, surveyed using a Sokkia 650X 6" reflectorless total station on loan from the University of California, Merced and a Topcon 3" total station on loan from Lisa Lucero. Data were displayed and organized using a Geographic Information System (ArcGIS 10). A digital elevation model (DEM) of the site, a plan view map of the constructions in the site core and plazuela group (Fig. 35), and a map of the cave were created (Fig. 30; Moyes et al. 2011).

Unit 1 (cave entrance chamber) was of particular interest. This unit was placed in the Entrance Chamber into a partially eroded platform with a plaster floor. A second floor was encountered below suggesting that there was more than one phase of construction within the cave. Initially, we thought that the earlier construction may have been quite old, but ceramic analysis demonstrated that this was not the case and that the cave was modified on more than one occasion in the Late Classic period. A total of 316 sherds were excavated within the unit, of which 62 were identifiable to type. Although there were redeposited sherds from the Late Preclassic (Sierra Red Group) and Early Classic period Petén Glosswares, both constructions primarily contained sherds dating to the Spanish Lookout/Tepeu II complex. Additional artifacts encountered including chert flakes, a chert biface, and animal bone, bolster our argument that, rather than representing a unique cave assemblage, the artifacts in the fill of the platform are typical of mixed fills from surface site excavations elsewhere (Moyes et al. 2011: 17-19).
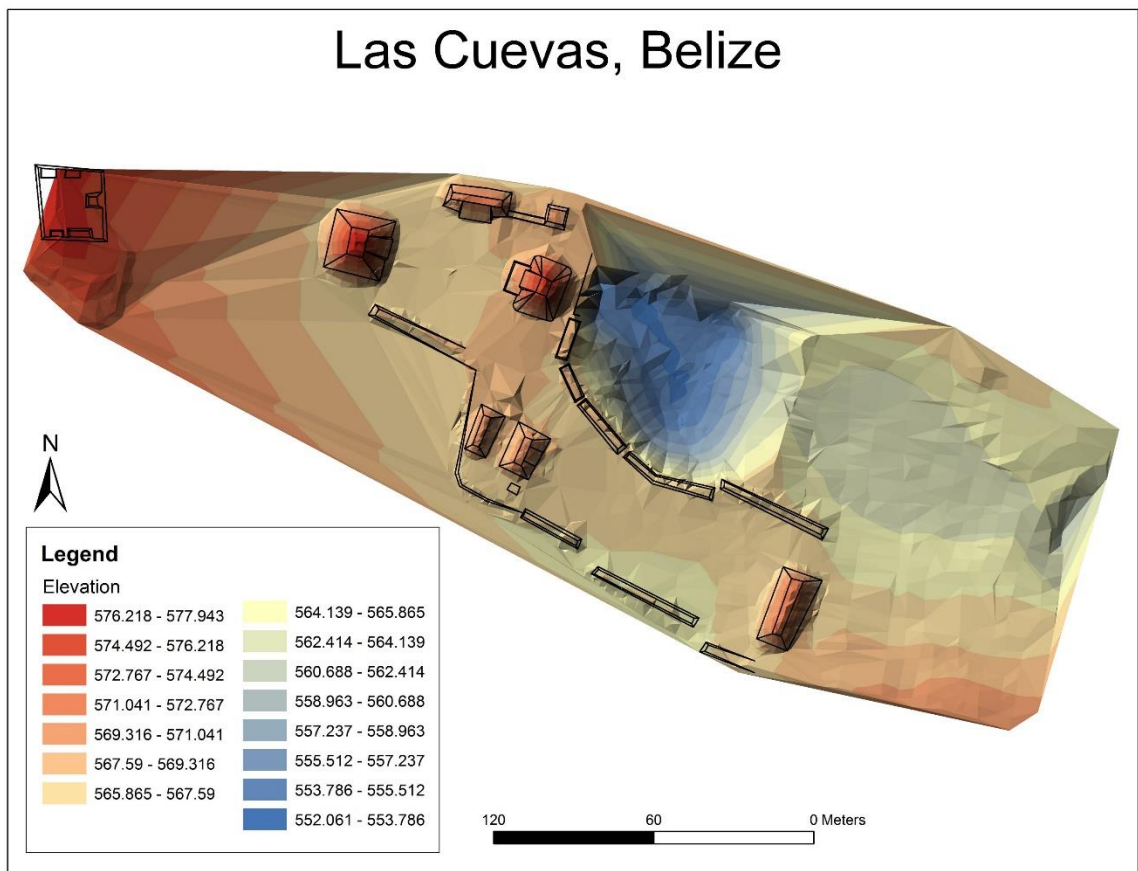
Figure 35. Digital Elevation Model of Las Cuevas site core and plazuela group (Courtesy of the Las Cuevas Archaeological Reconnaissance).

Unit 2 (caves chamber 1) is located in an alcove that has a large imposing stalagmite positioned in front of the narrow passageway that leads into the alcove from the direction of the cave's entrance. Unit 2 (1 x 1m) was located on the east side of a protruding rock that was surrounded by abundant flat-lying sherds. The diagnostics ceramics belong to the Spanish Lookout Ceramic Complex pertaining to the Late Classic Period (A.D. 700-900; Moyes et al. 2011: 19-21).

The excavation process of units 1 and 2 was completely recorded in 3D using the two techniques: triangulation laser scanner, Minolta Vivid 910 (Fig. 36); and dense stereo matching. Data from the Minolta acquisition allowed for the acquisition of a 3D model with sub-millimeter resolution. The characteristics of the cave environment (medium to no natural light conditions) allowed for better control of the lighting of the excavation area.

Eight artificial lights were used to give a more homogenous distribution of light on the scanned area. A regular lighting distribution was obtained positioning the lights around the excavation area on tripods (2 meters from the ground level).
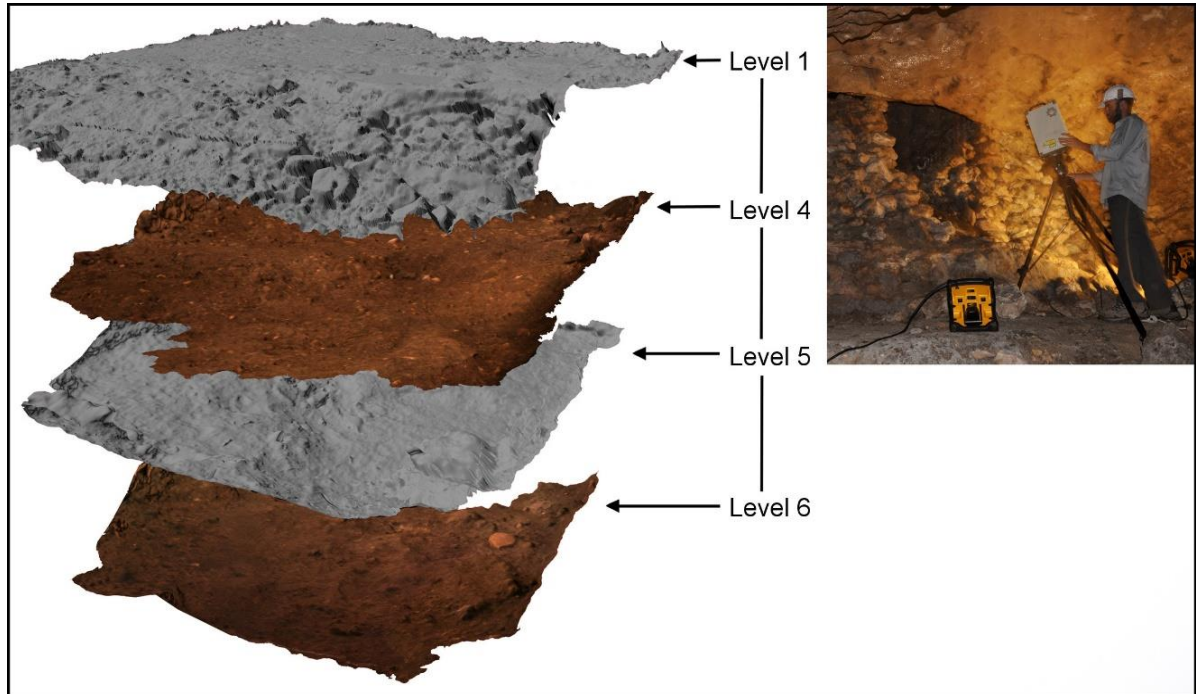
Figure 36. Three dimensional stratigraphic sequence of Unit 1 (cave entrance chamber).

The first positive aspect in the use of the triangulation laser scanner technique is the extreme detail of the meshes acquired (Fig. 37). The second benefit is the possibility to acquire meshes and not point clouds. This allows, during the post-processing phase, one to avoid point clouds filtering, alignment, and triangulation, saving almost half of the total post-processing time. One of the negative aspects of this technique is the sub-optimal resolution of the textures. The camera integrated in the scanner is a low resolution camera (number of output pixels: 307,000/FINE mode, 76,800/FAST mode). Moreover, this technique is not recommended for scanning large areas for two main reasons: primarily, the post-processing and alignment of different meshes obtained from the scans will be extremely time-consuming. The Minolta, in fact, allows acquiring just a small area at a time.

The optimal 3D measurement range (0.6-1.2 m) is able to record an 80x80 cm surface. Secondly, the fieldwork experience showed that the cave environment, because of

the high humidity levels, remarkably affects laser scanner performance. After about 90 minutes the hardware stopped working properly. This amount of time allowed us to acquire measurements of a six square meter surface; the acquisition of a larger area would drastically slow down the excavation process.
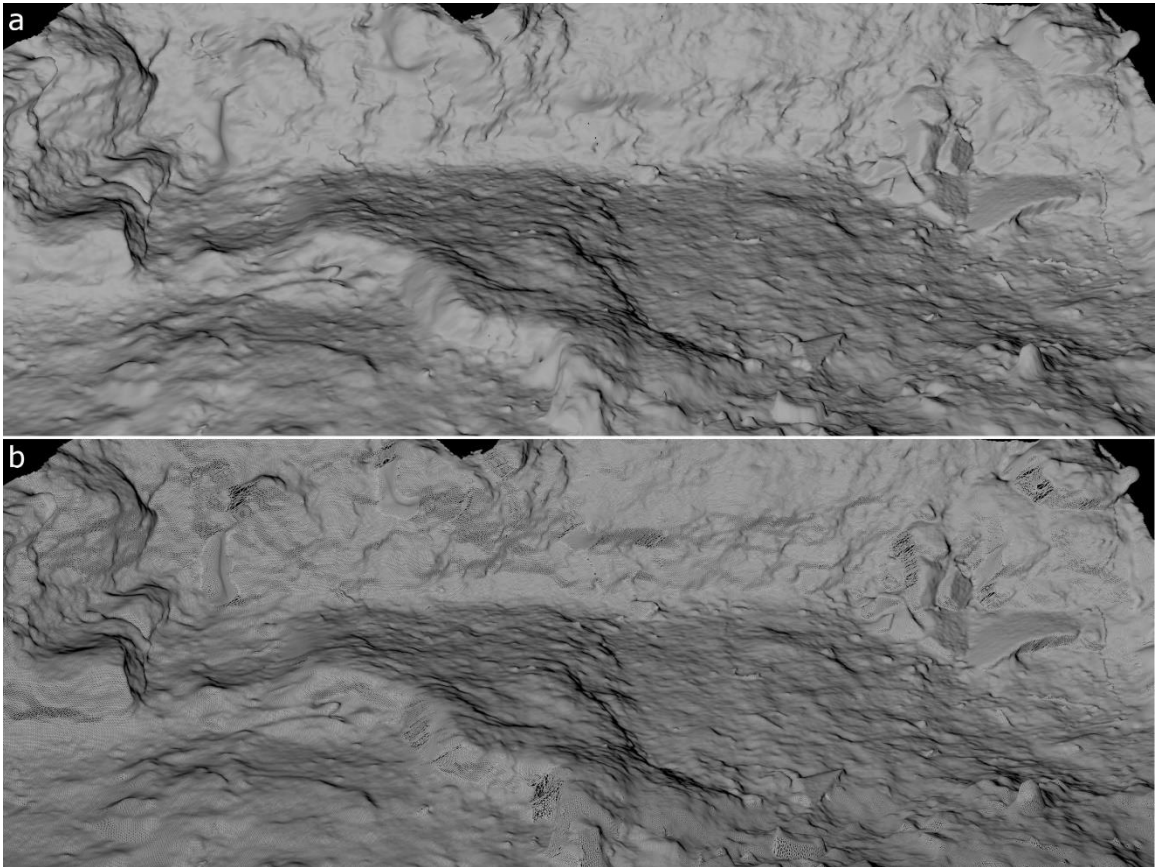
Figure 37. Three dimensional model of Unit 1, Level 6 (cave entrance chamber), acquired through the triangulation laser scanner, Minolta Vivid 910: a. mesh; b. wireframe.

The same unit's measurements were acquired using dense stereo reconstruction tools. The purpose of this paper is not to give an overview and comparison of the different dense stereo matching software. Some evaluations have already been done between three tools: Arc3D webservice (VISICS 2011), Photosynth/Bundler+PMVS2 (SFMToolkit) and AutoDesk PhotoFly. Comparisons show it is possible to obtain the same numerical results from both systems. The differences between them are in terms of data density, resilience to non-optima photo dataset, visual quality of data, and tool flexibility (Callieri et al. 2011).

Photosynth/Bundler+PMVS2 seemed to be the best choice between the three different tools tested, as it is the only one that can be executed on a local machine. This represents a fundamental characteristic in archaeology; during on-site 3D documentation, the probability of being connected to a webserver is extremely low, this is especially true in remote site like Las Cuevas. The possibility to perform tests directly in the field is the best approach to find a strong processing pipeline. Moreover, it gives us the opportunity to refine, in real-time, acquisition processes during excavation.

A different kind of dense stereo matching software was used for the 3D documentation of the Las Cuevas stratigraphy, Photoscan (Agisoft LLC 2011). This software uses an algorithm similar to the one adopted by Photosynth/Bundler+ PMVS2, but was preferred because it is the only dense stereo matching software that allows complete 3D model restitution (alignment, creation of the geometry and texture). Moreover, thanks to its graphic interface, it is possible to separately manage the geometry and texture creation from the alignment. All images used during data acquisition were acquired using a Nikon D90 with Nikkor lenses (10-100 mm), with a resolution of 12 MPixel. Dellepiane et al. (2012) demonstrated the repeatability and effectiveness of dense stereo reconstruction tools. The measurement of the geometrical deviation between two 3D models of the same excavation area acquired in different moment during the fieldwork campaign, was less than 1 cm for 90%, and less than 0.5 cm for 50% of the mesh (Dellepiane et al. 2012: 6). Starting from the satisfactory results obtained in the mentioned research, it was decided to test dense stereo matching in different environmental and lighting condition, and remote areas, comparing this technique with triangulation light laser scanner technology (Minolta Vivid 910).

In the last few years, because of logistical issues connected to fieldwork in remote environments, archaeologists have started to test this technique as a possible alternative to laser scanner technology. Also, the site subject of this study, Las Cuevas, is located in a very remote area of the Chiquibul Reserve in western Belize. The site is a four hour drive from the closest town, San Ignacio. In this kind of environment transporting heavy equipment like laser scanners is difficult, therefore the possibility to acquire 3D models by simply taking pictures makes dense stereo reconstruction tools extremely flexible.

Another positive aspect in the use of this technique consists in the possibility to consistently reduce both acquisition and post-processing time. The acquisition time with the Minolta laser scanner for a surface of 2x2 meters was about twenty minutes, while the pictures capture for the dense stereo matching took abound five minutes. The post-processing of the same surface with the Minolta took about 1 hour (mesh optimization and alignment), while with Photoscan, data processing took about four hours, however, data loading took only 15 minutes, the remainder was machine processing.

All the units' levels were scaled to real measures and aligned using the measurements made with the total station. Four targets located at the four corners of the excavation area were taken as reference points to align the total station data survey and the 3D models acquired using the Triangulation Light Laser Scanner technology (TLS) and the Dense Stereo Matching (DSM) techniques. In this way, the models can be easily brought into the same reference frame used for the survey of the site and geo-referenced.

Results

This research shows the results of the metrical comparison between 3D models obtained using triangulation laser scanner technology (TLS) and Dense Stereo Matching (DSM) of one of the units' levels collected during fieldwork (Unit 1, level 6). The comparison of the co-registered surfaces was performed in commercial (CS; Rapidform) and open source (OS; Meshlab) point cloud and mesh processing software programs based on the shortest point-to-mesh distance considering the normal to the mesh faces (In the three-dimensional case a *surface normal*, or simply *normal*, to a surface at a point *P* is a vector that is perpendicular to the tangent plane to that surface at *P*). The estimated distances between surfaces allows for calculating a wide rage quality metrics of the 3D models. Using different software for the comparison on the same 3D models increased the reliability and relevance of the test.

The commercial software (CS) allows calculating the root mean square (RMS) which describes the surface's average absolute accuracy, and the standard deviation (SD) which is an index of the surface's noise (a measure of the variation in the measurements). The open source software (OS) permits the calculation of the Mean deviation between the surfaces (the

average of the sum of the squares of the deviations) and the RMS. The number of produced points for level 6 (unit 1) was 670,278 for TLS and 90,971 the DSM. The difference in terms of density between the TLS and the DSM is evident (Fig. 38). This research investigates if the different densities of the models correspond to higher or lower accuracy. To do so, quality metrics from the 3D comparison were computed and presented in table 2.
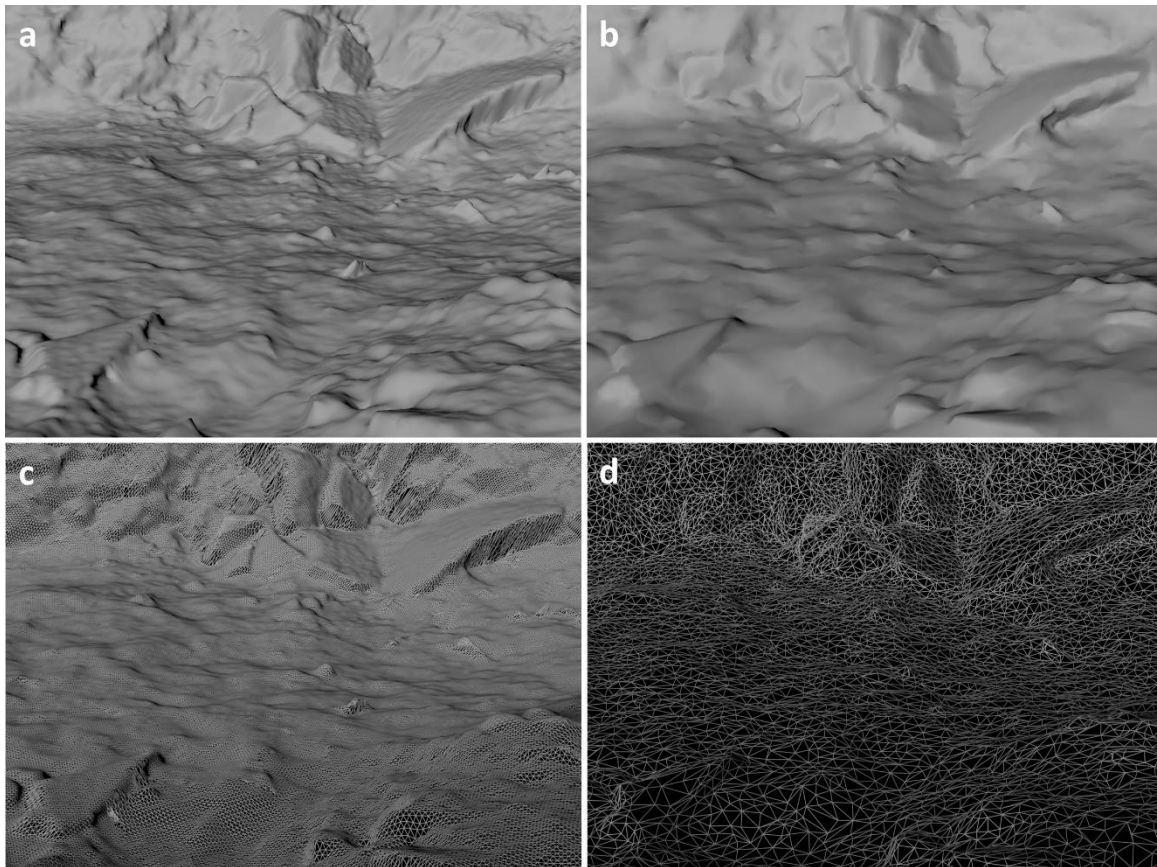
Figure 38. Three dimensional models of Unit 1, level 6 (cave entrance chamber), acquired using two different techniques (TLS and DSM): a. TLS mesh; DSM mesh; c. TLS wireframe; d. DSM wireframe.

TLS-DSM	STD (mm)	Mean distance (mm)	RMS (mm)
CS (Rapidform)	± 1.582	-	1.706
OS (Meshlab)	-	1.520	1.910

Table 2. Descriptive statistics for TLS and DSM deviation measurements considering the all mesh.

The comparison run with CS and OS software between TLS and DSM shows very close values for the RMS (1.706 – 1.910 mm; figs. 39-40). The comparison showed that 65.18% of the model point comparisons, obtained through the DSM technique, fell within ± 1.5825 mm from the average (0.6369 mm). More interestingly 96.36% of the point comparisons in this model fell within ± 3.165 mm from the average (Fig. 41).
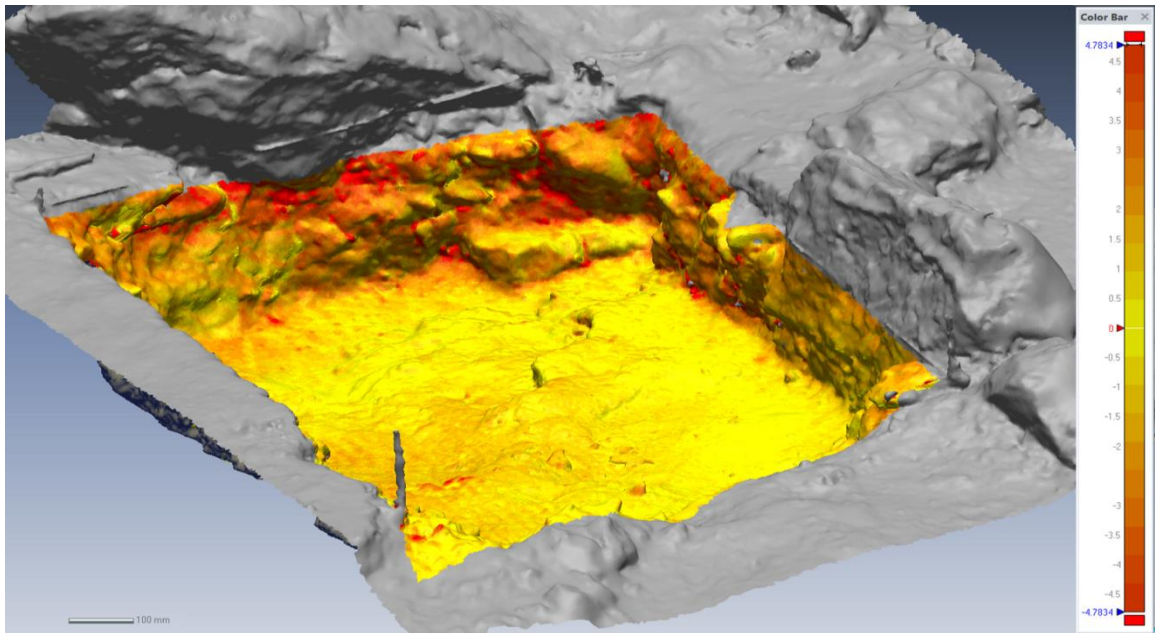
Figure 39. CS (Rapidform) geometrical deviation of the aligned 3D models (TLS and DSM).
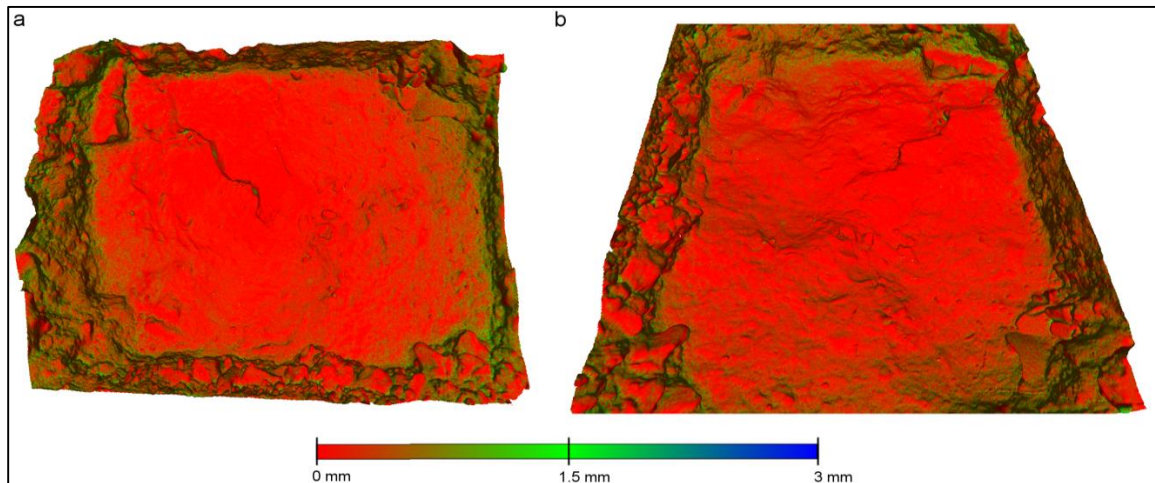
Figure 40. OS (Meshlab) geometrical deviation of the aligned 3D models (TLS and DSM): a. Top view; b. Perspective view.
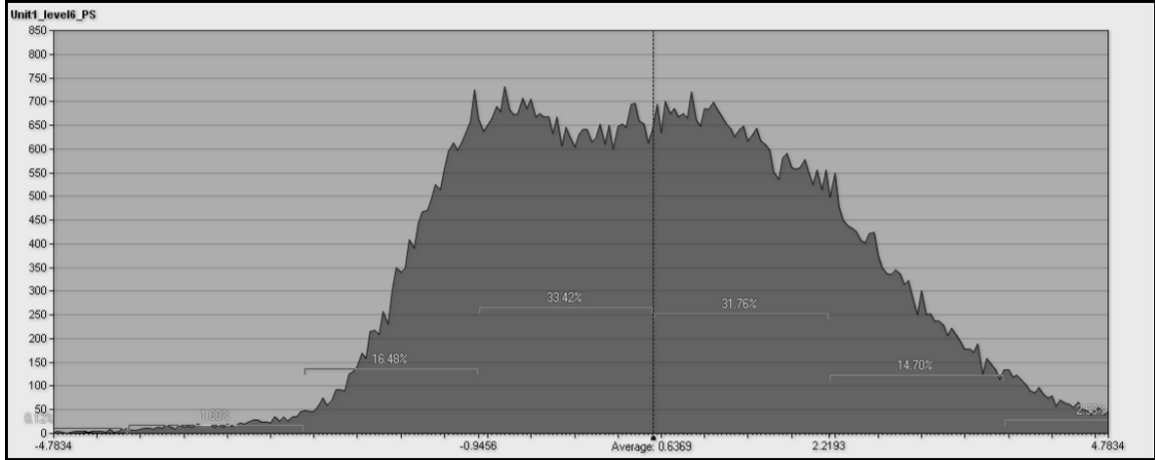
Figure 41. Geometrical deviation's histogram of the aligned 3D models (TLS and DSM).

The color coded image shows that the vertical section of the unit's level was less accurate than the horizontal-central part of the layer (orange-red form ±2 mm to ± 7 mm; yellow ±2 mm; figs. 39-40). For this reason, a second metrical comparison was run only examining this part of the 3D models (tab. 3). For this part of the models the number of produced points was 392,694 for the TLS and 42,117 for the DSM. The comparison was run with both CS and OS software on the horizontal-central part of the models and shows very close values for the RMS (1.171 – 1.258 mm; figs. 42-43). Here, 68.94% of the point comparisons in the model fell within ± 1.1513 mm from the average, and 95.6% of the point comparisons fell within ± 2.3026 mm from the average (Fig. 44).

TLS-DSM	STD (mm)	Mean distance (mm)	RMS (mm)
CS (Rapidform)	± 1.1513	-	1.171
OS (Meshlab)	-	0.912	1.258

Table 3. Descriptive statistics for TLS and DSM deviation measurements considering just the horizontal-central part of the mesh.
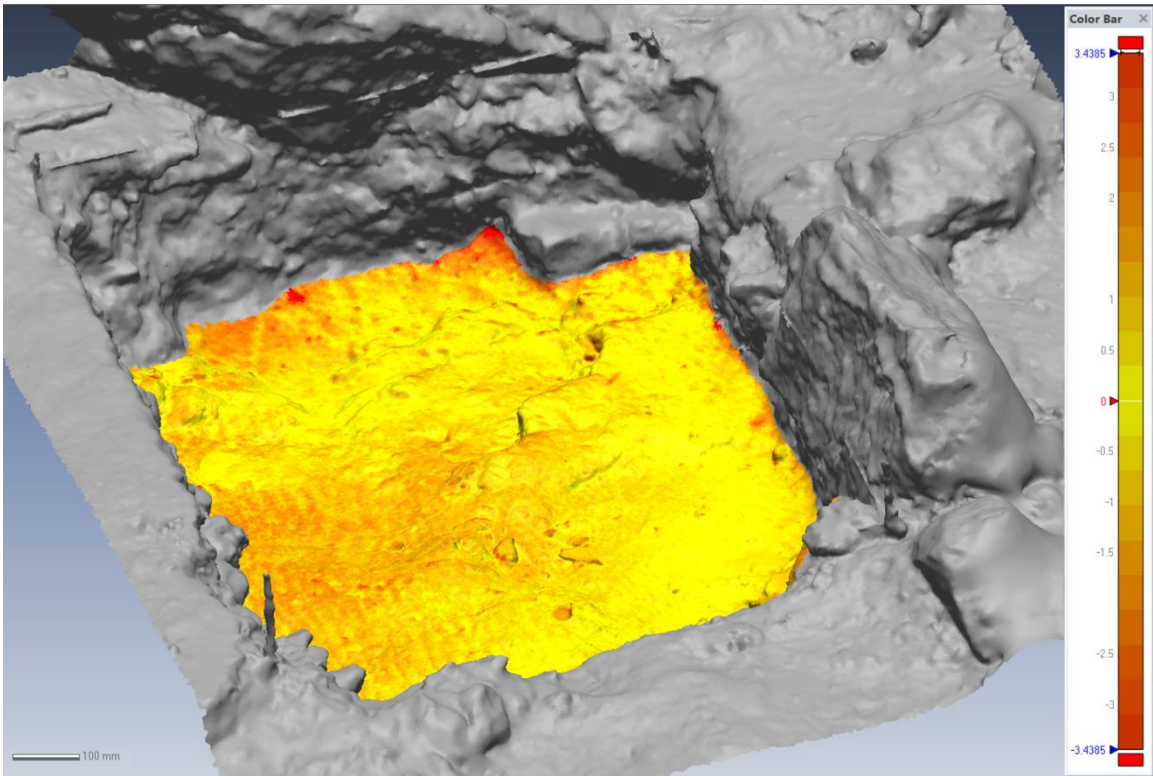
Figure 42. CS (Rapidform) geometrical deviation of the horizontal-central part of the aligned 3D models (TLS and DSM).
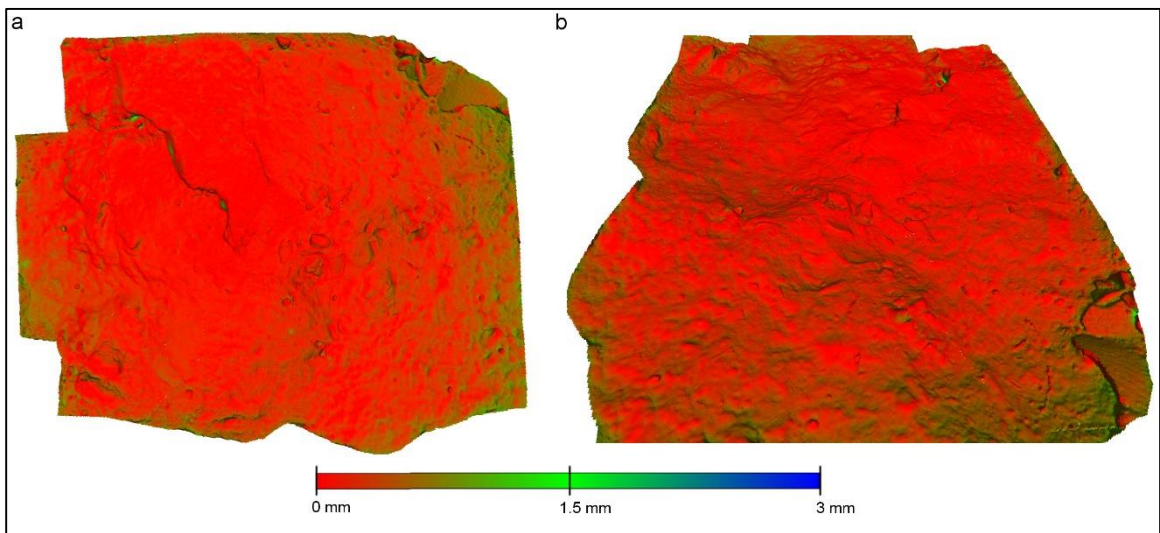
Figure 43. OS (Meshlab) geometrical deviation of the horizontal-central part of the aligned 3D models (TLS and DSM): a. Top view; b. Perspective view.
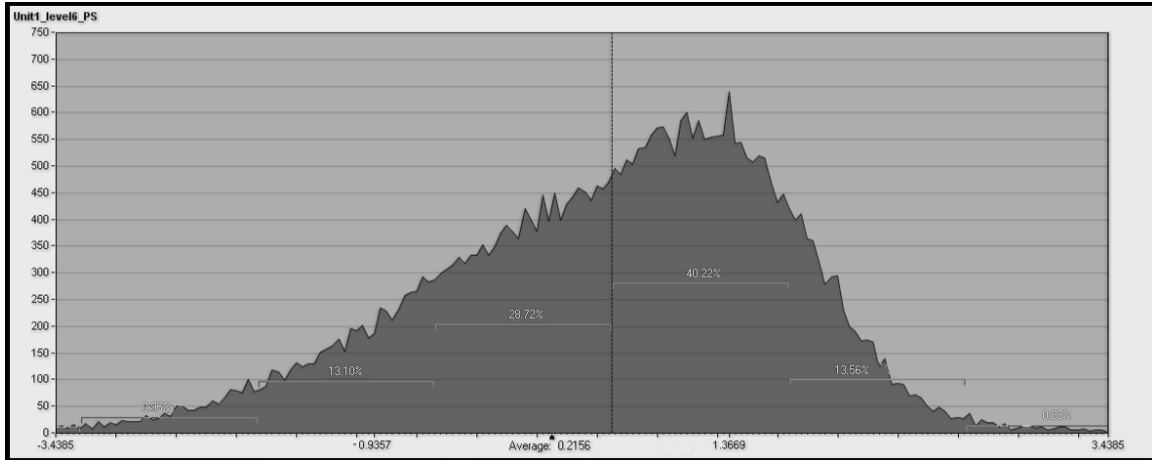
Figure 44. Geometrical deviation's histogram of the horizontal-central part
of the aligned 3D models (TLS and DSM).

These results confirm that the horizontal-central part of the acquired unit's level presents a lower geometrical deviation compared to the entire 3D model (including the vertical sections). These data show that 95.6% of the point comparison deviations are between −2.3026 and +2.3026 mm, and 68.94% of the deviations are between −1.1513 and +1.1513 mm. While considering also the vertical section of the level, 96.36% of the point comparison deviated between −3.165 and +3.165 mm, and 65.18% deviated between −1.5825 and +1.5825 mm.

This demonstrates that geometrical deviation between the 3D models acquired using the two techniques increases in the marginal area of the surface; this could be related to the camera's ability to focus during image capture. The central part of the picture is usually the area that is most in focus during the capture. The focusing quality frequently degrades as the absolute distance from the focal point increases, for this reason the margins (the most distant areas from the focal point) are more blurred. A test conducted by Koch and Kaelher on the relief of the Apadana Palace in Persepolis, Iran, indicated a similar result. "Details evaluated in the center of an image reach a higher accuracy (± 1 mm) than details located on the margins (± 3 mm)" (Kock and Kaelher 2009: 6).

Nonetheless, the Dense Stereo Tools technique gave good results in term of meshes' accuracy (SD between −3.165 and +3.165 mm) the difference between this technique and the triangulation laser scanner technology was still relevant. The comparison of the 3D

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models obtained from the two techniques, in fact, showed that just the triangulation laser scanner technology allowed for the preservation of all figure details and features contained in the strata (Fig. 38). For this reason, DSM technique should be integrated with other techniques when the goal of the acquisition process is data collection of micro-stratigraphy, less than 3 mm (shards, small artifact, etc.; Güth 2010: 3105-3114; Mc Pherron et al. 2009: 19-24). The mesh comparisons reported here demonstrate that improvements over the last few years of DSM techniques render this technology as one of the most powerful and suitable in the area of 3D data acquisition of archaeological contests. The DSM technique is powerful for two reasons: first, a micro-stratigraphic acquisition is not always necessary, and second, there are considerable differences in costs, usability, data processing and post-processing between this technique and laser scanner technologies.

The preservation of the unit textures' quality was problematic for both of the 3D recording methods. The use of external lights markedly affected the texture color in the Minolta data acquisition. Lighting issues, which are very common in cave environments, were also evident in data acquired using the integrated camera of the laser scanner (Fig. 45a). The camera flash was used instead of external lights for the dense stereo matching data acquisition in the attempt to avoid the mentioned effects on the textures' color, but the result was exactly the same, the textures' color of the unit was altered (Fig. 45b).

Figure 45. Three dimensional texturized models of Unit 1, Level 6 (cave entrance chamber), acquired using two different techniques (TLS and DSM): a. TLS; b. DSM.

5.3. Comparison of phase shift variation laser scanning and dense stereo matching techniques

The 2011 fieldwork campaign showed the limits of triangulation laser scanner technique in the two outdoor areas (a ballcourt and an open area near the research station). For this reason, in the 2012 fieldwork campaign, the survey was conducted using dense stereo matching and phase shift variation laser scanning, FARO Laser Scanner Focus3D (Phase Shift technology measures the distance to a surface using an infrared laser beam that is sent out and reflected back to the system. The distance is measured by analyzing the shift in the wavelength of the returnbeam:http://www.faro.com/site/resources/download?ReturnUrl=/site/resources/down load/1772/), to understand if one of these technologies works better in differential environmental and lighting conditions of the Las Cuevas site. Two techniques in different excavation areas of the site were used. The first being an entrance chamber –cave environment; the second a temple –areas in shaded sunlight under the jungle canopy; and third a ballcourt –more direct sunlight in areas that have been cleared of brush or exposed by tree fall. A metrical comparison of the co-registered surfaces of the 3D models obtained using phase shift variation laser scanner (Faro Focus 3D) and dense stereo matching software (Photoscan, Agisoft) was performed in both open source and commercial point cloud and mesh processing software based on the shortest point-to-mesh distance considering the normal to the mesh faces. The estimated distance between surfaces permits one to calculate a wide range quality metrics pertaining to the 3D models. Before starting the comparison in the cave environment the entire cave system was reproduced in three dimensions using phase shift variation laser scanner technology (Faro Focus 3D; Lindgren and Galeazzi 2013).

5.3.1. Cave environment

3D recording projects in cave environments are often an opportunity for archaeologists to collaborate with scientists from different fields such as social sciences, environmental sciences and computer sciences.

The accurate and complete recording of cave sites is a challenging task. Walls, floors, and ceilings of sites present irregular surface shapes, characterized by wall concretions and stalactites that are difficult to record with high levels of detail. The two main challenges faced during 3D documentation of this kind of environment are the dense high-resolution geometry and the highly realistic rendered images acquisition.

Laser scanning technology has been used for cave recording since 1994, when Electricité de France and Mensi recorded the Cosquer cave (France) (Mensi 2000). The result was a 4.7 million point 3D model with the resolution of 30 mm (XY) and 1 mm at 5 m (Z). The time of flight laser scanner technology is the most widely used technique adopted for the documentation of archaeological site contexts, since it allows for fast acquisition of large areas (Galeazzi and Di Giuseppantonio Di Franco 2010; Doneus and Neubauer 2005; Zimmerman and Gerold 2007). However, this technology is less appropriate for rich sub-centrimetric accuracy (Koch and Kaehler 2009).

McPherron et al. (2009: 24) used structured light for the 3D data acquisition of two Middle Paleolithic sites in southwest France, Jonzac and Roc de Marsal (2009: 19), demonstrating that the use of this technology in the field is possible with some challenges (see chapter 3).

According to Blais and Beraldin's review of 3D laser scanners (2006), there are very few commercial laser scanners adequately built for very high-resolution visualization applications (prior to 2006), a transition between triangulation and time of flight laser scanner systems. For the 3D recording of the Neolithic cave *Grotta dei Cervi*, Beraldin et al. used a scanner known as "Big Scan", a research system prototype currently under development for high-resolution 3D digitization of large structures (object distance 0.5-10 m) that provides a resolution of 0.08 mm on cooperative surfaces at a standoff of 0.75 m (Beraldin et al. 2006). Preliminary results of this project show the potential of this laser technology to be used for the documentation and preservation of rock art in cave environments.

In 2012, Grussenmeyer et al. used the Faro Photon 120 for the 3D documentation of the Bronze Age cave of *Les Fraux* and the Faro ScanArm V3 (19200 points/sec and 0,035 mm accuracy) for the acquisition of the clay panels of the cave (Grussenmeyer et al. 2012).

Recently researchers are also exploring the opportunity to combine laser scanner technologies with close range photogrammetry for the 3D documentation in cave environment (Lerma et al. 2010; Galeazzi et al. 2013).

5.3.1.1. Cave system 3D acquisition

Planning

The 3D data acquisition of the Las Cuevas site was conducted to understand the impact of laser scanner technologies on the preservation, analysis, interpretation and communication of cultural heritage. Archaeological sites are continuously exposed to the risk of information loss. This danger is more of a reality in areas of the world characterized by extreme environments. The location of the Las Cuevas site, in the middle of the tropical forest, and the extreme conditions of cave environments increase the risk of losing the cave's physical information. For this reason the entire cave network was acquired in summer 2012 (9 chambers).

The creation of the 3D replica of the Las Cuevas cave could facilitate data analysis and interpretation of the site giving researchers opportunities to actively participate in a shared and collective interpretation process to increase the understanding of the past social and cultural dynamics associated with the site.

Moreover, this work will make this remote site accessible to more visitors. People who will never have the opportunity to visit the real cave will be able to visualize the 3D virtual reproduction. Thanks to new technologies this project wants to showcase the Las Cuevas site and underline the importance of this site in the Maya social-cultural system.

The Belizean cave helped us understand how 3D laser scanner technology works in cave environments and containing extremely complex geometry, characterized by irregular structures that demand complicated scanning strategies. In combination with the substantial size of the cave this is a scanning task that is a bit out of the ordinary.

The cave is a natural geological structure, divided into nine chambers in succession. The cave circles around so that the last chamber connects into the first, about 10-15 meters

up on one of the walls. The different divisions of the chambers varies from clearly manmade structures to more or less natural boundaries.

From the beginning it was decided not to try to capture color information in the cave, but settle only for geometry. Capturing color information would demand large amounts of portable lights to illuminate the cave properly. Bringing ample light would have been costly with regard to money and time and far beyond the scope of this project.

Technology (Faro Focus 3D)

The 3D scanning was done with a Faro Focus 3D scanner. This terrestrial laser scanner allows for a measurement rate up to 976,000 points/sec and distance accuracy up to ± 2mm. It is a compact, functionally self-contained scanner that is easy to carry. The device uses battery power, scans data in its raw format, and stores information on removable memory cards. The scanner is easily operated via touchscreen. Older scanners are often much larger, requiring a separate computer to operate using external batteries which can often weigh up to 10 kilos. The Faro Focus 3D (including its tripod) weighs about 8 kg and is therefore ideal for missions that involve maneuvering in tight spaces and scanning from positions other scanners could not manage. The small format of the scanner allowed for the scanning of the complete cave in just eight days.

Not only is the scanner easy to use and functionally convenient; it is also able to handle special climates like those in Las Cuevas. Las Cuevas is in the subtropical jungle and our data was collected during the rainy season. A season characterized by high levels of humidity and temperature. Inside the cave the temperature was slightly lower, but the humidity was significant. The scanner handled these conditions well for most of the time. The battery ran out faster than usual, but that was expected. The only problem experienced was that the touch panel of the scanner stopped working on a number of occasions. The touch panel is mainly used to adjust the settings for the different scans, such as resolution or whether the scan should be done with color or not. Once these settings are made, the need to use the touch panel is not that big, with the very important exception of starting each new scan. Hence a non-functioning touch screen could be a serious problem. Fortunately, the scanner also provides a more stable button under the touch screen, which can be used just to

start scans if it is not possible to start them otherwise. Except the occasionally malfunctioning touch screen, there were no problems with the scanner at all. To prevent problems with humidity, the scanner bag was equipped with several small bags of silica gel during the entire period in Belize. It is used as a desiccant to control local humidity and may have done some good in keeping the scanner in such a good shape.

Data acquisition

Before starting the acquisition campaign, an inspection of the site was conducted to decide on an optimal scanning strategy. Each scan produces a pointcloud which has its own local coordinate system. The first part of the post processing procedure is to register or align the different pointclouds into a common coordinate system. There are several different methods for doing this. The position of each scan could be measured with a total station or differential gps. These measurements are then used to position the pointclouds, using special software. However, these methods were not available all parts of the cave. An alternative method is to place markers in such a way that they can be seen in several different scans. Special alignment software could, with a little help, recognize the markers and align the scans automatically. Since the cave is such a large structure, it would have yielded many different marker setups to keep track of, which was estimated to be complicated and time-consuming to coordinate. For this reason a different strategy was used. The different scans were overlapped one another other and then manually aligned using recognizable control points.

At the beginning, a fairly normal scanning strategy for larger structures was applied. This was a relatively efficient approach in the entrance chamber (Fig. 46), but moving further into the cave scanning procedures proved to be increasingly difficult. With such an extremely irregular geometrical structure found in the cave, the risk of missing important parts was much higher than usual. For this reason, the scanning strategy altered after a few days and scanning positions were moved closer together to ensure adequate coverage. Scanning culminated in the fifth chamber, which included rocks, stalactites, stalagmites, narrow cavities and hidden structures.

The complex geometry of the fifth chamber led to a scanning strategy, in which different scan positions were placed only a few meters from each other. This is not at all common during normal scanning. The result, of course, was many more scans than initially planned. All in all, more than 300 scans were made to cover the entire cave (about 400 GB of scanner data).
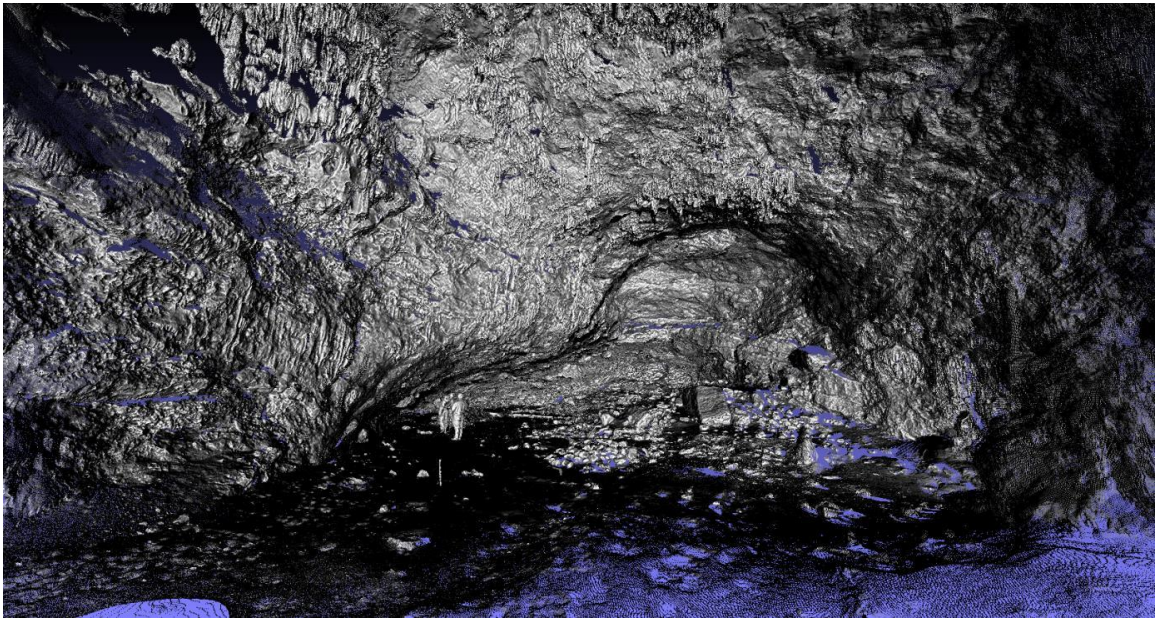
Figure 46. Cave's entrance chamber: 3D data collected through phase shift variation laser scanner (Faro Focus 3D scanner).

Data processing

The first step in post processing is to spatially align the different scans (Fig. 47). The open source software Meshlab was used to accomplish this alignment. In working with manual alignment the same features in different scans are labeled and Meshlab calculates relative positions of the scans based on these labels. One problem is the size of the individual scans. A Dell precision Workstation T1500 with 24 GB memory and Nvidia Quadro FX 580 graphics adapter was able to process about 10 scans at one time. In total there were more than 10 total scans, so it was necessary to reduce the number of points in each scan as well as divide the cave into different sectors and align them separately. Once the alignment was done it was necessary to clean the data in each scan. When the overlapping scans method

is used during acquisition, a lot of data necessary for alignment to be reached was redundant and therefore removed. The next step was to mesh the pointclouds. Different filters in Meshlab have been tested and it is clear that the current version has some difficulty meshing large structures like the ones found in this cave.

The main goal is to obtain satisfactory results at different scales. When a complete chamber was meshed, many details were lost. So, as with alignment, meshing needed to be done in small sections. At this writing the meshing is not finished. The meshing has taken much longer to accomplish than expected.
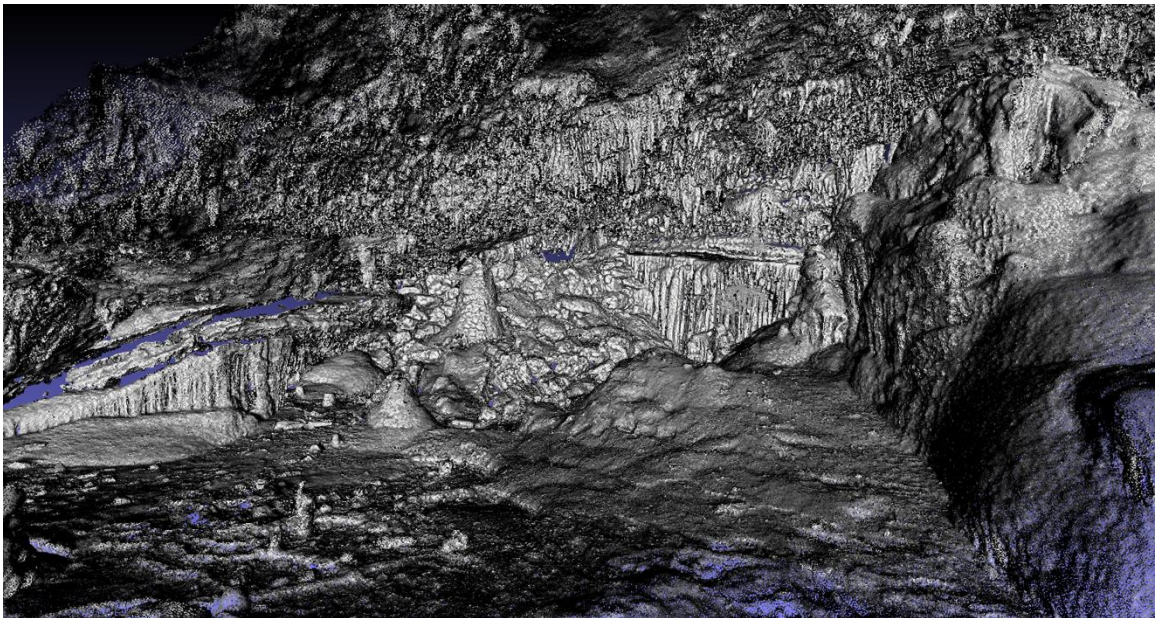
Figure 47. Cave's chamber 7: 3D data collected through phase shift variation laser scanner (Faro Focus 3D).

5.3.1.2. Techniques comparison in cave environment (cave's entrance chamber)

The 2011, 3D data acquisition at Las Cuevas showed both potential and limits in the use of triangulation laser scanning techniques in cave environments. One of the main limits of this technique resides in the ability to acquire only small areas at a time. The optimal 3D measurement range (0.6-1.2 m) records a surface of about 80x80 cm. For this reason, during the 2012 fieldwork campaign, the comparison in cave environments was conducted using the phase shift variation laser scanning technology (Faro Focus 3D), instead of the triangulation

laser scanner technique used in 2011. The new laser scanning technology seemed more appropriate for obtaining a reliable comparison with dense stereo matching technique, since the Las Cuevas team decided at the beginning of the 2012 fieldwork season to conduct an open-area excavation in the entrance chamber of the cave.

Methodology

Cave unit 3 is an excavation (8x5 m) located in the passageway at the end of the entrance chamber of the Las Cuevas cave, and situated on a flat-lying area in proximity of a constructed stone wall built by the ancient Maya to close the passageway. A small doorway was left open to allow the access to the deeper recesses of the cave. The excavation areas were divided in thirty 1x1 m subunits (Voorhies 2013: 74; fig. 48). Two layers of the excavation were recorded through laser scanning and dense stereo matching techniques (unit 3, level 1 and 2; Fig. 49).
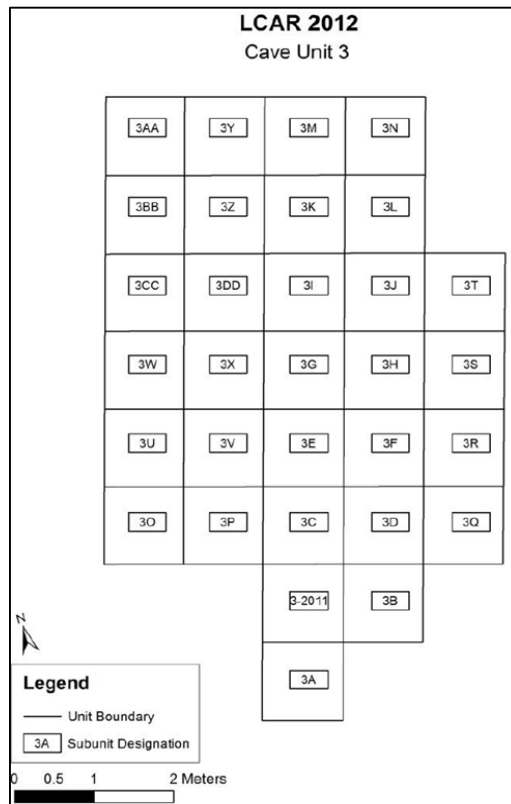
Figure 48. Schematic plan of the subunits of cave unit 3and their designations
(Courtesy of the Las Cuevas Archaeological Reconnaissance).

Level 1/stratum 2 is rich in charcoal, pottery sherds and other small cultural material embedded within a clay matrix (Fig. 50a). This stratum is present over most of the excavated unit and include artifacts, such as a chert flake; two possible elongated polishing stones; a speleothem; a shell pendant; a bivalve shell; several bones; jute shells; two small slate objects: a slab, and a thin fragment that might be a fine chisel or inscriber; a human molar cap, and a partial ceramic figurine. Two very interesting features associated with stratum 2 are rock clusters that lack a defined shape. Notably, an assortment of interesting artifacts was found among the rocks: three bones; a projectile point fragment; a *jute* shell; a handstone; an olive shell tinkler; a perforated small marine univalve resembling a conch shell; a complete projectile point; and a long bone. These objects were unburned and most were intact. None appeared to have been intentionally smashed at the time of deposition (Voorhies 2013: 83).

Figure 49. Cave's entrance chamber, unit 3, level 1: 3D data acquisition through phase shift variation laser scanner (Faro Focus 3D scanner; Courtesy of the Las Cuevas Archaeological Reconnaissance).

Level 2/stratum 4 is a charcoal-rich, ash-laden sediment layer with a clay matrix that dips sharply away from the constructions (Fig. 50b). The color of Stratum 4 is Gray (10 YR 6/1), but the matrix contains inclusions of consolidated Brownish Yellow (10 YR 6/8) hard clay fragments and abundant black, medium- to coarse-sized charcoal inclusions.

This stratum is probably the result of accumulated thermal related debris and includes several significant finds such us two hammerstones; a perforated bone tube; a speleothem; a medium-sized slate slab; and an adze head.
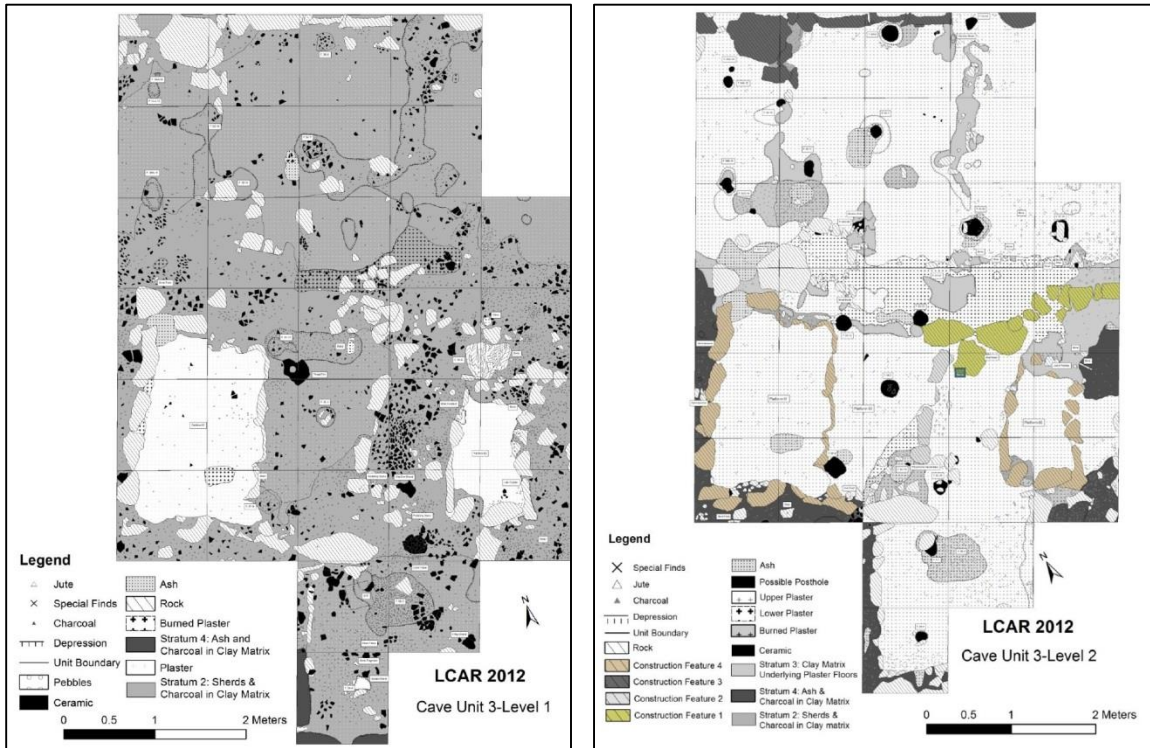
Figure 50. Las Cuevas: a. Map of stratum 2 at the close of level 1; b. Drawing of the architectural complex of Cave unit 3 at the close of level 2 (Courtesy of the Las Cuevas Archaeological Reconnaissance).

The investigations at unit 3 show the presence of ritual activity in the cave, as clearly evidenced by the burned material within a polychrome vessel fragment within a fire basin that is strategically located in front of a standing rock; the presence of artifacts in a cylindrical hole sealed at the top with potsherds containing ash and charcoal; and the deposition of assorted objects, including valuables (e.g., shell pendant, worked bone, etc.), in stratum 2. This spatial distribution of small objects, that at least to some degree are concentrated around platform 60, suggests that the platform may have been the focus of the ritual activity involving the deposition of these objects as ritual offerings (Voorhies in preparation: 90).

Instead of acquiring each subunit excavated by the excavation team, it seemed more appropriate to acquire the entire level at the completion of the excavation of the subunits (Fig. 48). This approach allowed both teams to save time, since the documentation team needed around 5 minutes for the equipment setup. The acquisition of the subunits would have required a longer equipment setup (around 150 minutes, 5 minutes x 30 subunits) compared to the acquisition of the entire level (around 5 minutes).

Acquisition of color in unit 3 was crucial, and for this the built-in scanner camera was used. However, a prerequisite for this method is ample light. Six lamps (DeWALT DC020 fluorescent light) were used to provide adequate light for the scanner camera to be capture color information.

The lamps were powered by batteries that, according to the manufacturer, would last for at least 2 hours. However, in the high humidity of the cave, they lasted 40 minutes. To record the excavation 7 scanner positions were needed and each of them took about 6-7 minutes to complete. Different strategies were tried to solve this problem. One was to light the area with fewer lamps and thus having the possibility to replace the lamps that run out of power first. Another was to turn lamps on only during the time the scanner actively capturing information. Despite these efforts, the resulting color information varied between the scans and it was difficult to achieve uniform color in the final model.

The first part of point processing and editing of the excavation area was performed with FARO Scene software supplied by the scanner manufacturer. The single scans obtained from the 7 scanner positions were cleaned and exported using an exchange format (ptx). The scans were imported in Meshlab. The single scans were filtered, aligned and meshed in Meshlab using the *Poisson surface reconstruction* approach (http://meshlab.sourceforge.net/). Setting a 3 mm scan resolution during the acquisition process, it was possible to obtain very accurate meshes which allowed for the description of all the features contained in the levels (Fig. 51).

Since this reconstruction tool does not allow the projection of the pointcloud's vertex color, this information was applied to the refined mesh from the pointcloud using the *vertex attribute transfer* filter (http://meshlab.source forge.net/).
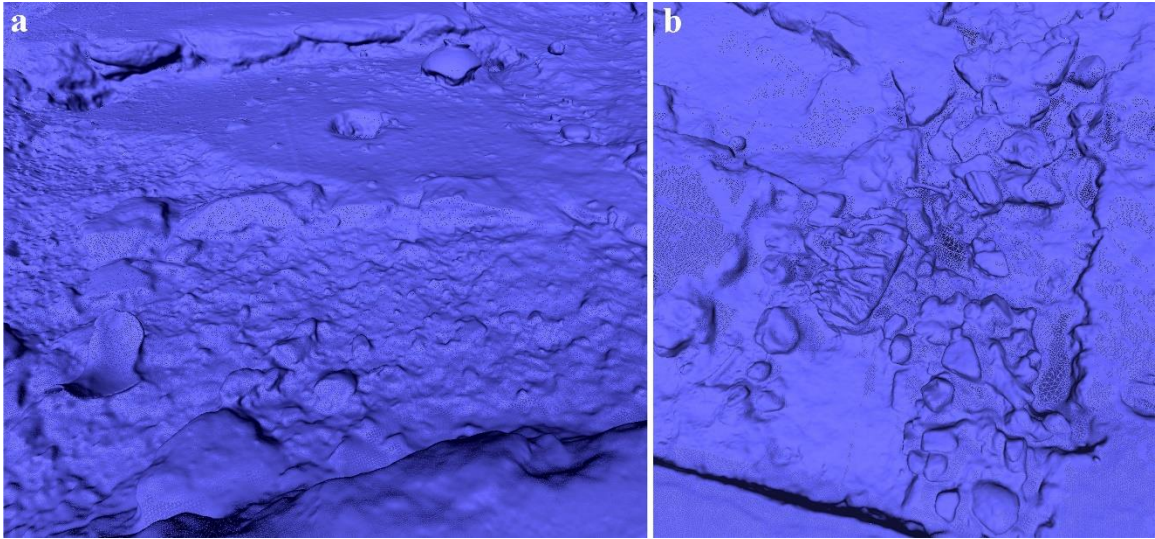
Figure 51. Meshes of unit 3 (cave's entrance chamber): a. level 1; b. level 2.

Despite the good quality of the acquired data in terms of mesh accuracy and texture reliability (Fig. 52), and the use of a constant light source during the acquisition of the 7 scans, it was impossible to get uniform colors in the final model (Fig. 53).

Figure 52. Cave's chamber 7: 3D data collected through phase shift variation laser scanner (Faro Focus 3D).

The two levels of unit 3 were also acquired through the dense stereo matching technique (Photoscan, Agisoft). The acquisition time with the FARO laser scanner for a surface of 8x5 meters was about 50 minutes, while the picture capture for the dense stereo matching took about 20 minutes.

Post-processing of the surface with the FARO took about 5 hours (mesh optimization, alignment and color per vertex projection), while the process with Photoscan took between 3 to 7 hours. The data loading and photo alignment took about 30 minutes, the rest was machine processing (10 M faces: 30 minutes of data loading and 6.5 hour of machine processing; 5M faces: 30 minutes of data loading and 4.5 hour of machine processing; 2M faces: 30 minutes of data loading and 2.5 hour of machine processing).

Figure 53. Cave's entrance chamber, unit 3, level 2: color per vertex projected using the *vertex attribute transfer* filter.

The two levels were scaled to real measures and aligned through control points acquired with the total station. Several targets located at the corners of the excavation were taken as reference points to align the total station data survey and the 3D models acquired

using the two techniques (phase shift variation laser scanning and dense stereo matching). These procedures allowed us to geo-reference the 3D models and align them with reference frames used for the survey of the site.

Results

The comparison of the co-registered surfaces acquired using the two techniques, Phase Shift Variation Laser Scanner Technology (PST) and Dense Stereo Matching (DSM), was performed in commercial and open source pointcloud and mesh processing software. Using different software packages for 3D model comparisons increased both the reliability and relevance of our findings.

The commercial software (CS) is the same package used in the comparison run during the 2011 fieldwork campaign. This software allows calculating the root mean square (RMS) which describes the surface's average absolute accuracy, and the standard deviation (SD) which is an index of the surface's noise (the measure of the variation in the measures).

The open source software (OS) permits us to calculate the mean deviation between the surfaces (the average of the sum of the squares of the deviations) and the RMS.

Moreover, a comparison was conducted between the high-resolution laser scanner 3D model and 3D models processed at different resolutions (1 million, 2 million, 5 million, and 10 million faces) using the dense stereo matching software (Photoscan, Agisoft). This comparison allows us to understand how resolution (face count) correspond to both quality and accuracy of the dense stereo matching model.

Unit 3, level 1/stratum 2- The number of produced points for level 1 (unit 3) was 12,886,110 for PST (about 25 million faces). The quality metric comparison between the PST and DSM (1, 2, 5, 10 million faces) were computed and are presented in table 4.

PST-DSM (1 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	7.095	9.665
CS (Rapidform)	± 9.406	-	9.417
PST-DSM (2 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	7.082	9.888

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CS (Rapidform)	± 9.962	-	9.970
PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	6.660	9.270
CS (Rapidform)	± 9.326	-	9.383
PST-DSM (10 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	6.679	9.163
CS (Rapidform)	± 9.477	-	9.735

Table 4. Descriptive statistics for PST and DSM deviation measurements.

The comparison run with OS and CS software between PST and 1 million faces DSM models shows very close values for the RMS (9.665 – 9.417 mm; figs. 54a, 55a). The comparison showed that 76% of the DSM model point's comparison fell within ± 9.326 mm from the average (0.4524 mm), and that the 94% of the point's comparison fell within ± 18.536 mm from the average.
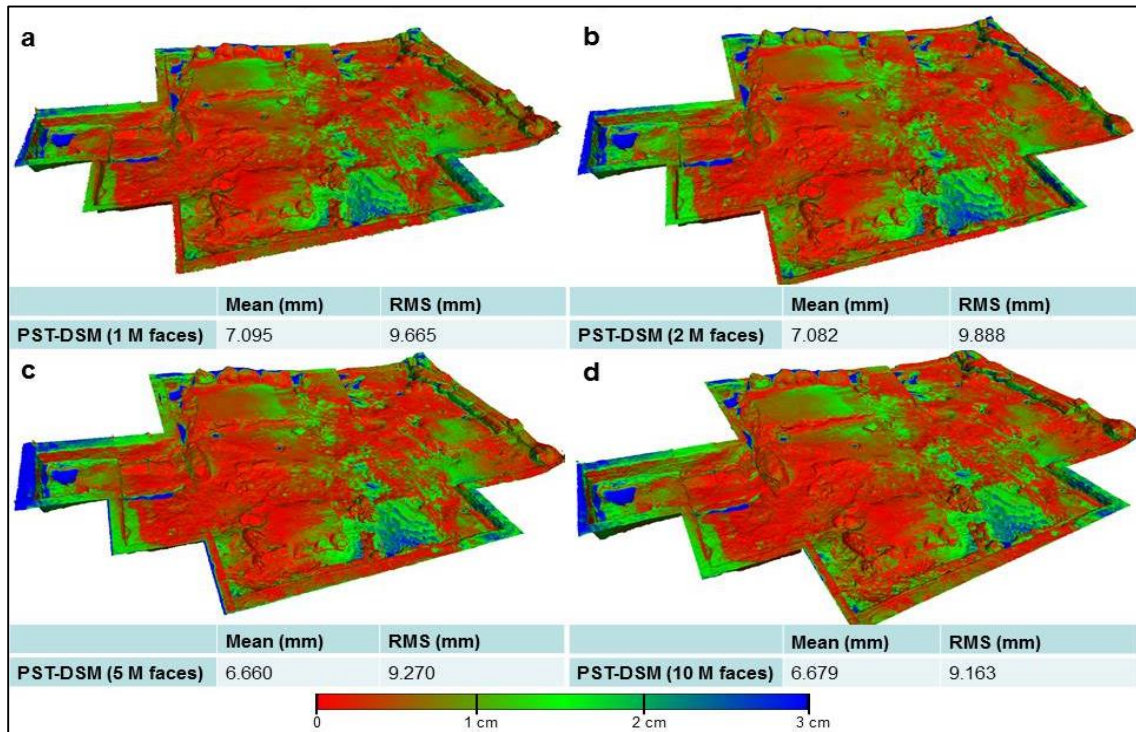
Figure 54. Geometry comparison of unit 3, level 1/stratum 2 (Meshlab): a. PST-DSM (1 M faces); b. PST-DSM (2 M faces); c. PST-DSM (5 M faces); d. PST-DSM (10 M faces).

The RMS values are very close also for the comparison with the 2, 5 and 10 million DSM models (2M: 9.988 – 9.970 mm, figs. 54b – 55b; 5M: 9.270 – 9.383, figs. 54c – 55c; 10M: 9.163 – 9.735, figs. 54d – 55d). The 76.5% of the 2M DSM model points' comparison fell within ± 9.962 mm from the average (0.397 mm), while the 93% of the point's comparison fell within ± 19.924 mm from the average. The 76% of the 5M DSM model points' comparison fell within ± 9.326 mm from the average (1.027 mm), while the 93% of the points' comparison fell within ± 18.652 mm from the average. The 76% of the 10M DSM model point's comparison fell within ± 9.477 mm from the average (2.227 mm), while the 94% of the points' comparison fell within ± 18.954 mm from the average.

The quality metric comparison between the PST and DSM models showed that there are not significant differences between the DSM models processed at different resolutions (1, 2, 5, 10 million faces). All comparisons presented about 2 cm of discrepancy for 76% of the DSM models and 3.7-3.8 cm of discrepancy for the 93-94% of the DSM models.
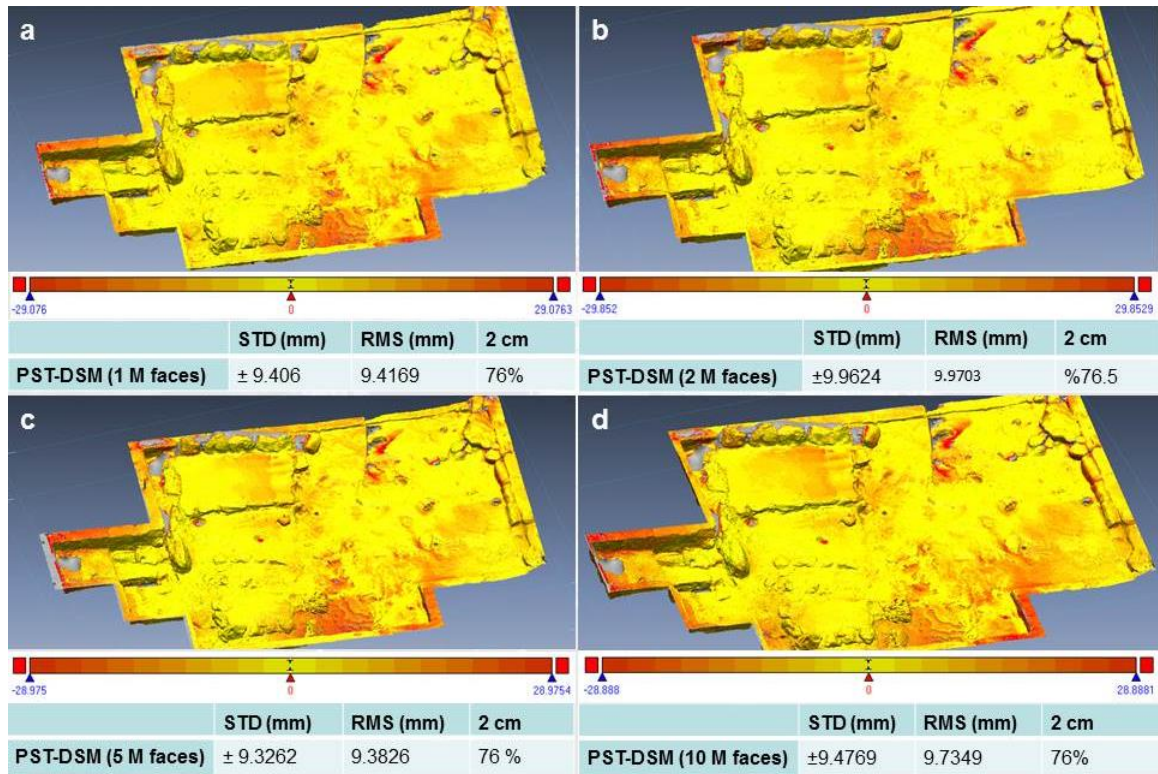
Figure 55. Geometry comparison of unit 3, level 1/stratum 2 (Commercial software): a. PST-DSM (1 M faces); b. PST-DSM (2 M faces); c. PST-DSM (5 M faces); d. PST-DSM (10 M faces).

Unit 3, level 2/stratum 4- The number of produced points for level 2 (unit 3) was 12,776,338 for PST (about 25 million faces). The quality metrics comparisons between the PST and DSM (1, 2, 5, 10 million faces) are presented in table 5.

The comparison run with OS and CS software between PST and 1 million faces DSM models shows very close values for the RMS (7.694 – 8.246 mm; figs. 56a, 57a). The comparison showed that 82% of the DSM model points' comparison fell within ± 7.907 mm from the average (2.339 mm), and that the 96% the points comparison fell within ± 15.814 mm from the average.

PST-DSM (1 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	5.441	7.694
CS (Rapidform)	± 7.907	-	8.246
PST-DSM (2 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	4.048	6.773
CS (Rapidform)	± 7.078	-	7.079
PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	3.480	6.366
CS (Rapidform)	± 6.667	-	6.733
PST-DSM (10 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	3.269	5.961
CS (Rapidform)	± 6.667	-	6.734

Table 5. Descriptive statistics for PST and DSM deviation measurements.

The RMS values are very close also for the comparison with the 2, 5 and 10 million DSM models (2M: 6.773 – 7.079 mm, figs. 56b – 57b; 5M: 6.366 – 6.733, figs. 56b – 57b; 10M: 5.961 – 6.734, figs. 56b – 57b). The 86% of the 2M DSM model points' comparison fell within ± 7.078 mm from the average (0.062 mm), while the 96% of the points' comparison fell within ± 14.156 mm from the average. The 86% of the 5M DSM model points comparison fell within ± 6.667 mm from the average (-0.937 mm), while the 96% of the points comparison fell within ± 13.334 mm from the average. The 86.5% of the 10M DSM model points comparison fell within ± 6.519 mm from the average (-1,6854 mm), while the 96% of the points' comparison fell within ± 13.038 mm from the average.
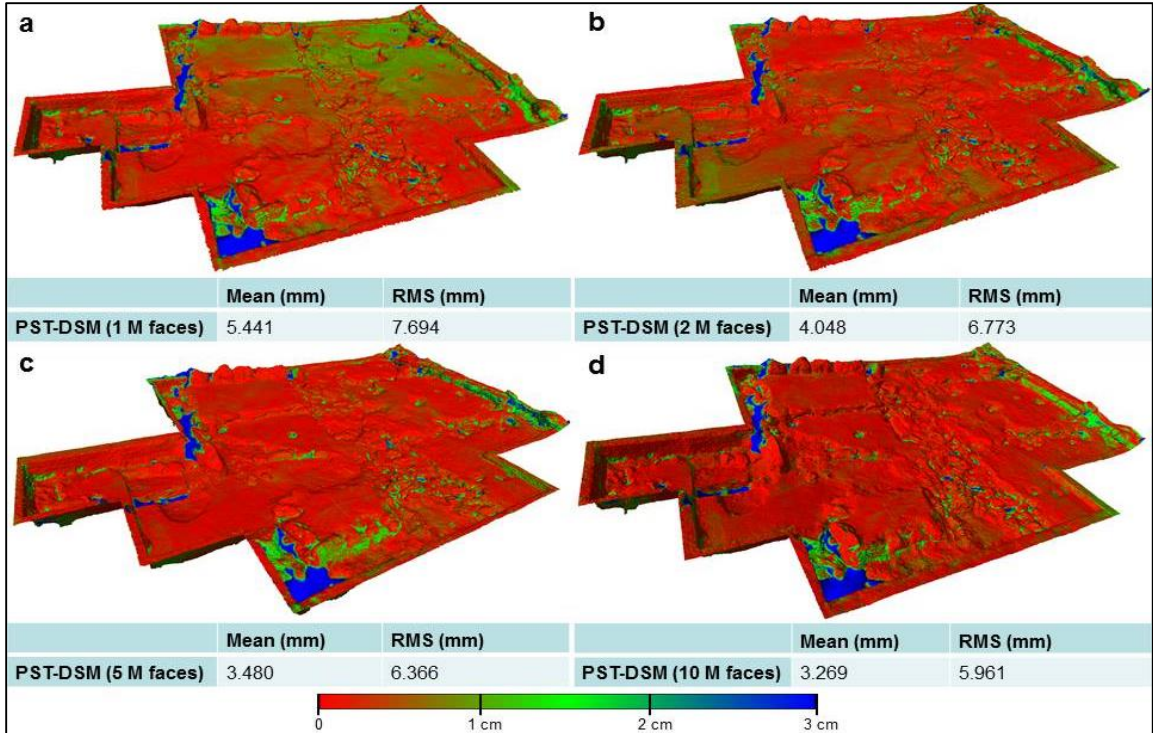
Figure 56. Geometry comparison of Unit 3, level 2/stratum 4 (Meshlab): a. PST-DSM (1 M faces); b. PST-DSM (2 M faces); c. PST-DSM (5 M faces); d. PST-DSM (10 M faces).

The quality metric comparison between the PST and DSM models showed that there are small differences between the DSM models processed at different resolutions (1, 2, 5, 10 million faces):

- 82% of the 1M faces DSM model presented 1.6 cm of discrepancy, while the 96% of the same model has 3.1 cm of discrepancy;
- 86% of the 2M faces DSM model presented 1.4 cm of discrepancy, while the 96% of the same model has 2.8 cm of discrepancy;
- 86% of the 5M faces DSM model presented 1.35 cm of discrepancy, while the 96% of the same model has 2.7 cm of discrepancy;
- 86% of the 10M faces DSM model presented 1.3 cm of discrepancy, while the 96% of the same model has 2.6 cm of discrepancy.

The difference between the 1M and the 10M faces models is 3 mm for the 86% and 5 mm for the 96% of the model.
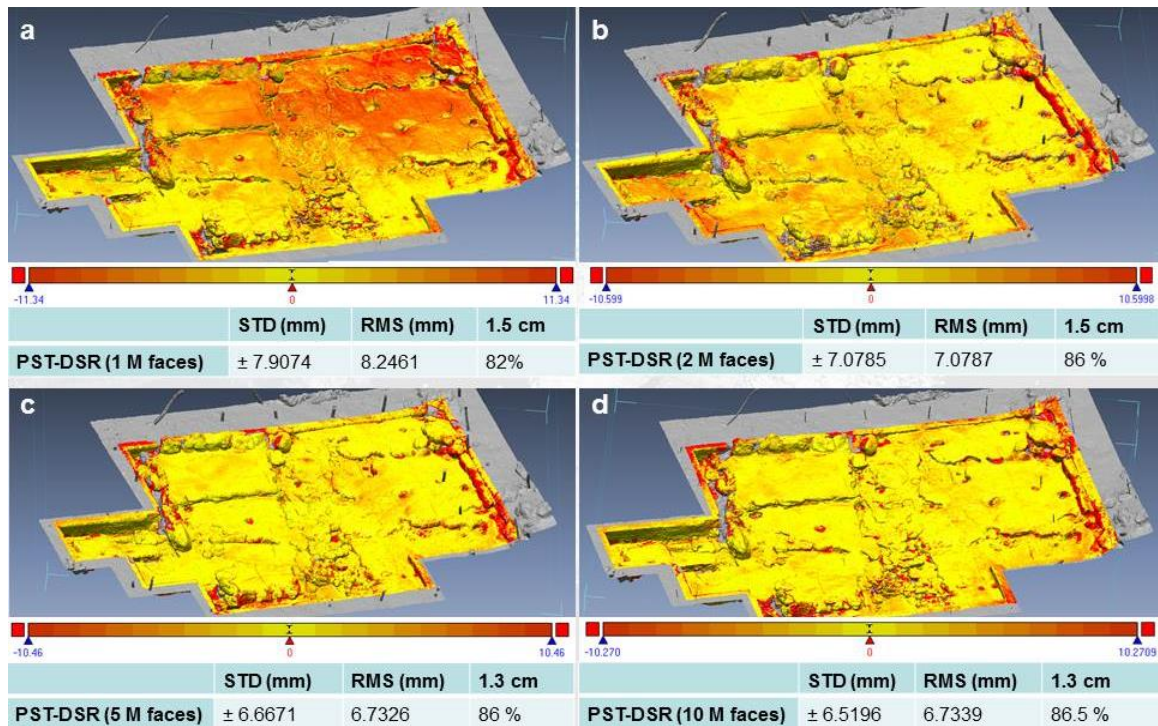
Figure 57. Geometry comparison of unit 3, level 2/stratum 4 (Commercial software): a. PST-DSM (1 M faces); b. PST-DSM (2 M faces); c. PST-DSM (5 M faces); d. PST-DSM (10 M faces).

The comparisons of the level 1/stratum 2 and level 2/stratum 4 gave different results in terms of discrepancy between the PST and DSM models. Level 1/stratum 2 presents a discrepancy of 2 cm for the 76% of the models and 3.7-3.8 cm for the 93-94% of the model. Level 2/stratum 4 presents a discrepancy of 1.3-1.6 cm for the 86 % and 2.6-3.1 cm for the 96% of the models. The better result obtained with level 2/stratum 4 can possibly be ascribed to the use of different methods during the acquisition process of the two levels. Level 1/stratum 2 was the first stratum of the 2012 fieldwork season acquired in cave environment. The picture data capture of this level was a beta test for the definition of best practices for the DSM pictures acquisition. For this reason the data collection of this first level was less accurate than level 2/stratum 4. However it was very helpful for the definition of a more reliable acquisition method. The method used for level 1, the capture of general context pictures (unit 3), was replaced by the new method used for level 2. This new method includes, in the DSM general context pictures (unit 3) process, the pictures taken for each single subunit. This new method allowed for increasing the quality of the DSM processed models.

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5.3.2. Techniques comparison: structure 1 (eastern pyramid, plaza A)

The 2011 3D data acquisition at Las Cuevas showed the limits of triangulation laser scanning techniques in areas of shaded sunlight under jungle canopy. This kind of technology does not work in direct sunlight conditions and the jungle canopy was not sufficient to mitigate the sunlight during the documentation process. For this reason, during the 2012 fieldwork campaign, phase shift variation laser scanning technology was chosen and compared to the dense stereo matching technique. The excavation area selected for the comparison was unit 9 at the top of structure 1, the eastern pyramid in plaza A (Fig. 58).

Methodology

Las Cuevas presents a typical ancient Maya site core plan, characterized by large masonry buildings organized around a central plaza. The eastern and western pyramidal structures (respectively 10m and 11m high) are the largest structures of the site. Excavation in 2012 focused on Structure 1, the eastern structure which resides beneath the cave entrance (Fig. 32). According to Robinson, the eastern structure is the area of the site that is frequently used for ceremonial activity and burying rulers, and associated with a complex cosmology of life, rebirth, astronomical movements and divine rule (Robinson 2013: 11).

Figure 58. Structure 1 (eastern pyramid, plaza A), unit 9: 3D data acquisition through phase shift variation laser scanner, Faro Focus 3D (Courtesy of the Las Cuevas Archaeological Reconnaissance).

Unit 9 is 3x3 m excavation located close to the center of the top of the structure. The unit was excavated using cultural levels. Four plaster floors were found and the fifteen natural and cultural stratigraphic levels encountered correspond to four major construction sequences, the sub floor construction fill, and post abandonment site formation (Fig. 59). The excavation reached a depth of 542 cm below ground surface (Robinson 2013: 12).
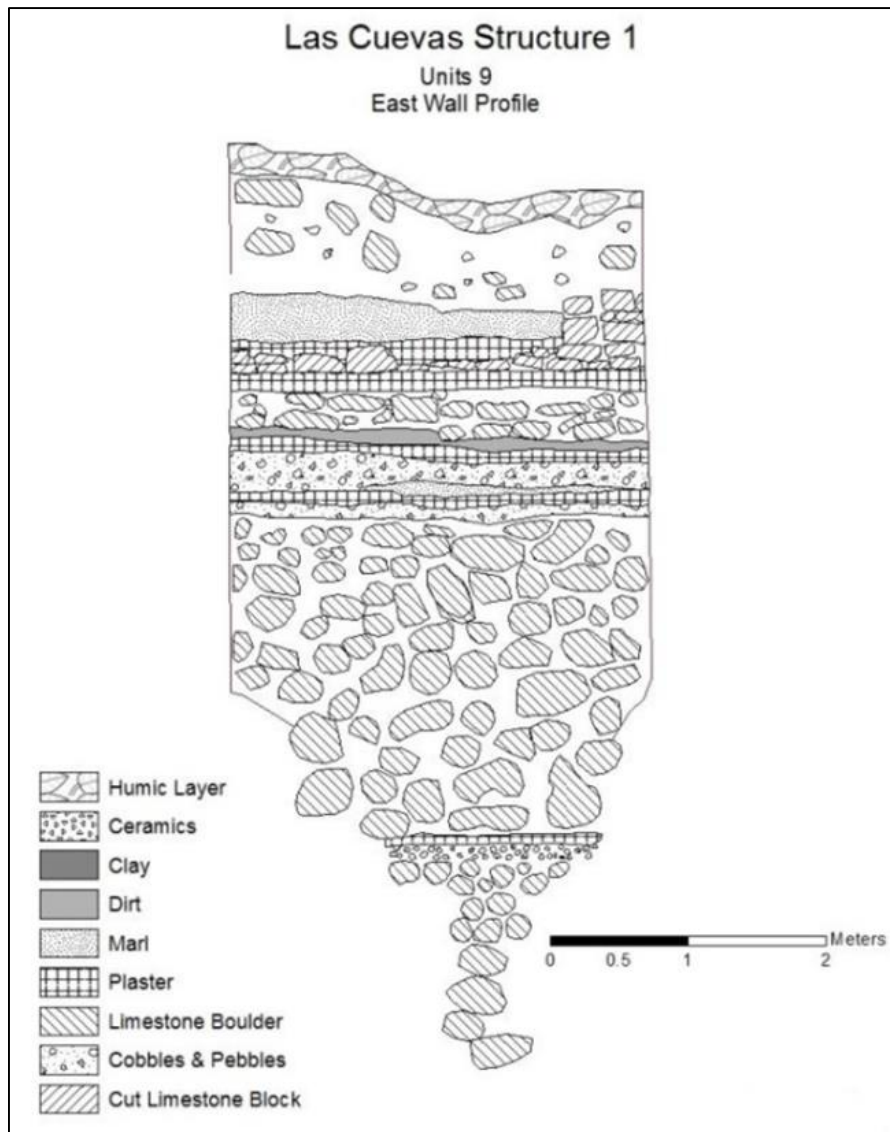
Figure 59. Unit 9 East Wall profile (Courtesy of the Las Cuevas Archaeological Reconnaissance).

Data comparisons were run on the 3D models of three most significant levels of Unit 9. These three levels correspond to three of the four floors found during the

excavation. The first one is level 10/floor 3 (Fig. 60a): "floor 3 consists of well-preserved plaster with distinct areas of discolouration. An area to the north appears to be burnt and an area in the northeast is red in comparison to the bulk plaster. No artifacts were found associated with the floor, but an uneven marl matrix covered parts of the floor. With an average depth of 0.6cm, the matrix did not cover the entire floor surface and reached a maximum thickness of 2.9cm. A sample of the marl was collected. There was no charcoal within the matrix" (Robinson in preparation: 14).

The second surface acquired is level 6/floor 2: floor 2 is "a 10cm plaster floor laid on top of the cobbles (Fig. 60b). A few broken sherds were associated with the floor surface. Diagnostic sherds are limited to a single Vaca Falls Red and a single Minanha Red sherd, dating to the late Late Classic and Early Classic respectively. Three seeds were recovered associated with the ceramic sherds on the plaster floor. The floor may also have sustained burning with distinct discolouration (10YR 5/3) and change in consistency in the northwest corner of the unit. A bluish colour (10YR 7/1) to the plaster surface in the north third of the unit may represent a wider area of burning and includes what appear to be burnt ceramic sherds. A dark patch in the northeast of the floor is associated with disturbed plaster and likely represents bioturbation from tree roots" (Robinson 2013: 13-14).
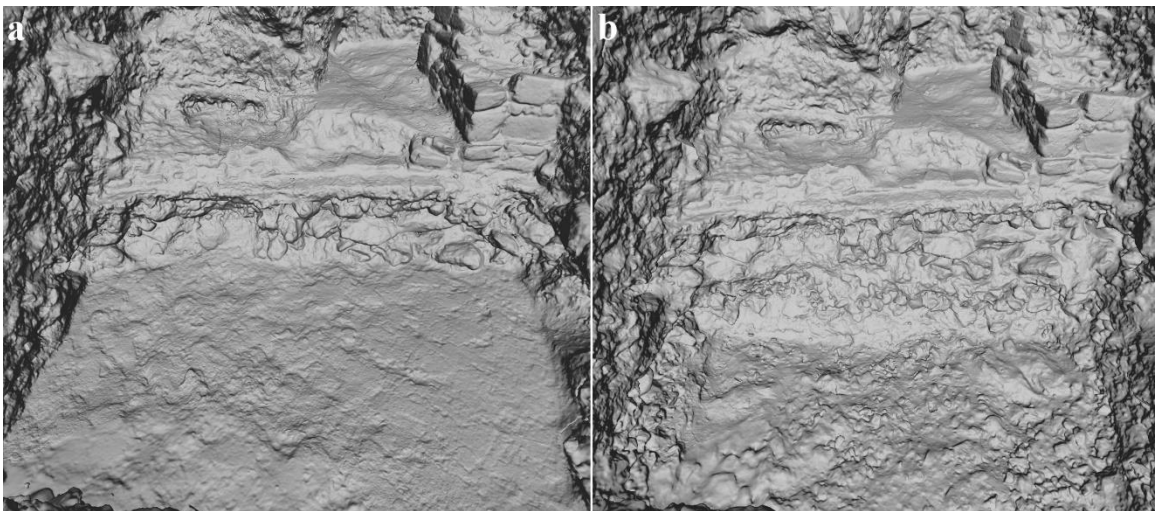
Figure 60. Meshes acquired through phase shift variation laser scanner (Faro Focus 3D) of unit 9 (structure 1, eastern pyramid, plaza A): a. Level 10/floor 3; b. Level 6/floor 2.

The last 3D model acquired is level 3/floor1 (Fig. 61): "A 12cm layer of loose dirt (105-117cm, 10YR 6/4) was placed on top of the floor before the construction fill was added. A few ceramics were found within the dirt matrix. The final construction event is composed of 28cm of cobbles and pebbles that supported the terminal plaster floor (65-77cm; Figure 2.10). Collapse of the masonry superstructure had covered the floor; however, six areas of ceramics represent in situ ceramic vessels that were left at abandonment. The vessels are all red slipped dishes dating to the late Late Classic, with no Terminal Classic markers present" (Robinson 2013: 15).

The current comparison was run on three significant levels of unit 9 (level 10/floor 3; level 6/floor 2; level 3/floor 1), but all the 15 excavated levels were acquired and preserved in three dimension and will be available for future analysis and interpretation.

The acquisition of unit 9 was faster than unit 3 since the use of artificial light was not necessary for the acquisition of the color information. The natural light under the jungle canopy was sufficient. Moreover, the excavation area of unit 9 (3x3 m) required just 4 scan positions instead of the 7 necessary for unit 3 (8x5 m) in the cave. The data processing procedure was exactly the same used for unit 3, but with different processing times.

The acquisition time with the FARO laser scanner for a surface of 3x3 m was about 25 minutes, 4 scanner positions of 6-7 minutes each, while the picture capture for the dense stereo matching took about 10 minutes. The post-processing of the same surface took about 3 hours with the FARO (meshes optimization, alignment and color per vertex projection) and 1.5 hours with Photoscan (30 minutes of data loading and 1 hour of machine processing).

One of the most challenging parts of the process was the mapping. The extreme variability of weather in these kinds of environments and lighting under the jungle canopy affected the color capture for both laser scanning and dense stereo matching techniques. The rapid change of lighting and shading on the excavation area between the different scanner positions and photo captures affected the quality of the 3D models' final mapping. As with unit 3, all the levels acquired for unit 9 were scaled and aligned to control points acquired with the total station. These procedures allowed us to geo-reference the 3D models and align them with the reference frame used for the site's survey.
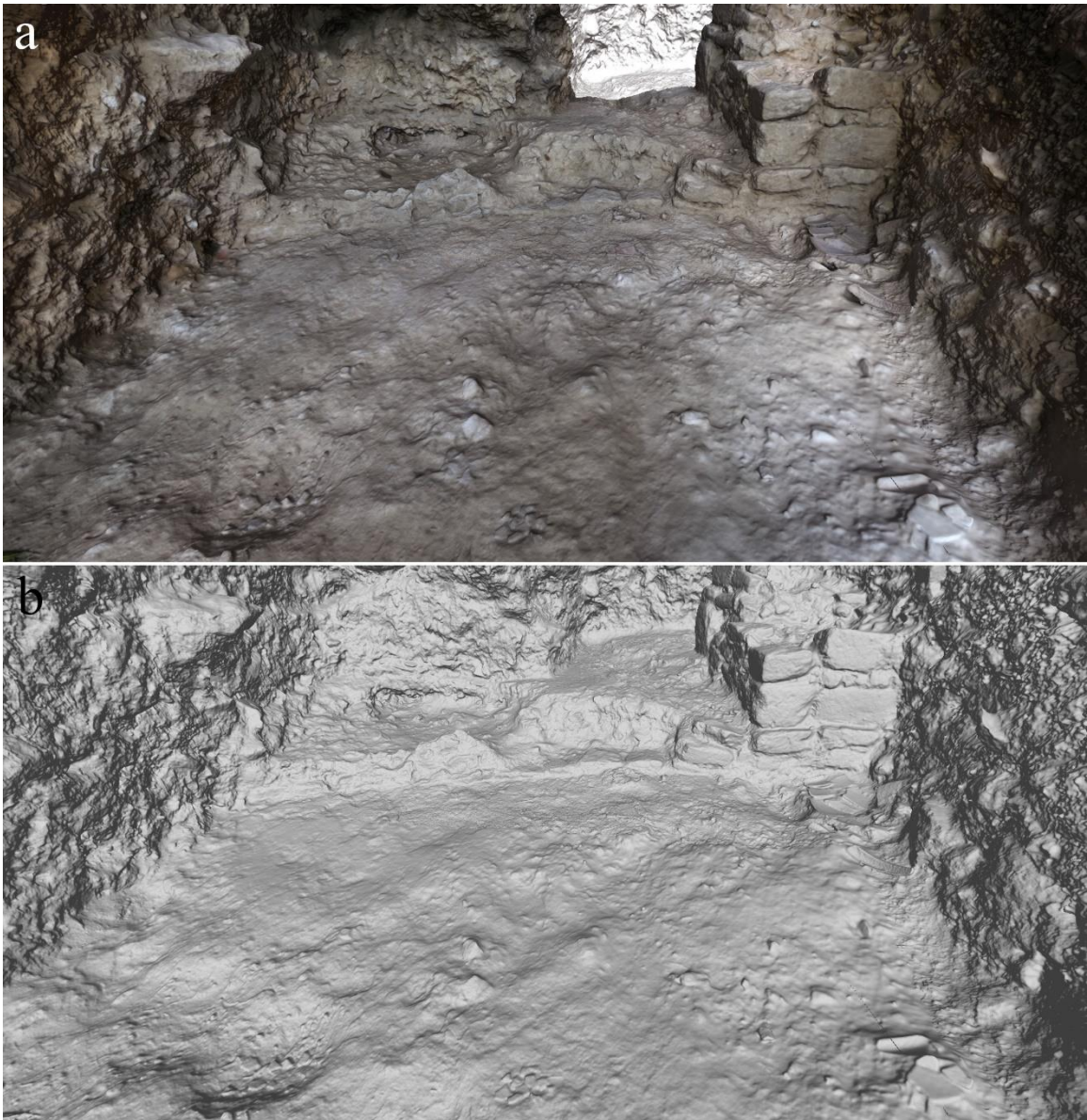
Figure 61. Three dimensional model acquired through phase shift variation laser scanner (Faro Focus 3D) of unit 9, level 3 (structure 1, eastern pyramid, plaza A): a. PST 3D model with DSM texture applied; b. Mesh.

Results

As for unit 3, the comparison of the co-registered surfaces acquired through PST and DSM were performed using the commercial (CS) and open source (OS) pointcloud and processing software. For the comparison of unit 9, the DSM 3D models where processed at the resolution of 5 million faces since the surface of all the levels acquired through laser scanner presented about 5 million faces. The results of the geometric comparison of unit 3

did not show significant differences in term of accuracy between the DSM 3D models processed at a resolution of 5 and 10 million faces.

Unit 9, level 10/floor 3- The number of processed points for level 10 (unit 9) was 2,840,797 for PST (about 5.6 million faces). The quality metrics comparison between the PST and DSM was computed and is presented in table 6.

The comparison run with OS and CS software between PST and 5 million faces DSM models shows very close values for the RMS (5.421 – 5.744 mm). The comparison showed that 85% of the DSM model points comparison fell within ± 4.963 mm from the average (-2.890 mm), and that the 96% of the points comparison fell within ± 9.927 mm from the average (Fig. 62).

PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	4.198	5.421
CS (Rapidform)	± 4.963	-	5.744

Table 6. Descriptive statistics for PST and DSM deviation measurements.
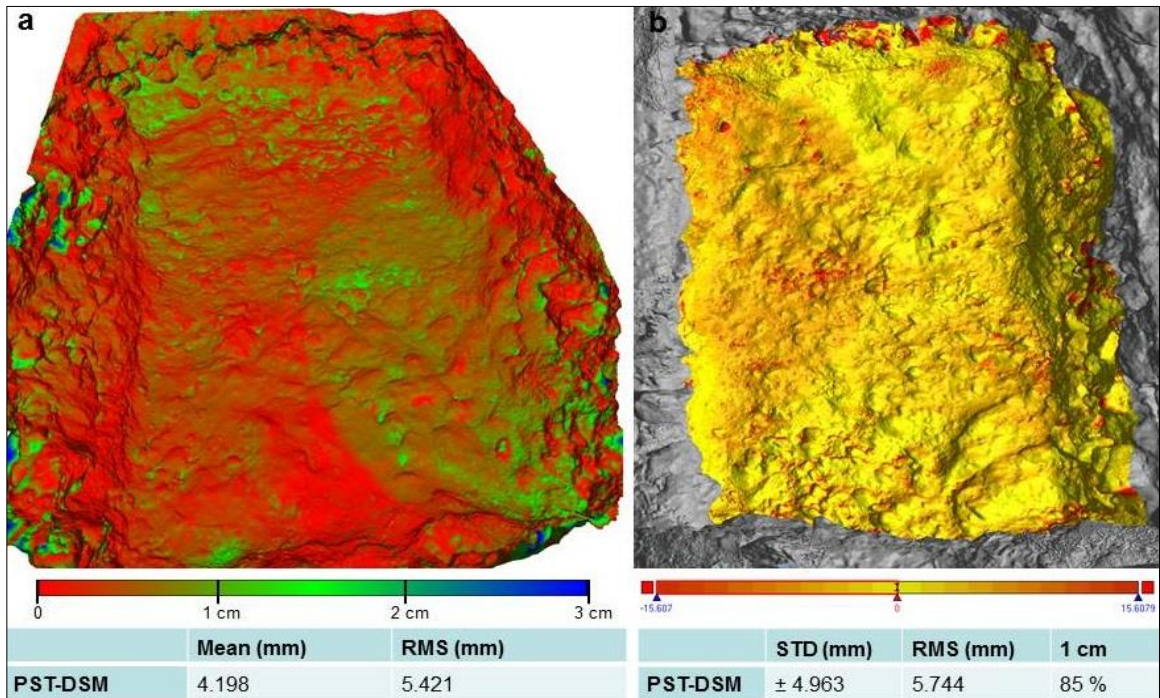
Figure 62. Geometry comparison of unit 9, level 10/floor 3: a. Meshlab; b. Commercial software.

Unit 9, level 6/floor 2- The number of processed points for level 6 (unit 9) was 2,348,700 for PST (about 4.7 million faces). The quality metrics comparison between the PST and DSM was computed and is presented in table 7.

PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	3.445	5.912
CS (Rapidform)	± 5.487	-	5.642

Table 7. Descriptive statistics for PST and DSM deviation measurements.

The comparison run with OS and CS software between PST and 5 million faces DSM models shows very close values for the RMS (5.912 – 5.642 mm). The comparison showed that 88% of the DSM model points comparison fell within ± 5.487 mm from the average (-1.316 mm), and that the 96% of the points comparison fell within ± 10.972 mm from the average (Fig. 63).
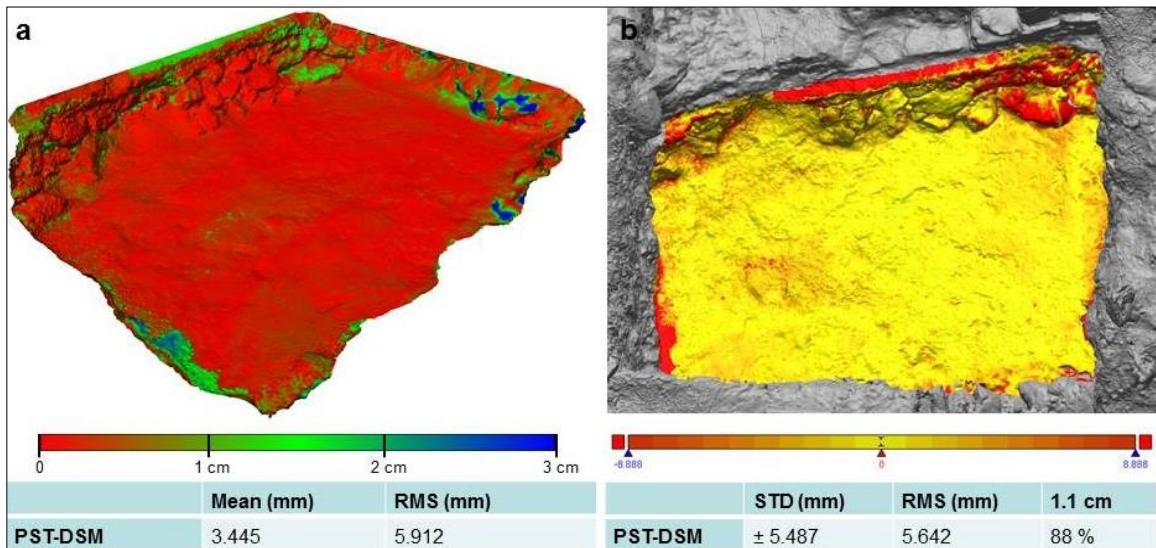
Figure 63. Geometry comparison of unit 9, level 6/floor 2: a. Meshlab; b. Commercial software.

Unit 9, level 3/floor 1- The number of processed points for level 3 (unit 9) was 2,764,789 for PST (about 5.5 million faces). The quality metrics comparison between the PST and DSM was computed and is presented in table 8.

PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	3.200	4.817
CS (Rapidform)	± 5.397	-	5.403

Table 8. Descriptive statistics for PST and DSM deviation measurements.

The comparison run with OS and CS software between PST and 5 million faces DSM models shows very close values for the RMS (4.817 – 5.403 mm). The comparison showed that 82% of the DSM model points comparison fell within ± 5.397 mm from the average (-0.249 mm), and that the 96% of the points comparison fell within ± 10.794 mm from the average (Fig. 64).
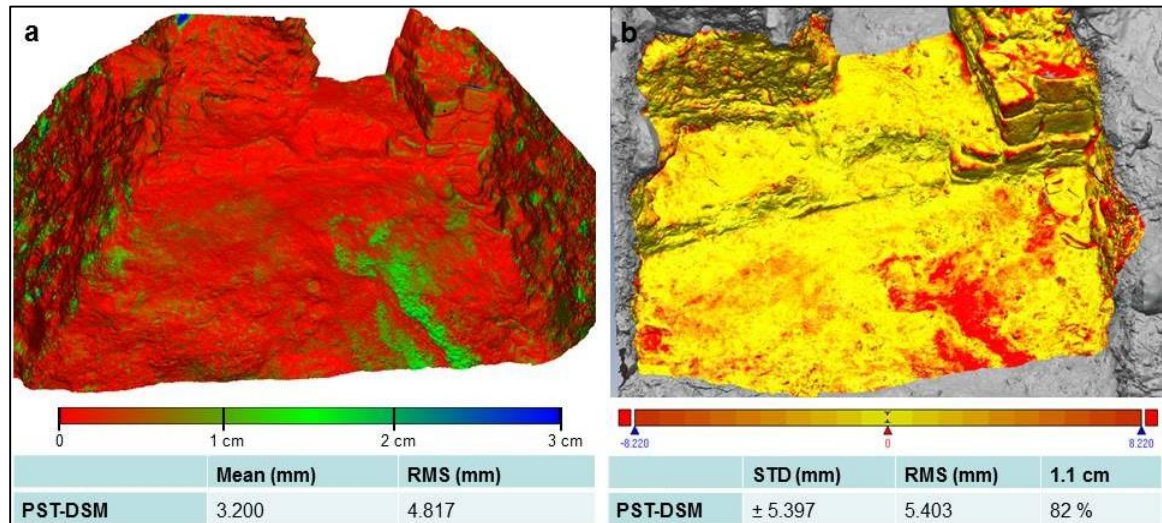
Figure 64. Geometry comparison of unit 9, level 3/floor 1: a. Meshlab; b. Commercial software.

The quality metric comparison between the PST and DSM models of the three levels of unit 9 showed that there are no significant differences between the compared levels (level 10/floor 3; level 6/floor 2; level 3/floor 1). All comparisons presented about 0.5 cm of discrepancy for the 82-88% of the DSM models and 1 cm of discrepancy for the 96% of the DSM models.

5.3.3. Techniques comparison: ballcourt

The 2011 3D data acquisition at Las Cuevas showed the limits of triangulation laser scanning technique in areas presenting direct sunlight. This kind of technology does not work in direct sunlight condition. For this reason during the 2012 fieldwork campaign the phase shift variation laser scanning technology was chosen and compared to dense stereo matching technique. The excavation area selected for the comparison was unit 17 opened over the southeast corner of structure 6, the eastern structure of the ballcourt. At the beginning of the 2012 fieldwork season this area had been cleared of brush, so it was a perfect area to understand the potential use of PST and DSM techniques in direct sunlight.

Methodology

Unit 17 was opened over the southeast corner of Structure 6 in the attempt to define and compare regional construction styles, such as the principal ballcourt of Caracol, this structure is characterized by rounded outside corners. An irregular trapezoid shaped (7x4 m) unit was established at the corner of the structure, including an area approximately 1 m off the structure to the east and south and extending up to the summit of the structure (Fig. 65a). The goal of the unit was to define and determine the corner construction (Robinson 2013: 61).

Level 1 consists of 17 cm of humid and recent soil accumulation, so the comparison was run on the base of level 2, where it was found "an intact plaster floor, 20 to 35 cm below ground surface and the front edge of the structure defined by a line of upright cut limestone blocks (Fig. 65b). The plaster floor gently slopes down to the northeast of the unit, presumably from subsidence, although intentional construction, such as for drainage, cannot be ruled out. The plaster continues under the upright cut limestone blocks that define the front edge of the structure. A large number of ceramics (1186 sherds) were recovered from the excavation as were a chert flake, jute, a piece of slate, and a piece of moulded stucco. Of particular note are three intact groundstone manos that were found in close proximity to each other within the collapse material close to the south east corner of the structure" (Robinson 2013: 63).

Figure 65. Unit17 (Structure 6, Ballcourt): a. Surface; b. Level 2 base (Courtesy of Las Cuevas Archaeological Reconnaissance).

According to Robinson "the continuation of floor 1 under the front of the structure suggests that there may have been more than one construction event for Structure 6, with possible remodeling of the structure. Future excavation will seek to answer questions regarding the construction history of the structure." (Robinson 2013: 60).

The acquisition of unit 17 was faster than unit 3. The direct natural light allowed capturing the color information without the use of artificial lights. The excavation area of unit 17 (7x 4 m) required 5 scan position instead of the 7 necessary for unit 3 (8x5 m) in the cave. The data processing procedure was exactly the same used for unit 3 and 9, but with different processing time.

The acquisition time with the Faro laser scanner for a surface of 7x4 m was about 35 minutes, 6 scanner positions of 6-7 minutes each, while the picture capture for the dense stereo matching took about 20 minutes. The post-processing of the same surface took about 5 hours with the FARO (meshes optimization, alignment and color per vertex projection) and between 2 and 5.5 hours with Photoscan (10 M faces: 30 minutes of data loading and 5 hour of machine processing; 5M faces: 30 minutes of data loading and 3 hour of machine processing; 2M faces: 30 minutes of data loading and 1.5 hour of machine processing).

As for unit 9, one of the most challenging parts of the process was the mapping. The extreme variability of weather in this kind of environments affected the color capture for both laser scanning and dense stereo matching techniques. The rapid change of lighting and shading on the excavation area between the different scanner positions and photo captures affected the quality of the 3D models' final mapping. As for unit 3 and 9 all the

levels acquired for unit 17 were scaled and aligned to control points acquired with the total station. These procedures allowed us to geo-reference the 3D models and align them with the reference frame used for the site's survey.

Results

As for units 3 and 9 the comparison of the co-registered surfaces acquired through PST and DSM were performed using the commercial (CS) and open source (OP) pointcloud and processing software.

A comparison was conducted between the high-resolution laser scanner 3D model and the 3D models processed at different resolutions (2 million 5 million and 10 million faces) using the dense stereo matching software (Photoscan, Agisoft).

The number of produced points for level 2 (unit 17) was 5,263,652 for PST (about 10.5 million faces). The quality metric comparison between the PST and DSM (2, 5, 10 million faces) were computed and are presented in table 9.

PST-DSM (2 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	5.152	7.514
CS (Rapidform)	± 8.172	-	8.180
PST-DSM (5 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	5.297	7.727
CS (Rapidform)	± 8.133	-	8.134
PST-DSM (10 M faces)	STD (mm)	Mean distance (mm)	RMS (mm)
OS (Meshlab)	-	5.563	8.090
CS (Rapidform)	± 8.273	-	8.572

Table 9. Descriptive statistics for PST and DSM deviation measurements.

The comparison run with OS and CS software between PST and 2 million faces DSM models shows very close values for the RMS (7.514 – 8.180 mm). The comparison showed that 85% of the DSM model points' comparison fell within ± 8.172 mm from the average (0.356 mm), and that the 96% of the points' comparison fell within ± 16.345 mm from the average (Fig. 66).

The RMS values are very close also for the comparison with the 5 and 10 million DSM models (5M: 7.727 – 8.134 mm; 10M: 8.090 – 8.572 mm). The 85% of the 5M DSM model points' comparison fell within ± 8.133 mm from the average (0.105 mm), while the 96% of the points' comparison fell within ± 16.266 mm from the average (Fig. 67). The 85% of the 10M DSM model points' comparison fell within ± 8.273 mm from the average (0.436 mm), while the 96% of the points' comparison fell within ± 16.546 mm from the average (Fig. 68).

	Mean (mm)	RMS (mm)		STD (mm)	RMS (mm)	1.6 cm
PST-DSM	5.152	7.514	PST-DSM	± 8.172	8.180	85 %
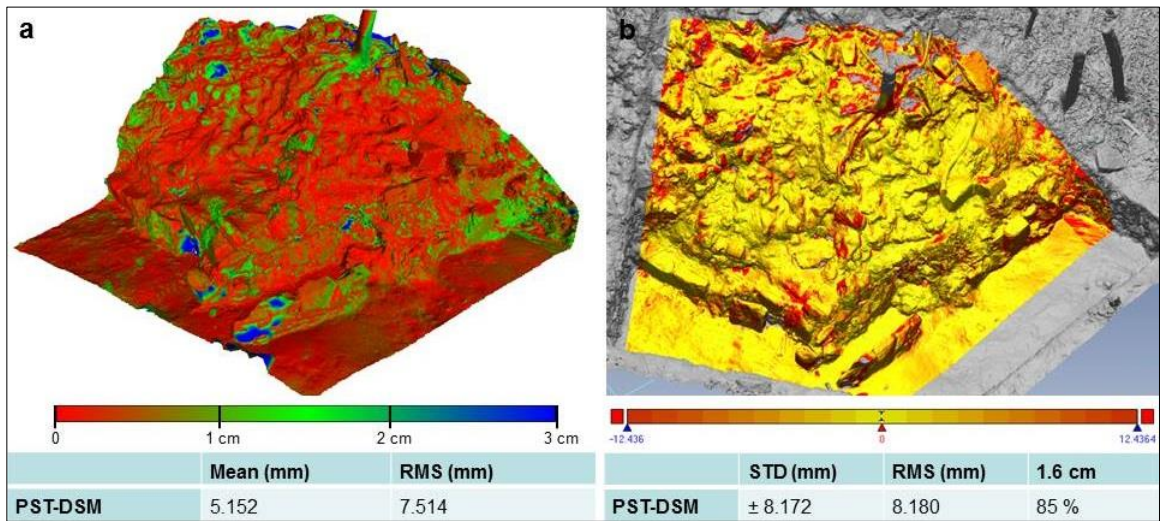
Figure 66. Geometry comparison of unit 17, level 2 (PST - 2M DSM): a. Meshlab; b. Commercial software.

	Mean (mm)	RMS (mm)		STD (mm)	RMS (mm)	1.6 cm
PST-DSM	5.297	7.727	PST-DSM	± 8.133	8.134	85 %
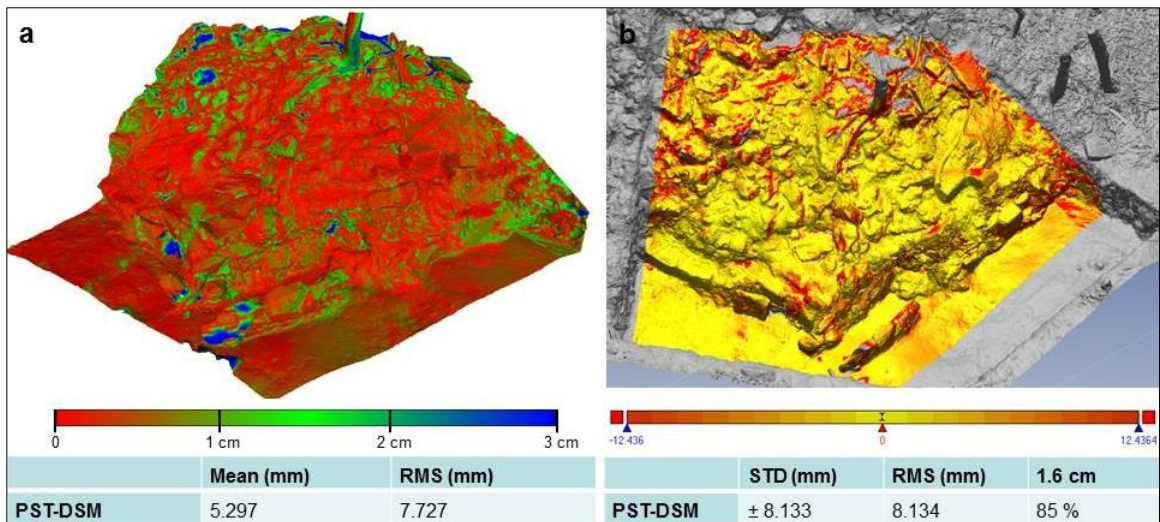
Figure 67. Geometry comparison of unit 17, level 2 (PST - 5M DSM): a. Meshlab; b. Commercial software.

The quality metric comparison between the PST and DSM models showed that there are not significant differences between the DSM models processed at different resolutions (2, 5, 10 million faces). All comparisons presented about 1.6 cm of discrepancy for 85% of the DSM models and 3.2 cm of discrepancy for the 96% of the DSM models.

	Mean (mm)	RMS (mm)		STD (mm)	RMS (mm)	1.6 cm
PST-DSM	5.563	8.090	PST-DSM	± 8.273	8.572	85 %
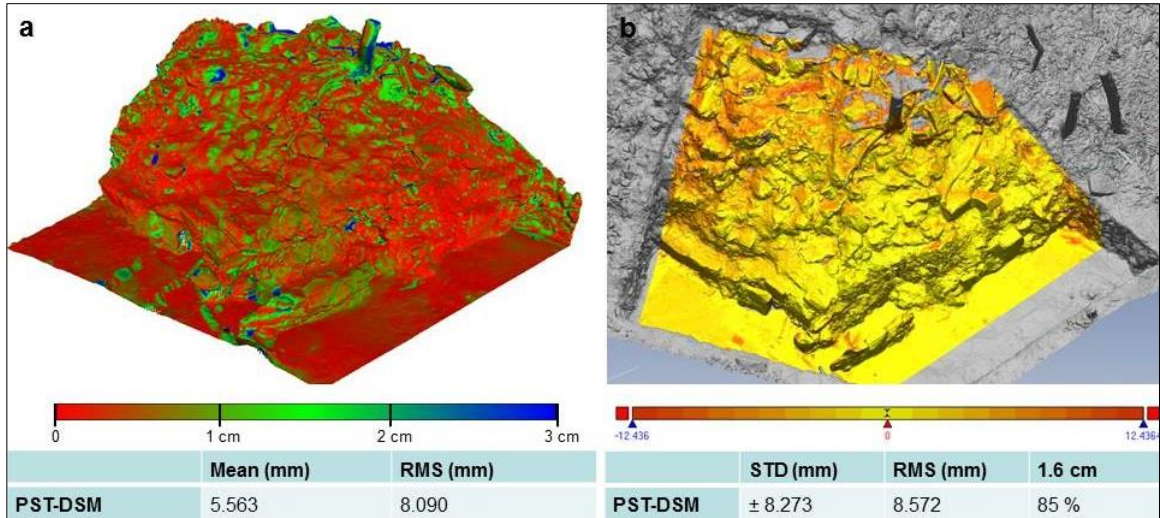
Figure 68. Geometry comparison of unit 17, level 2 (PST - 10M DSM): a. Meshlab; b. Commercial software.

5.4. Conclusions

Interest in archaeological 3D documentation has greatly accelerated over the past decade. Today, 3D technologies are being used more commonly in archaeology, and the use of technologies is well established for the documentation of archaeological sites (e.g. Dellepiane et al. 2012; Dell'Unto et al. 2008; Doneus et al. 2011; Craig et al. 2006; Neubauer et al. 2005; Galeazzi et al. 2007). However, there are only a handful of scholars who have made quantitative comparisons between different techniques on site (Dell'Unto et al. 2006; Koch and Kaehler 2009; Hermon et al. 2010). The research presented here compared three techniques: triangulation light laser scanning (Minolta Vivid 910); phase shift variation laser scanning (Faro Focus 3D); and dense stereo matching (Photoscan, Agisoft). This on-site, comparative analysis is fundamental to the goal of having a complete

and comprehensive understanding of these techniques' technical abilities and research related potential, as well as the ability to verify their use and integrate these technologies effectively in the 3D documentation process.

The results obtained in the first Las Cuevas 3D documentation campaign showed the considerable flexibility of the DSM technique for logistics, data acquisition and post-processing time. This technique allowed for the saving of data acquisition and processing time, when compared to triangulation light laser scanner technology.

During the 2011 fieldwork campaign TLS and DSM techniques were compared and the results showed that DSM saved 15 minutes during data acquisition (5 minutes vs. 20 minutes), and 45 minutes during data processing (15 minutes vs. 60 minutes), without considering the machine processing in this estimation (about three and a half hours), when compared to the triangulation light laser scanner method. These data allow us to conclude that in this particular environment, the acquisition through triangulation laser scanner technology slows down the excavation process more than the dense stereo reconstruction data recording, especially for an area larger than six square meters.

The limitations of TLS resulting from the 2011 fieldwork data acquisition and comparison allowed us to test a different laser scanner technology (PST) in the following 2012 Las Cuevas fieldwork season. The results of this second comparison showed that DSM allowed saving between 15 to 30 minutes for the data acquisition and between 30 minutes to 2 hours for data processing depending on the dimensions of the acquired area (see table 10), without considering the machine processing in the estimation (1 to 6.5 hours).

	Data acquisition (PST)	Data acquisition (DSM)	Data processing (PST)	Data processing (10M DSM)
Unit 3 (8x5m)	50 min (7 scan positions/6-7 min. per scan)	20 min.	5 hours (meshes optimization, alignment and color per vertex)	7 hours (30 min. data loading; 6,5 hours machine processing)

Unit 9 (3x3m)	25 min (4 scan positions/6-7 min. per scan)	10 min.	3 hours (meshes optimization, alignment and color per vertex)	1,5 hours (30 min. data loading; 1 hours machine processing)
Unit 17 (7x4m)	35 min (5 scan positions/6-7 min. per scan)	20 min.	5 hours (meshes optimization, alignment and color per vertex)	5,5 hours (30 min. data loading; 5 hours machine processing)

Table 10. Comparison of PST and DSM data acquisition and processing time.

The results of the geometry comparisons performed during the two fieldwork seasons allow us to make some conclusions on the reliability and accuracy of the different 3D documentation techniques in this kind of environment. The results obtained are both impressive and unexpected. The original hypothesis of this research conveyed to the identification of accuracy differences between the 3D documentation techniques depending on the diverse lighting exposure existing in the different areas of the site. Otherwise, the geometry comparison pointed to both the dimension of and the complexity of the acquired surface as critical elements in the acquisition of accurate geometries. In fact, geometry accuracy is higher for the smaller and less complex, unit 1 (2x2 m; figs. 42-45) and unit 9 (3x3 m; figs. 63-65), than unit 17 (7x4 m; figs. 67-69) and unit 3 (8x5 m; figs. 55-58). Table 11 shows that geometry accuracy increases with the growth of the dimension of the acquired area.

	STD (mm)	Mean distance (mm)	RMS (mm)	Accuracy discrepancy (%)
Unit 1 – Meshlab				
Unit 1 – Com. Software	± 1.6	-	1.7	65% about 3.2 mm 96% about 6.3 mm
Unit 9 - Meshlab	-	3.6	5.4	
Unit 9 - Com. Software	± 5.3	-	5.6	85% about 5 mm

				15% about 10 mm
Unit 17 - Meshlab	-	5.3	7.8	
Unit 17 - Com. Software	± 8.2	-	8.3	85% about 16 mm 15% about 32 mm
Unit 3 - Meshlab	-	4.0	6.7	
Unit 3 - Com. Software	± 7.0	-	7.2	86% about 14 mm 15% about 28 mm

Table 11. Descriptive statistics for deviation measurements.

One of the most interesting aspects of the DSM technique for the 3D documentation of archaeological stratigraphy lies in the possibility to revise acquired 3D models directly on site during the excavation process itself. This is because data processing time is reduced when compared to time needed using a laser scanner. Archaeological excavation is a destructive and unique process. When stratum are removed, it is not possible to "go back" and repeat the operation a second time. For this reason, it is important to understand if DSM techniques allow revising final 3D models on site before stratum are removed. In this sense, one of the most challenging aspects related to DSM data processing is machine processing time. Processing a high-resolution 3D image of 10 million faces took about 7 hours for unit 3 (8x5 m) and 5.5 hours for unit 17 (7x4 m) using a computer with the following specifications: i7 -3770 3,50 GHz processor; 36 GB of memory; and Nvidia GeForce GTX 670 graphic card. The reliability of DSM techniques during the excavation process strictly depend on the possibility of reducing the machine processing times on site. The active integration of both traditional and innovative practices for archaeological documentation can be feasible when the use of 3D technologies will not affect the excavation process with regard to time or logistics. In this sense data acquisition has to be as fast as possible while simultaneously reducing invasiveness. Of additional importance is the time dedicated to data processing, giving researchers the opportunity to integrate 3D technologies effectively in the archaeological excavation process.

In the attempt to understand if it possible to reduce the DSM machine processing time, a geometry comparison between PST and DSM 3D models, processed at different resolutions (1, 2, 5, 10 million faces), was conducted for units 3 and 17. Processing the

DSM 3D models at lower resolutions allowed for a reduction in machine processing time. This research aims to investigate if processing at different resolutions corresponds to lower accuracy of the DSM 3D model. The discrepancy between the 2 M and the 10 M faces models is 2 mm for 85% and 4 mm for 96% of the model for unit 3, while there were no significant differences seen for unit 17 (see table 3, 4, 8). These results show how there was a slight difference in terms of accuracy between the models. Conversely, as shown in table 12, the differences in machine processing times between the DSM 3D models processed at different resolutions is substantial.

	Unit 3 (2 M)	Unit 3 (5 M)	Unit 3 (10 M)	Unit 17 (2 M)	Unit 17 (5 M)	Unit 17 (10 M)
Data Proc. (hours)	3	5	7	2	3.5	5.5

Table 12. Machine processing time required to process the DSM 3D models at different resolutions.

The possibility to process a 3D model at lower resolutions with a contained difference in term of accuracy if compared to the higher resolution 3D model (2-4 mm), supports the reliability of the DSM technique for onsite documentation and analysis of archaeological stratigraphy. This research shows that DSM techniques can be integrated into day-to-day archaeological excavation practices through a two-step strategy: First, process the images at low resolution. This gives the opportunity to revise the final 3D model and start the analysis onsite before removing the stratum, since machine processing can take between 2 and 3 hours. And second, the images can be processed in the lab at higher resolution.

The results of this study strengthen the usage potential of dense stereo matching for 3D documentation of archaeological sites, confirming the technological improvements, over the last few years, of this technique's ability to capture levels of detail needed for research purposes. This technique allows for good reliability in the metric representation of unit information, and more importantly, it is the most economical, portable, flexible, and widely used approach for 3D documentation of archaeological sites, to date. However,

when preservation of *all* feature details is paramount, laser scanner techniques seem more indicated for the 3D reproduction of a unit's micro-stratigraphy (Fig. 69).

For now, the integration of laser scanner technologies, optical (Minolta Vivid 910) and phase shift variation laser scanner (Faro Focus 3D), with dense stereo matching seems like the optimal solution for the acquisition of all archaeological features contained in a stratum. Optical laser scanner technology is appropriate in environmental conditions where it is possible to control lighting, and for the acquisition of small areas (2x2 m), where a 3D capture of less than 3 mm of accuracy is required (Güth 2010: 3105-3114; Mc Pherron et al. 2009: 19-24).
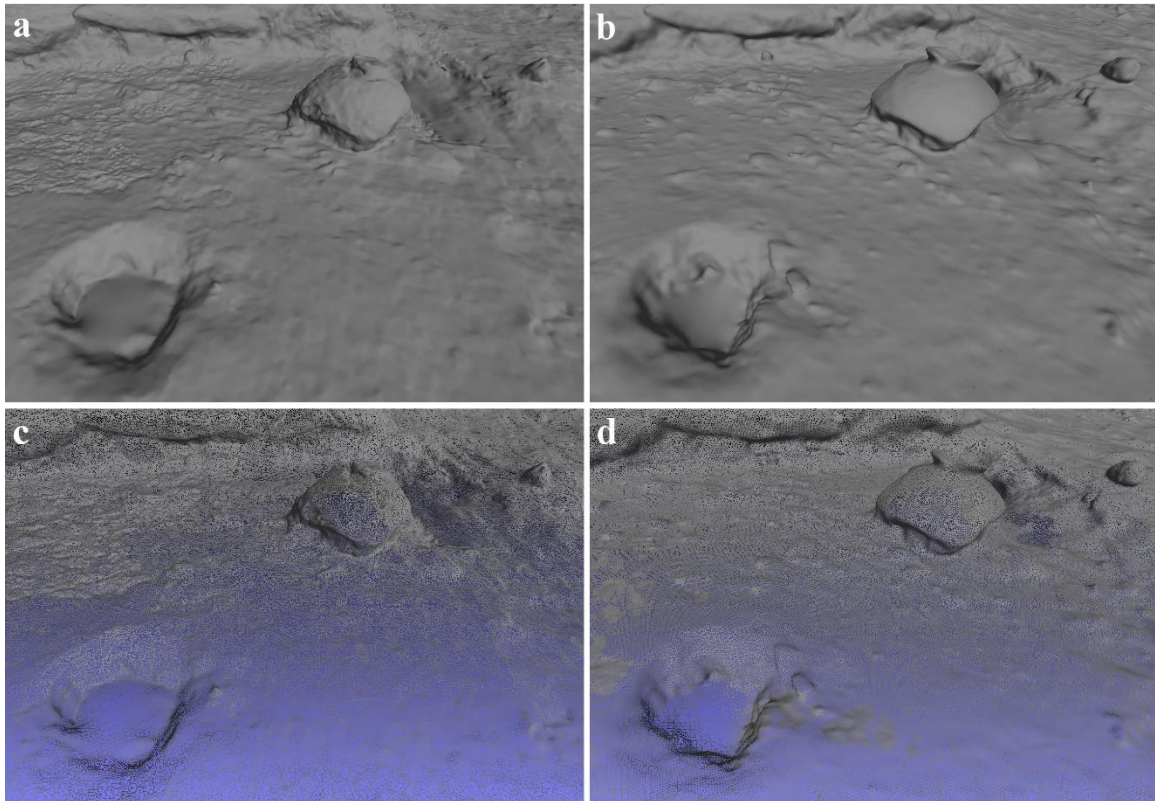
Figure 69. Three dimensional models of unit 3, level 1/stratum 2 (cave entrance chamber), acquired using two different techniques (DSM and PST): a. DSM mesh; b. PST mesh; c. DSM wireframe; d. DSM wireframe.

Phase shift variation laser scanner technology is more appropriate for the acquisition of larger areas. This technology worked properly in all of the environmental and lighting conditions tested here. The reliability of this technique is considerable if

compared to optical laser scanning technology. In fact, PST allows for the acquisition of a geometry accuracy that is extremely close to the TLS, about 5 mm; so it can be considered the best laser scanner solution available today for the 3D documentation of archaeological stratigraphy.

The initial quality of the raw images being acquired is a fundamental element for the correct rendering of the final 3D model. The limitation of the color per vertex acquired by the laser scanner (Faro Focus 3D) consists of two main elements:

- The limited resolution of the scanner's built-in camera. Nonetheless, the Faro Focus 3D has a decent quality integrated color camera (70 megapixels parallax-free color overlay), the laser scanner camera does not allow the same control of the images' capture and quality of external high-resolution cameras.
- The correct use of artificial lighting in cave environments for the collection of realistic images is a complex task to be accomplished.

For these reasons, different acquisition methods of consistent color information for the acquired 3D models were tested:

- For unit 3 in the cave environment, because of the low quality of both PST and DSM color information, high-resolution images acquired through a digital camera (Nikon D90 with Nikkor lenses−10-100 mm−, with a resolution of 12 MPixel) were applied to the 3D model using perspective projection methods (texture mapping) that have successfully been demonstrated in the last ten years (Galeazzi et al. 2010; Galeazzi at al. 2008; Blais and Beraldin 2006; Beraldin et al. 2005; Godin et al. 2002; fig. 70).
- For unit 9 and 17 it was possible to conduct color projection from 3D models acquired using dense stereo matching technique (Photoscan, Agisoft) on the high-resolution 3D models coming from phase-shift variation laser scanner technology (Figg. 71-72). The color information was applied to the high-resolution 3D model in Meshlab using the *vertex attribute transfer* filter (http://meshlab.source forge.net/).
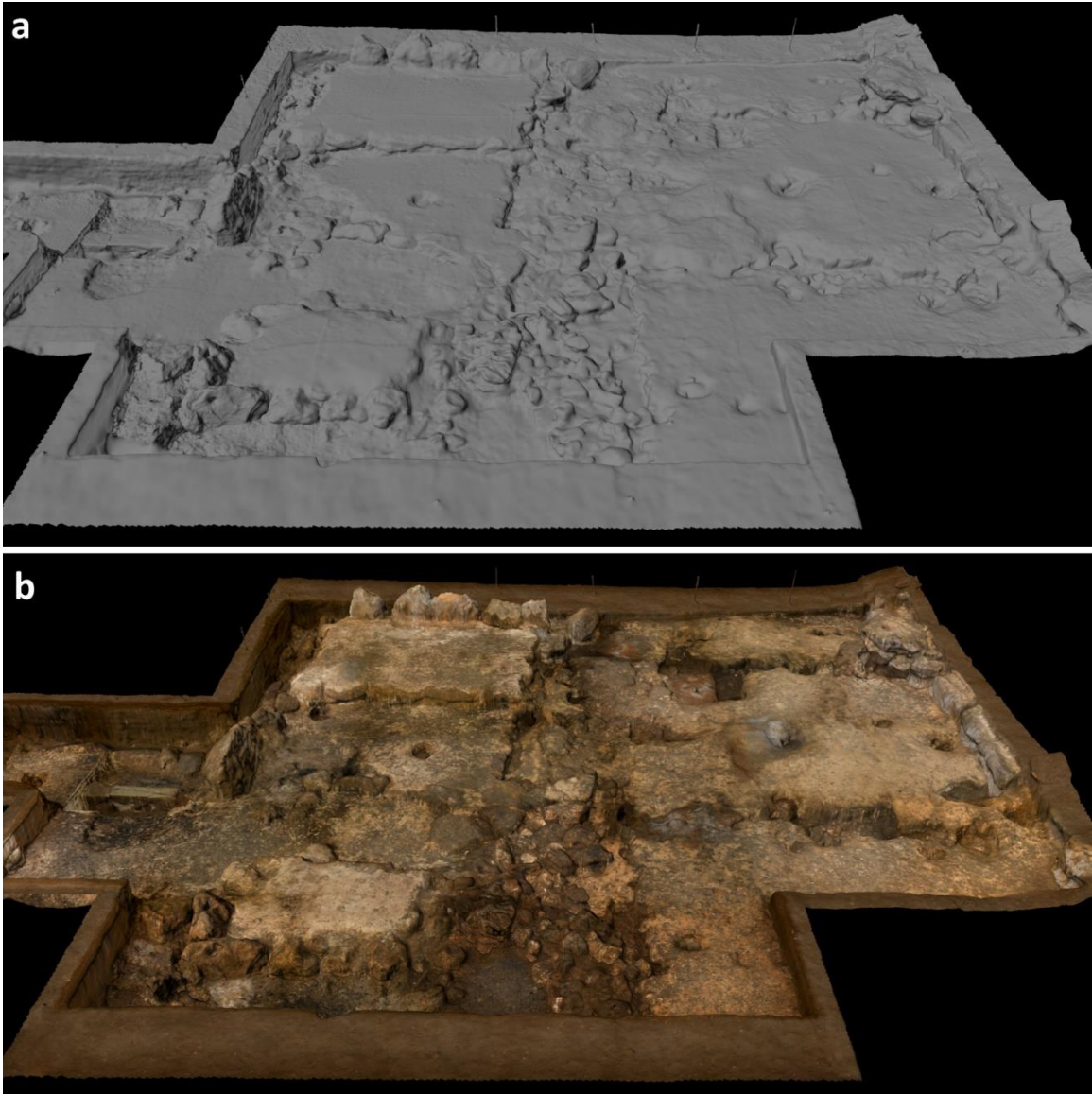
Figure 70. Three dimensional model acquired through phase shift variation laser scanner (Faro Focus 3D) of unit 3, level 2 (cave's entrance chamber): a. Mesh; b. Digital camera's high-resolution images applied to the 3D model using perspective projection methods (texture mapping).

The latter approach, taking advantage of the potential of the two techniques (PST and DSM), allows for the production of 3D models characterized by the high-resolutions of both geometry (PST) and texture (DSM).

Archaeologists and heritage specialists are debating on the real potential of different documentation techniques, and one of the most important aspects in this discussion is related to the accuracy of the acquisition process.
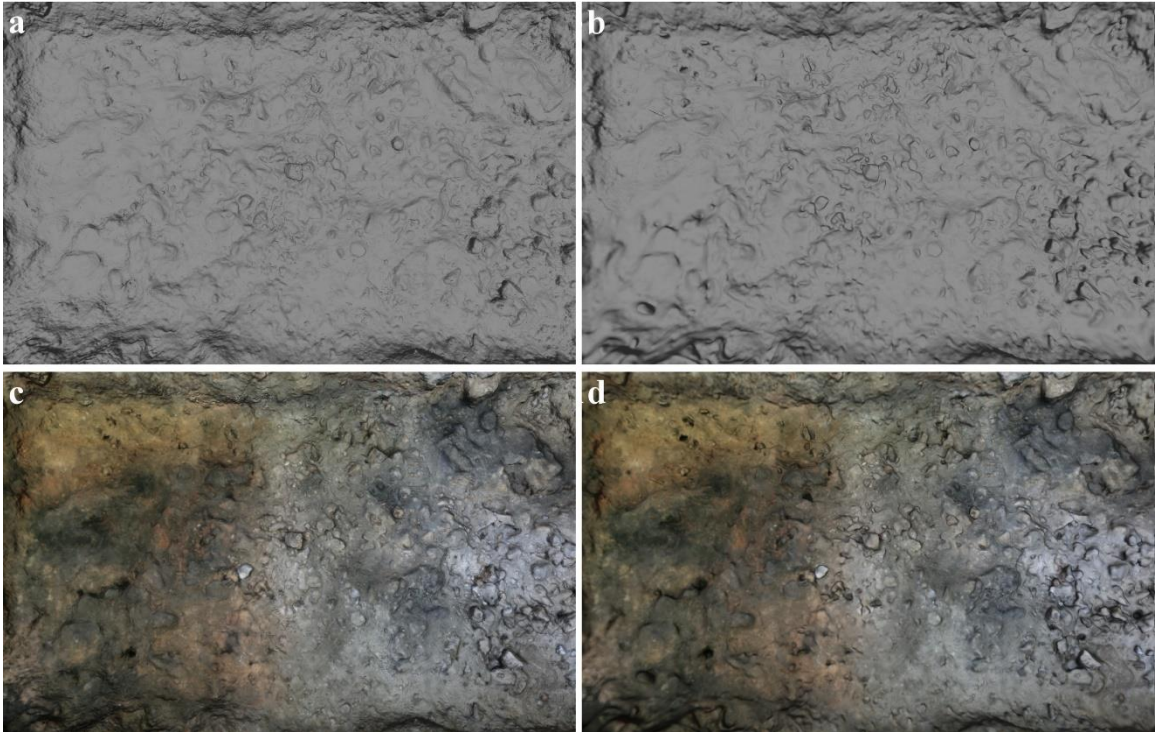
Figure 71. Unit 9, level 10/floor 3: a. Mesh acquired through DSM; b. Mesh acquired through PST; c. DSM mesh with color information; d. PST mesh with DSM color information applied through color projection.

What kind of accuracy is really needed for documenting the archaeological stratigraphic record? Is the centimetric accuracy that it is obtainable from the DSM technique sufficient to archaeologists needs? Or is the reproduction of millimetric 3D models mandatory for a correct analysis and interpretation of the archaeological record.

Scholars have different opinions about these different technologies. However, the potential of DSM techniques in archaeology it is a fact today. Most likely, in few years, technological improvements of image-based technologies will revolutionize archaeological practice, making laser scanner technology inefficient or obsolete compared to DSM, but this time is not yet upon us.
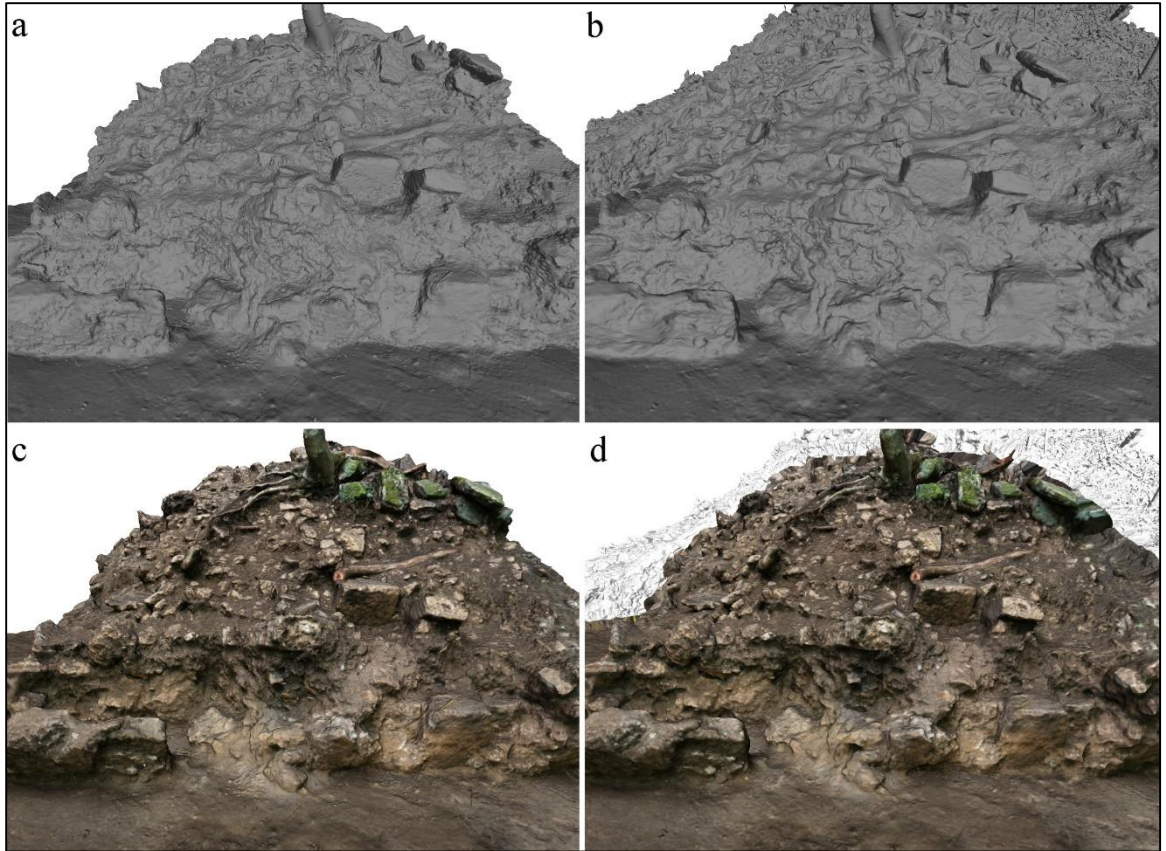
Figure 72. Unit 17, level 2: a. Mesh acquired through DSM; b. Mesh acquired through PST; c. DSM mesh with color information; d. PST mesh with DSM color information applied through color projection.

Chapter 6

3D interactive systems for the spatial analysis, preservation and simulation of the archaeological record

6.1. 3D virtual reproductions and simulations of the past: real or fake representations

6.1.1. Introduction

The importance of metrically reproducing archaeological sites and the excavation process in all its different aspects, from the artifacts contained in the units to the general context, was extensively discussed in the previous chapter. This chapter analyzes how, by starting from these metrical reproductions and all the information coming from the excavation process and ancient sources, when available, it is possible to reproduce and visualize in 3D not only the past tangible aspects of the site, but also intangible social and spatial phenomena that can be recollected through analysis and interpretation.

Digital technologies give the opportunity to fill the gaps that exist between past and present, guiding people in emotional, immersive experiences that can improve the consciousness of the past, which is described by Lowenthal as always less relevant in a contemporary society that is built on the huge expectation for the future. The global society lives its present life with eyes looking forward: "I must be modern: I live now" (Davies 1983: 124). The consequence of this future-oriented existence is the loss of most of our past. As a result, using Lowenthal's words, "The past [becomes] a foreign country; they do things differently there" (Lowenthal 1985: xvi), since people consciously decide to create barriers between past, present, and future, giving more importance to that which is forward.

Despite people's detachment from their past, we all know how significantly our knowledge of the past can influence choices and plans for the future. This is why archaeologists, museum curators, and heritage scholars are concentrating their efforts in

developing new methods for the preservation and dissemination of our past. Archaeological sites, historical monuments and ancient artifacts represent the material remains of our ancient past. Therefore, these remains can be important instruments for bridging past and present and should not be considered just ruins without meaning, but animated objects. "A ruin, an abandoned building, gives hospitality to melancholic ghosts that a good restore and its appropriate reuse can certainly exorcise" (Ruggieri Tricoli 2000: 11). Throughout a site's history, in fact, the diverse societies had changed and re-used material remains found there, changing their shape and symbolic meaning. This process can be considered an evolution, or the biography of things, which always refers to past experiences, and can be traced analyzing monuments and artifacts. Several scholars have exhaustively faced "things" by analyzing their biographies, starting from Igor Kopytoff (1986) who discusses the cultural biography of things in archaeology. From this discussion other scholars have used the form of object biographies for the analysis of material culture (Spector 1993; Tringham 1994; Holtorf 1998, 2002; Knappett 2002). Allan Pred describes "humanly made objects" as having life histories that have continuous paths through time and space, and that intersect with one another (Pred 1984: 281).

From the perspective of object biography theories it seems clear how the study of ancient artifacts should consider not only their original context, but also their present *status* of *physical remains*. It is with this *status* that archaeologists and the general public relate. Moving in the present landscape, people experience a constant embodied engagement with past material remains that fundamentally conditions our daily life routine. This engagement is strongly influenced by the relation that exists between our body and our mind (Seremetakis 1994; Lakoff and Johnson 1999; Varela et al. 1999). By analyzing artifacts, in fact, we can try to perceive the maker's feeling and, after a decoding process, the meaning and the function of these objects. According to Nadia Seremetakis, "the senses are embodied in objects that can provide a multiplicity of possible and always autonomous prospects on their human authors" (1994: 4-7).

People are the result of their bodily experiences in a physical and cultural environment, while their material creations are a personal interpretation of that environment. The starting point of any imitative and creative process is always the cultural and social

context. We are the consequence of physical and emotional interaction with a surrounding composed of individuals and objects. This relation is the origin of our ideas, feelings and being and its effect – our reactions – that determines our life path, establishing who we are.

Thanks to a sensorial experience with past material remains, which can be conceived as a sensory landscape, our mind is able to activate subjective mental interpretation processes to simulate its potential original shape and context. In this process of the mind there are at least two steps: first, the mental construction of the contemporary site that we create through our working memory (Tversky 2001: 371); and second, the more complicated part of the process, the mental interpretation of its original shape. In fact, visiting an archaeological site, if we try to close our eyes with the remains in front of us, they suddenly disappear, substituted by our interpretations of their past.

People today have experiences only with what remains of ancient artifacts. The decontextualized ruins retain the shape of their memories, not the original spirit of these monuments. The efforts of anthropology, archaeology and history to study the past move in the same direction. The shared idea of these disciplines is to preserve and study present evidence not only to understand and reconstruct the past, but to create, develop and produce different and innovative tools to allow people better understanding of the connections that exist between past and present space and landscape.

The meaning of "space" is the result of human mental processes. As such, it is to be clarified and understood from the perspectives of the people who have given it meaning. For this reason, specific places present to us a condition of human experience. As agents in the world we are always "in place," much as we are always "in culture" (Tuan 1984: 1). The cultural and social element forms in the human mind at least two different perceptions of space. Contemporary society, characterized by an increasingly scientific and technological view, is transforming the subjective point of view – a centered view in which we are embedded within a place and time – into an objective point of view – a decentered view in which we seek to transcend the here and the now (Entrikin 1991: 7). According to Yi-Fu Tuan we have both an internal and external perception of place; we live our lives in place and have a sense of being part of a place, but we also view place as something separate (1977). Scientific theorists stress the capacity of present society to increase the

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"distance" between the subjective and the objective view as a result of the decentered view of science's successes – a decentralization that has supported a perspectiveless view, a "view from nowhere" (Nagel 1986: 70).

Is it really possible to decree the defeat of the local and subjective perception of space in favor of the global and objective one? In order to answer this question, it is necessary to understand how the approach to space and landscape has changed in the last twenty years with the incredible development of technologies and communication systems. In fact, today virtual reality allows holistic and 360 degree visualization of the space, providing a different level of perception of the physical landscape.

The actual conception of virtual reality is very different from that defined by Bergson in the twentieth century. In fact, it is not the mental reality built on our consciousness anymore, but a virtual instrument that we use in order to show our interpretation of the past. This interpretation starts virtually, but "little by little it comes into view like a condensing cloud; from the virtual state it passes into the actual; and as its outlines become more distinct and its surface takes on color, it tends to imitate perception" (Bergson 1988: 171). But analyzing virtual reality today, it is possible to identify its Bergsonian origin. When the representation becomes distinct and clear in our mind, we have two possibilities: one is to decide to leave it in a mental imaginative state; the other is to transform it into something more physical and concrete, such as a 3D virtual world. Reconstructing in this way makes it possible to simulate multiple different pasts, navigate within these interpreted realities, and have an embodied experience. Thanks to the use of new technologies it is possible to interpret and recreate the monument in its original contexts, and to virtually restore artifacts (fig. 73, 74). People's mental landscapes can be fixed in a virtual simulation that, originating from a scientific process of interpretation (fig. 75), can increase comprehension of the past.

Considering that our long-term memory cannot preserve these mental landscapes and our working memory is too limited to construct them (Tversky 2001: 376), these 3D representations can be a powerful tool to fix them graphically and preserve them in time. In this way it will possible to compare different interpretations of our past landscape.

Figure 73. Villa di Livia (Ancient Via Flaminia Project): overlapping between the 3D reconstruction of the ancient villa and the 3D survey of the actual archaeological site (Galeazzi 2008: 132).

Figure 74. Villa di Livia (Ancient Via Flaminia Project): 3D reconstruction (Galeazzi 2008: 130).

Figure 75. Villa di Livia (Ancient Via Flaminia Project): 3D reconstruction of the landscape (Forte 2008: 1).

6.1.2. 3D replicas of the real

Before discussing all the implications related to the 3D simulation process of ancient sites and landscapes, it is important to stress the differences that exist between the simulation of past landscapes and the 3D metrical reproduction of contemporary sites through the use of 3D documentation techniques such as laser scanner and photogrammetry.

In the past ten years these technologies favored the considerable growth of 3D digital copy/facsimile industry in archaeology and heritage studies. Since the 1960's, digital practitioners within museums have struggled with the concept of "aura", introduced in 1968 by Walter Benjamin (1968). Starting from the definition of authenticity of a thing as "the essence of all that is transmissible from its beginning, ranging from its substantive duration to its testimony to the history which it has experienced" (Benjamin 1968: 221), he defines the aura of a thing "as the unique phenomenon of a distance, however close it may be. If, while resting on a summer afternoon, you follow with your eyes a mountain range on the horizon or a branch which casts its shadow over you, you experience the aura of

those mountains, of that branch (Benjamin 1968: 222-23)". Benjamin believes that copies of the original −films and images created by the age of the mechanical reproduction− lack the "authentic" aura of their sources (Benjamin 1968: 223).

Benjamin's discourse on the "authentic" aura is still central today in discussions about the real value of 3D reproduction of contemporary monuments/sites. The diffusion of laser scanning technologies and 3D prints increased the diffusion of 3D replicas of art work in museums. For example, the Van Gogh Museum in Amsterdam, in cooperation with Fujifilm, has developed a technique for the creation of 3D reproductions of Van Gogh masterpieces.

> The special 3d technique, by means of which these reproductions are produced, goes by the name of Reliefography. This technique is a combination of a three-dimensional scan of the painting and a professional, high-resolution print. A Relievo consists of a faithful reproduction of the front of the painting, as well as of the back and comes in a frame. During the production process, experts of both Fujifilm and the Van Gogh Museum closely monitor highly rigorous quality checks. Size, colour, brightness and texture are reproduced as accurately as possible to create a full-scale premium 3D replica of a Van Gogh painting. The final result has been approved by the curator of the museum" (http://www.vangoghmuseum.nl/vgm/index.jsp?lang=en&page=327966).

This diffusion of 3D digital replicas of archaeological sites and monuments has fostered the discussion on the real value and nature of those replicas between archaeologists and experts in heritage studies interested in the analysis and preservation of the excavation process and material remains. Is it possible to generate a tangible heritage's copy that comprises its "aura"?

Recently Bruno Latour and Alan Lowe proposed to imagine the migration of the aura in the reproduction or reinterpretation of the original (Latour and Lowe 2012: 283). They underline the obsession of the age for the original, and how this obsession increases as more accurate copies of the original are available and accessible. Latour and Lowe argue that "the real phenomenon to be accounted for is not the delineation of one version from all the others but the whole assemblage of one−or several− original(s) *together with* its continually rewritten biography" (Latour and Lowe 2012: 278). They move the attention

in their analysis from the common question−"is it an original or merely a copy?"−to another more decisive question, especially in a time of digital reproduction−"is it *well* or *badly* reproduced?" Latour and Lowe theorize that:

> To say that a work of art grows in originality thanks to the quality and abundance of its copies, is nothing odd: this is true of the trajectory of any set of interpretations (Latour and Lowe 2012: 279)…" [F]acsimiles, especially those relying on complex (digital) techniques, are the most fruitful way to explore the original and even to help re-define what originality actually is (Latour and Lowe 2012, 278).

According to Latour and Lowe, three main factors are essential for the determination of a replica's originality: the re-location of the copy in the original context; the availability of the original; the reproduction of all the surface features (Latour and Lowe 2012: 285-86).

But what happens when these three elements are reconsidered in respect to 3D digital heritage reproductions? Does the presence of all the three elements also increase originality of 3D replicas of archaeological sites/monuments?

The first aspect, the re-location of the 3D replicas of archaeological sites and monuments, is achievable through the use of 3D technologies. The 3D reproduction of a site/monument can be visualized on site and allows comparison between the original monument and its 3D copy. There are several preservation projects which use 3D replicas to monitor the physical decay of tangible heritage over time (Gruen et al 2002; Kuzminsky and Gardiner 2012; Sanz et al 2010). But the real added value of 3D replicas of archaeological sites and monuments is the multilocation. These reproductions can be visualized and analysed by multiple experts through the web, and favor new interpretations of the same context. But the internet and cyberspace do not allow for re-location of the 3D replicas in the real physical context, preventing the attainment of the first factor for adding originality to the copies. In fact, cyberspace only allows for the virtual re-location of the site/monument in a 3D reconstructed simulation of the original context, which cannot give the comprehensive sensorial experience of the real landscape.

The second element of originality is *availability*. In the last few years, rapid urban development has forced archaeologists to quickly collect all the information on the ancient

sites before they are to be covered again, and disappear under modern buildings. An example is the Cuizhuyuan, also known as Green Bamboo Garden tomb (M1). This Western Han Dynasty mural tomb was acquired in three dimensions within the "Virtual Museum of the Western Han Dynasty Project" (Di Giuseppantonio Di Franco and Galeazzi 2013: 346; Fig.). The second tomb acquired, the Xi'an University of Technology mural tomb (M27), is still accessible, but because of the precarious condition of the frescos, cannot be open to the public (Galeazzi and Di Giuseppantonio Di Franco 210: 97). In fact, the paintings inside the tomb are disappearing because of the critical conditions of plasters and colours. Since they are made over a very thin layer of clay, directly applied on the bricks composing the structure, their removal from the walls and preservation inside a museum is impossible.

For these tombs and other world heritage sites and monuments that cannot be open to the public because they are at risk, 3D technologies are of extreme importance, because they permit the preservation of the monument through the digital documentation and allow the visualization of the metrical copy in virtual exhibits that can be easily reproduced in different parts of the world. In absence of the real, the delocalized facsimile provides appropriate access to the public, while keeping the real site/monument safe and accessible only to the small number of specialists who require such access for continued study and monitoring.

For an increasing number of sites, the 3D copy provides the only means of public access. Moreover, 3D replicas allow a superior visualization of the site/monument because they do not carry the physical constraints of the real. The 3D virtual space gives users the opportunity to explore challenging archaeological contexts which would otherwise be difficult or impossible to access, such as remote areas in recesses of caves or subterranean tombs.

The third element of originality is the reproduction of surface features. Two main factors prevent 3D replicas from perfectly reproducing the surface features of tangible heritage: the first one resides in the impossibility of producing an objective copy of the real. In spite of the fast development of 3D technologies for the documentation and reproduction of archaeological sites/monuments today, it is not possible to produce 3D

copies/replicas of the real that are objective in all its parts. The 3D reproduction process is characterized by different steps, such as data collection onsite, data processing, and data visualization. The role of the operator is still necessary in all parts of the procedure, making the process subject to operator choices:

- During the 3D documentation onsite, the operator decides the resolution of the acquisition and how to acquire the scans and images that will be used for the creation of the 3D model (i.e. position, the best acquisition time during the day, etc.).
- For the laser scanner data processing, the operator decides the best scans for the alignment, which parts of the scans are unnecessary for the final 3D model, the filters to apply on the scans, etc. For the image data processing he selects the images and chooses the different parameters for the processing. For example, as shown in chapter 4, it is possible to select the number of faces of the final 3D model affecting its accuracy.
- Moreover, the role of the operator is crucial in the optimization of the processed 3D model for the visualization of the 3D replica in an interactive visualization system. He decides the tools to be used and the extent of the 3D model's optimization.

It is clear from this description that, although there is currently a movement toward total automation of the process, the 3D reproduction of real archaeological sites/monuments is still subjective. For this reason it is not possible to reproduce objective copies/replicas of the real.

Secondly, while assuming the possibility of reproducing an objective replica in terms of shape, color, and texture, it is still not yet feasible to reproduce copies that give people the same sensorial experience of the real. But is the reproduction of the real really central to the documentation, analysis and preservation of archaeological sites and monuments?

The real value of 3D replicas of archaeological sites and monuments does not reside in the creation of the objective and perfect copy of the original, but in the ability that these 3D copies give to researchers to analyze and interpret, and to students and general public to understand, cultural heritage. 3D technologies play a fundamental role in the preservation and dissemination of cultural heritage.

However, preservation and dissemination are not the only positive aspects related to the use of 3D replicas of archaeological sites and monuments. There are other less recognized but extremely important aspects inherent in the use of these reproductions such as analysis and interpretation. Because of their digital nature, 3D replicas give new opportunities for exploration and analysis of archaeological sites. They increase dissemination, giving the opportunity for multiple scholars to analyze and interpret the same archaeological context. The *trajectory* of the work of art described by Latour and Lowe (Latour and Lowe 2012: 278) assumes new significance when applied to 3D digital reproduction of cultural heritage and the attempt to reproduce the "aura" of the real. The possibility of retrieving the aura from the flow of the copies has to be reconsidered today in relation to the web. In a discussion about the reproduction of text, Latour and Lowe argue how it is crucial:

> …to consider what happens to *the original* now that we are all inside that worldwide cut-and-paste scriptorium called the web. Because there is no longer any huge difference between the techniques used for each successive instantiation of some segment of a hypertext, we accept quite easily that no great distinction can be made between one version and those that follow (Latour and Lowe 2012: 283).

The internet and cyberspace increase diffusion of the reproduced context through multiple 3D digital replicas, which in turn can be reinterpreted and originate new 3D reproductions. However, while offline virtual applications may give the opportunity to analyze the virtual with the real object and context, online visualization systems totally detach the 3D replicas from the real. This detachment can represent a risk for the analysis and interpretation of the site/monument, since 3D copies do not substitute for the real but want to be an added value for the exploration of the surface features of an object. It is

crucial to be able to discriminate between good and bad reproductions through accuracy, understanding, and respect, and this is only possible with a punctual analysis that starts from the original, tangible heritage. The attention of the museums and archaeological sites' visitors has to be shifted "from the detection of the original to the quality of its reproduction…the word 'copy' need not be derogatory; indeed, it comes from the same root as 'copious,' and thus designates a source of abundance. A copy, then, is simply a proof of fecundity (Latour and Lowe 2012: 278)."

6.1.3. Reconstructing the past: original or fake

Three dimensional metrical replicas of archaeological sites/monuments are powerful tools for the analysis, understanding, and interpretation of tangible heritage, but only when accompanied by an accurate and transparent illustration of the 3D documentation process. These 3D replicas preserve the information digitally through time. This gives the opportunity to revisit 3D copies over the long-term by different scholars, favoring multiple interpretations of the site/monument based on new discoveries and technological developments. In fact, starting from the 3D metrical replica of archaeological sites and monuments facilitates activation of different interpretation processes and may result in multiple 3D simulations of the past landscape.

The reconstruction of the past is not a new phenomenon. Human beings have always interpreted and simulated the past. The wonderful etchings of the nineteenth century, such as those of Canina and Piranesi, are clear examples of reconstruction. Luigi Canina in the 1850s interpreted the Ancient Appia road in which he created "before" and "after" drawings of the ruins and reconstructions. He not only drew the existing remains of Rome, but also turned them into fantastic and visionary spaces, populated with fragments of disparate elements from many archaeological sites. His etchings are the result of his mental recollection of these elements that he reinterpreted and recreated in his own vision of Italian heritage and its past.

What is the origin of this human need to reproduce, reconstruct and simulate the past through its material remains? Baudrillard believes the first reason of this need for

reconstruction and simulation is the absence of the real, stating that when object and substance have disappeared, "there is a panic-stricken production of the real and the referential, above and parallel to the panic of material production" (Baudrillard 1986: 121). He states that this need for simulation brings to the production of hyperreality of culture that is the "cutting up", "regrouping", "interference of all cultures" and "unconditional aestheticization", all common practices in the contemporary traditional museums (Baudrillard 1994: 68).

Umberto Eco sees the need to preserve and celebrate the past in a full-scale, authentic copy, especially in United States, as the result of a philosophy of immortality as duplication. Thinking about what he defines as 'Fortress of Solitude', the full-scale reproduction of the Oval Office or the Lyndon B. Johnson Library, he affirms that:

> To speak of things that one wants to connote as real, these things must seem real. The 'completely real' becomes identified with the 'completely fake'. Absolute unreality is offered as real presence. The aim of the reconstructed Oval Office is to supply a 'sign' that will then be forgotten as such: the sign aims to be the thing, to abolish the distinction of the reference, the mechanism of replacement. Not the image of the thing, but its plaster cast. Its double, in other words (Eco 1986: 6-7).

In his hyperreality journey in the United States, Eco tried to underline where the North Americans' imagination "demands the real thing and, to attain it, must fabricate the absolute fake; where the boundaries between game and illusion are blurred, the art museum is contaminated by the freak show, and falsehood is enjoyed in a situation of 'fullness', of *horror vacui*" (Eco 1986: 8). The examples go from the Johnson Oval Office and the reproduction of the drawing room of Mr. and Mrs. Harkness Flagler, where the living room was inspired by the *Sala dello Zodiaco* in the Ducal Palace of Mantua, the ceiling was copied from a Venetian ecclesiastical building's dome, and the wall panels are in Pompeian-pre-Raphaelite style in the Museum of the City of New York, to the Las Vegas copies of the European roots and the incredible numbers of Wax Museums spread all over the United States (Eco 1986: 10-21).

One of the most incredible representations of Eco's 'Fortress of Solitude' can be found in central California, where William Randolph Hearst built his own 'castle' (fig. 76a). In 1865 he purchased 40,000 acres of ranchland and bought palaces, abbeys, and convents in Europe. They were dismantled, packaged and shipped across the ocean to be reconstructed on his California hill. The core of his residence was the 'Casa Grande', a Spanish style cathedral with two towers, whose portal frames an iron gate that was brought over from a sixteenth century Spanish convent (fig. 76b).

The floor of the vestibule contains a Pompeian mosaic. The door into the Meeting Hall is by Sansovino. The great hall is fake Renaissance style presented as Italo-French. The Refectory has an Italian four-hundred-year-old ceiling, and on the wall, there are banners of an old Sienese family. An authentic Richelieu bedroom is in the master bedroom, and a Gothic tapestry adorns the billiard room. This is only a small part of the long list of furniture and architectonical elements that decorate the Hearst house. Today the 'castle' is a State Park and is presented to the general public with the slogan: "Hearst Castle. Building the Dream".

Hearst guests could enjoy swimming in an outdoor 'Neptune Pool' (fig. 77a) and an indoor 'Roman Pool' (fig. 77b), exploring wonderful gardens, and staying in the 'Casa del Sol', an 18-room guesthouse facing the majestic Pacific Coastline.

Figure 76. Hearst Castle: a. Aerial view; b. 'Casa Grande'.

Figure 77. Hearst Castle: a. 'Neptune Pool'; b. 'Roman Pool'.

But what was really the original nature of this project? This is not an example of a copy of the real. In Hearst's mind there was not the intention to perfectly reproduce European monuments, but the egocentric desire to build his own simulacrum of success by using, in a discretionary way, different artifacts and bricks coming from the European past. According to Eco, the place is characterized by "the obsessive determination not to leave a single space that doesn't suggest something, and hence the masterpiece of bricolage, haunted by *horror vacui*, which is here achieved" (1986: 23). More than Hearst's nineteenth-century aspiration of monumentality, the actual musealization and presentation of this monumental residence is objectionable. The State Park guided tour and website emphasizes an old style and colonial idea of power. As underlined by the slogan ("Hearst Castle. Building the Dream"), everything is possible with the right motivations, including indiscriminately destroying monuments to build your own residence, following the example of the magnate and great man William Randolph Hearst. The presentation and communication of Hearst Castle is aimed at telling the story of a man who become famous thanks to the "American Dream", but also stresses old-fashioned colonialist attitudes that can be extremely dangerous in the formation of following generations' social consciousness, since they highlight a lack of respect for heritage preservation.

6.1.4. Fake vs original: from the physical to the digital

Canina's etchings are a perfect example of Lowenthal's idea of the past: "the benefits the past confers vary with each epoch, culture, individual, and stage of life" (1985). Cultural tangible heritage is the physical representation of the past, and its interpretation depends on the perspectives through which it is viewed. Heritage symbolic meaning mutates when epoch, culture, or individual changes, but it also appears differently each time we visit it (Dave 2008: 41). For this reason, it is fundamental to create different interpretations of heritage not only to communicate its shape and texture, but also to allow the different relationships that people coming from different cultural backgrounds may have with it.

What has changed with digital technologies in the reconstruction process? The added value of the virtual is the interactivity. Whereas with the "old technology" it was possible to do just one interpretation, one reconstruction, one visualization at a time, with the new technology, it is possible to create, analyze and interact with multiple 3D reconstructed environments. It is possible, in fact, after having built a personal reconstructive model charged with all the particular knowledge, to compare it with other simulations of the same past environment.

The creation of different possible interpretations and virtual simulations of the monument and its context can activate a process of multivocality in the interpretation process of our cultural heritage. Multivocality is one of the main and most important aspects in the understanding of our past's cultural and social dynamics and in the attempt to increase the objectivity of their interpretation (Hodder1997: 694). Multivocality permits us to improve our knowledge of the landscape/site and increase the objectivity of the scientific interpretative act (Hodder1997: 694). In this sense 3D reconstructions and virtual environments can be challenging in the simulation of the original context of ancient remains. Working on the creation of as many interpretations as possible, these innovative tools allow, in fact, to increase the objectivity in the interpretation and reconstruction process.

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An example of this phenomenon is the 3D reconstruction of the Canina's etchings. Canina's interpretation of the ancient roman road was recreated and reinterpreted in 3D and visualized in an immersive virtual reality system together with other visual interpretations of the same heritage: the 2D Canina representation (fig. 78a); the 3D immersive environment reproducing the 2D Canina etching (fig. 78b); the contemporary landscape (fig. 78c); and the 3D simulation of the contemporary landscape, surveyed using 3D technologies (fig. 78d; Forte et al. 2004).

Figure 78. Virtual reality system of the Ancient Via Appia; 3D reconstruction realized using Canina's etchings.

Three dimensional modeling has the potential to partially solve the problem of the irreversible and destructive nature of archaeology. 3D technologies allow us to record and to reconstruct archaeological sites through a simulation process which provides, not the absolute representation of the ancient remains, but only one possible interpretation.

Three dimensional reconstructions and immersive environments, in fact, allow the simulation of multiple, different pasts, giving users the opportunity to navigate within this interpreted reality and have an embodied experience.

But a fundamental question arises from these considerations: how should we consider these digital and virtual simulations? Are they original digital representations of our cultural heritage or just virtual 'fakes'?

The attempt to find an answer to this challenging question is necessary, since in the last twenty years the phenomenon of fake reconstruction has become digital. With the development of new technologies, the physical fakes, such as the Hearst Castle, have been substituted by digital fakes. The number of 3D digital simulacra is continuously increasing, resulting in the first moment in the history of new technologies in which the aesthetics of models, and not scientific accuracy, was the only important aspect. For this reason, a large number of 3D reconstructions of ancient monuments and archaeological sites are spectacular but inaccurate reproductions, since they lack scientific accuracy. According to Maurizio Forte, this 'wow factor' should give way to methodological advancements which consider the accuracy and the information the 3D models conveyed (2008b: 24). For this reason the 'transparency' of the analytical process of study must be a fundamental aspect of the ontology of this simulation process (Forte 2009: 58).

Both of the examples analyzed, Canina's etchings and the Hearst Castle, are fakes and incorrect representations of monuments' and material culture's original context. But the difference between these two case studies consists in the 'transparency' of the reconstruction process. In fact, while the 3D reconstruction of the Canina etchings simulates a possible original context −the artist's mental interpretation of the ancient Appia road− the Hearst Castle is just a collection of decontextualized objects that don't allow the understanding of their possible original environment.

Baudrillard describes the contemporary world as a simulation which does not admit "originals, origins, *real* referents" but just the "metaphysic of the code" (Baudrillard 1983: 116). Similarly, in his writing on hyperreality Umberto Eco destructures the boundaries between the copy and the original, or between sign and reality, to deconstruct the conception of authenticity. Eco gives Disneyland or Disney World as the most typical

example of hyperreality. Since this world is born out of imagination, and there is no original to which to refer, the debate about its "real or false" nature appears irrelevant (Eco 1986: 8). But what about the mind and mental process that developed the constructed world, in this case Walt Disney?

The Canina etchings described in this dissertation are perfect examples of what mental interpretations can bring to the creation of new worlds. Considering Eco's statement, these etchings cannot be considered originals (Eco 1986: 8), but neither can they be considered fakes, since they are the result of an original process: Canina's interpretation. In this sense, the etchings can be likened to Baudrillard definition of simulacra: something "not unreal…, never exchanged for the real, but exchanged for itself, in an uninterrupted circuit without reference or circumference" (Baudrillard 1994: 6).

So should we consider the Canina etchings 'original fakes'? There is space, in fact, for a double interpretation of the Canina etchings. If we consider the etchings in relation to the past original context, we can state that they are 'fakes', since they are not a good scientific simulation of the original. But what happens when we consider the third element, Canina's mental interpretation? Canina's mental interpretation cannot be considered hyperreal in Baudrillard's sense, "a real without origin or reality" (Baudrillard 1994: 1), since it is possible to find its origin and reality in Canina's mind. Therefore the etchings can be considered 'original' to Canina's mental interpretation and 'fake' to the past original context.

Scholars are debating on the authenticity of 3D digital reproductions in heritage and archaeology (Bendix 1997; Benjamin 1968; Orvell 1989; Trilling 1981), but there are no clear guidelines for the definition of 'authentic' cultural heritage. This is because it is not possible to create universal predetermined categories in the definition of the 'authentic'. The concept of authenticity changes when the individual, culture, and time changes. More than defining the absolute 'authentic', we should probably consider the relative 'authentic'. This is the 'authentic' coming from our subjective mental interpretation of the cultural heritage, stressing and underlying the process that allowed the interpretation through the analysis of the scientific data. So the transparency in the interpretation process can help us to define the 'authentic' in a subjective and relative more than in an objective and absolute sense.

The mural paintings of the Western Han Tomb M27 represent a clear example in this sense. The frescos contain a very complex interpretation code, which shows the symbolic relations between life and death during the Western Han dynasty. Both the simple description of the subjects and the 3D virtual reconstruction of the tomb are insufficient for approaching its correct cultural interpretation. For this reason, a 3D virtual cybermap was created. The cybermap (or hypertextual map in three dimensions) is the graphic layout of a set of relations between each scene and its context. Interacting with it, users are able to acquire as much information as possible on the tomb's iconographic apparatus (Galeazzi et al. 2010: 97-108. Fig. 79-80).
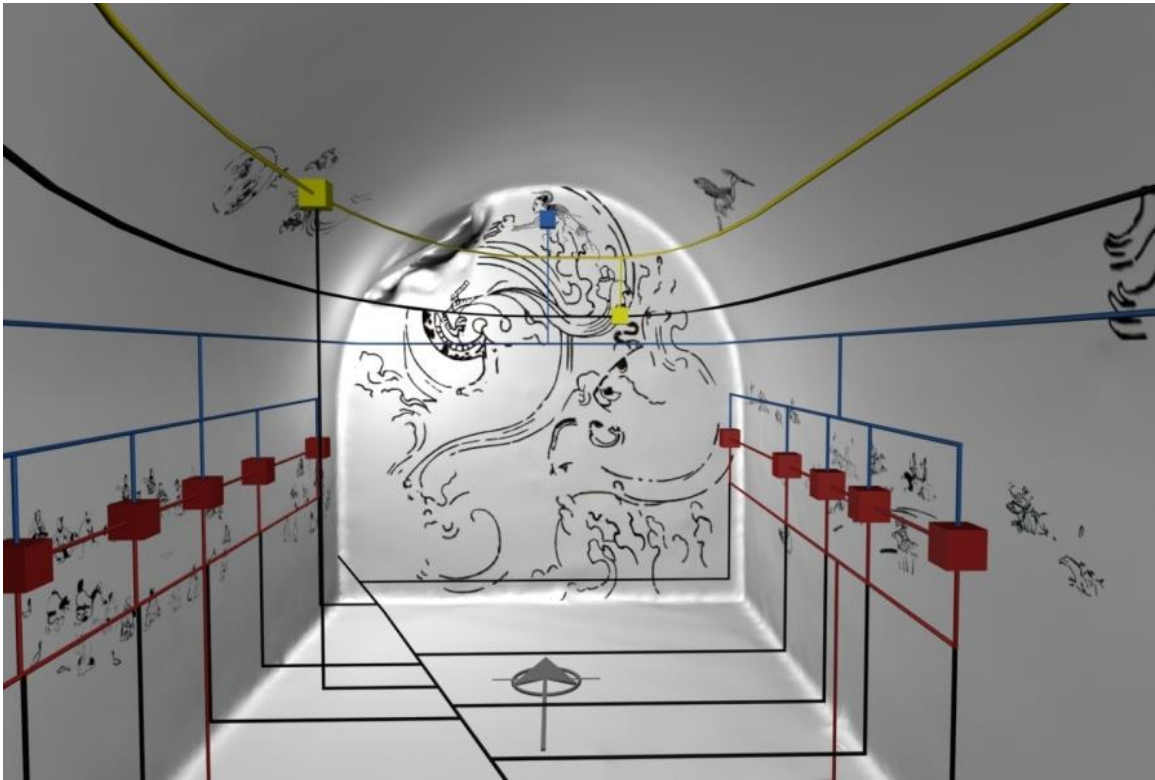
Figure 79. Cybermap of the Western Han mural tomb M 27 (Xi'an, China); 3D model mapped with the drawings made by archaeologists.

The main goal in this kind of virtual reality system is to build a cybermap of affordances that involve the users to such an extent that it reduces their perception of being in an artificial world. James Gibson defined affordances as all the "action possibilities"

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latent in the environment, objectively measurable and independent of the individual's ability to recognize them, but always in relation to the actor and therefore dependent on their capabilities (1979).

In this kind of approach, the user is no longer an external observer; he is not passively in front of the archeological material culture. Instead, he or she is a protagonist in the cultural process and participates in an active way in the knowledge system.

In the 3D reconstruction, every scene represented in the frescos was translated in a simple object (a cube). The creation of connection between the scenes (cubes) highlighted their spatial relations. Moreover a color was assigned to each theme to show the spatial location of the four themes in the tomb (daily life/red; ascension to heaven/blue; five phase/yellow; Yin and Yang/black; see Galeazzi et al. 2010 for a more detailed description of the M27 cybermap).

Figure 80. Cybermap of the Western Han mural tomb M 27 (Xi'an, China); 3D model mapped with the drawings made by archaeologists, overlapped with the tomb high-resolution pictures.

The rigorous analysis of the scientific data allowed the subjective interpretation of the frescos, and the definition of the narrative that is described in the mural tomb's iconographic apparatus through four main themes (Loewe 2005: 38-43; Hardy et al 2005: 5-6):

Daily life/red: symbolizes the social status of the owner, and testifies the introduction of Confucianism as the official imperial doctrine (Loewe 1970; 1982). The scenes are also symbols of earth and mortality. They are painted on the two lateral walls of the tomb. On the eastern wall there are hunting scenes underlying men activities; on the western one there are nightly activities as scenes of banquet, where mainly women are represented.

Ascension to heaven/blue: on the northern wall (opposite to the entrance), the yuren stands waiting for the deceased for the immortal life transfer. The yuren is the means of this transfer. The trip symbolically starts from the entrance where, on the two sides, are guardian animals (tiger and dragon) defending the sacred place from intruders. It continues with the daily life scenes, then with yuren on the northern wall, and ends on the ceiling where heaven is represented.

Five Phases/yellow: this path is designed on the ceiling, where the red bird, green dragon, black snake, and white tiger define a map themselves, being symbols of cardinal points. The path shape is circular, and it describes a continuous movement, defining a circular conception of time (eternal repetition).

Yin and Yang/black (Kohn 2000): following this path the tomb can be divided in two triangles, where the vertices are cardinal points: the South-East/North-East/South-West triangle represents the yang (light, male, day); the South-West/North-West/ South-East triangle represents the yin (dark, female, night).

The interpretation of the narrative described in the frescos can be considered 'authentic' not in an absolute sense, since we do not have enough elements to reconstruct the motives that led to the creation of the frescos (absolute 'authentic'), but in a relative sense, creating our subjective scientific interpretation of the painter's mind (relative 'authentic').

6.2. 3D visualization and analysis of the archaeological record

6.2.1. Immersive visualization systems in research

The role of immersive visualization systems has become a major theme in the 3D reconstruction of archaeological sites. Virtual reality systems and collaborative virtual environments (CVE) can involve the users in a collaborative learning process between them and the environment. A collaborative virtual environment is an application that uses a virtual environment to support human-human and human-system communication. Within such virtual environments, multiple users can convene, communicate and collaborate. The interaction with the different virtual 3D reconstructions can, in fact, increase our understanding of cultural heritage through experience and presence in the virtual environment.

According to Francisco J. Varela, Evans Thomson, and Eleanor Rosch, it is fundamental to study human cognition as embodied experience because the human mind is an embodied mind: "using the term embodied we mean to highlight two points: first, that cognition depends upon the kinds of experience that come from having a body with various sensory-motor capacities, and second, that these individual sensory-motor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context" (1991: 172-173).

John V. Draper, David B. Kaber, and John M. Usher identify three types of presence in the literature: simple, cybernetic, and experiential. The first is simply the ability to operate in the virtual environment, and the second is concerned with aspects of the human-computer interface (Draper et al. 1998). But the third, the experiential, is probably the most influential in the creation of an immersive simulation for the users. This is the same sense of presence defined by Mel Slater and Anthony Steed as "a mental state in which a user feels physically present within the computer-mediated environment" (2000: 414).

Franceso Antinucci agrees that in this kind of immersive system the central aspect is the experience (2004). When we can see and touch things, we use our preferred learning system that is based on perception and action. On the other hand, if we cannot perceive and touch, we use another system – that of the word, of the abstract and conventional symbol. The first one, the sensory-motor, is more powerful than the second, the symbolic-reconstructive. This is because ancient artifacts and works of art "are fundamentally visual objects, and any verbal treatment of them implies a translation of their most essential intrinsic characteristics, which are of a visual and perceptual nature, into a textual form" (Antinucci 2007a-b: 84).

The reproduction of 3D ancient landscapes and the creation of immersive virtual spaces that increase users' sense of presence are not sufficient to the development of an effective immersive 3D visualization system. A key aspect is the creation of a map of information in the virtual space that can help the user to obtain extra information from the 3D models and environment in real-time. This is possible using just the two main aspects involved in the creation of immersive 3D viewers for the analysis of the archaeological records: the archaeological contents that the users will visualize in the viewer; and the way in which the contents will be visualized, that is, interface and media (text, picture, video, etc.).

An example in this sense is the immersive visualization system of the Western Han mural tomb M27 developed and implemented in the powerwall visualization and motion capture facility at UC Merced, available thanks to the collaboration between the World Heritage program and the Computer Graphics Lab (Galeazzi et al: 2010: 103; Camporesi and Kallmann 2013; fig. 81).

The powerwall is a large, high-resolution display wall owned by the University of California Merced and used for projecting large computer-generated images. The powerwall is complemented by a Vicon full-body optical tracking system that allows full-body immersion in a virtual environment. The Vicon system permits interactive real-time motion capture interface that allows non-skilled users to model realistic upper-body actions and gestures by direct demonstration. In other words, with the use of the Vicon it is possible for on-line virtual humans to perform learned actions and gestures precisely,

in a more realistic and fully immersive virtual excavation context. "The Powerwall is retro-projected (4.56m by 2.25m) and consists of seven commodity Linux-based rendering nodes (Pentium Q9550 2.83GHz GeForce GTX 280 4Gb RAM), twelve projectors with circular passive polarization filters (1024x768px resolution each), an external windows device server, and a Gigabit Ethernet" (Camporesi and Kallmann 2013).
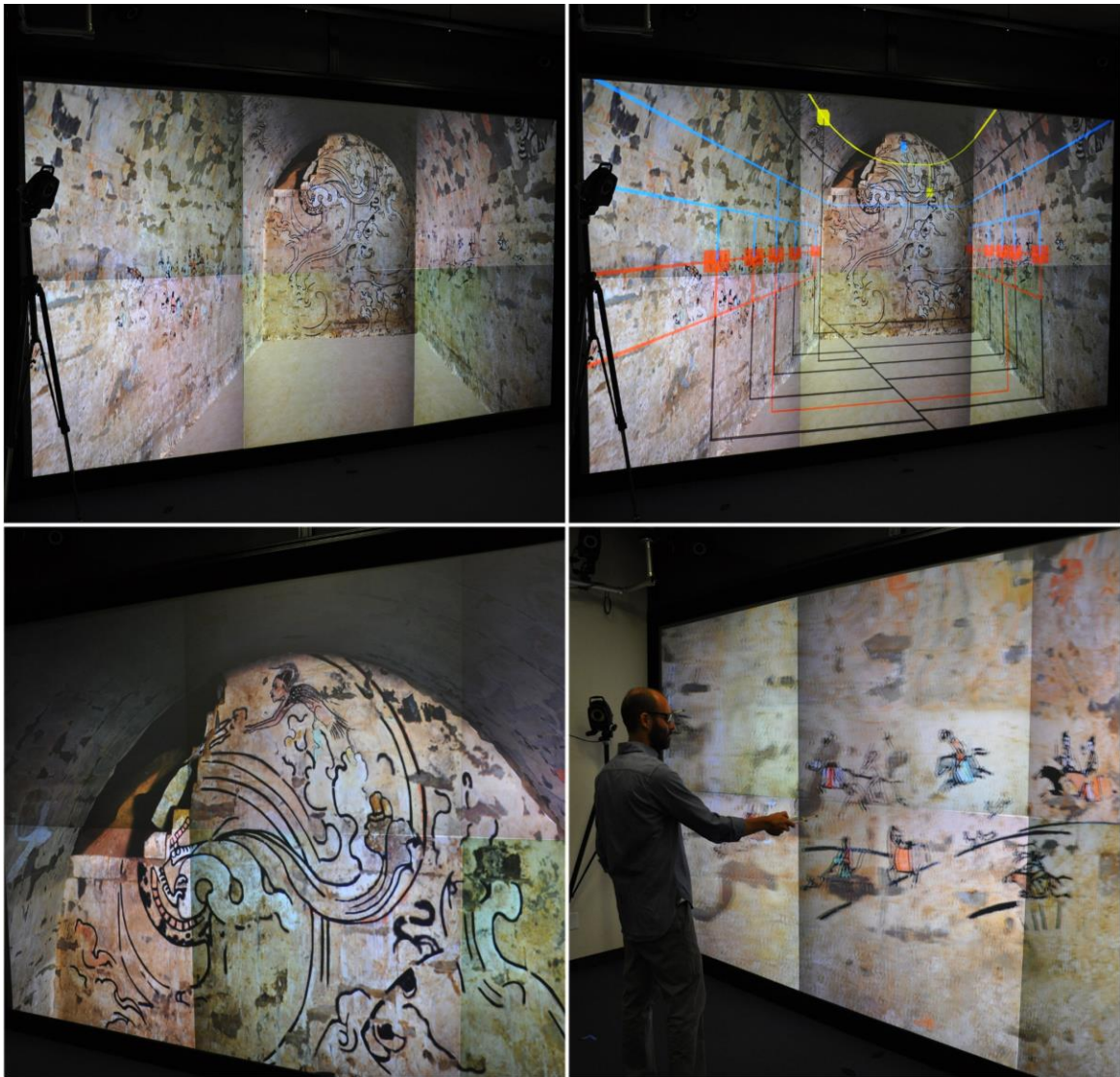
Figure 81. Cybermap of the Western Han mural tomb M 27 (Xi'an, China): powerwall visualization and motion capture facility at UC Merced.

The idea for this work originates from the fieldwork. The paintings are realized on a white clay stratus which hides the material support, giving the sense of an immaterial whole with intangible boundaries constituted by the frescos' contents and spatial and semantic relationships.

The understanding of the tomb's contents is possible just by removing those intangible boundaries through a simulation process that allows the potential semantic re-composition of the tomb, creating new metaphors of learning and communication. The iconographic complexity of the tomb frescos requires a cybernetic approach that could permit the decoding of the individual representations and their pragmatic relations. Thanks to the cybermap, it is possible to underline the strong symbolism that springs from the scenes.

The tomb is the logical and practical result of the revolutionary historical moment in which it was built −the end of the Western Han Dynasty−, and its paintings partially narrate and describe this period. They are visual narratives composed by scenes and themes. It is well known that the human brain compensates for its inability to process all the visual elements of a scene simultaneously. As our eyes move from one point to another, the brain creates a continuous narrative that is perceived as a seamless whole (http://www.moma.org/visit/calendar/exhibitions/304).

The cybermap facilitates this function by guiding visitors in a virtual tour, showing the main iconographic themes and paths; therefore it helps people to recreate narratives, moving from one scene to another in the right sequence. We should think of human consciousness as emerging from the complexity of such optical narratives through cause-and-effect-models, graphs and timelines. For a century, the dominant view of the brain has been that of a simple "reflexive" organ. In this view, human brains are little more than input-output machines. But it has been demonstrated that neurons don't simply wait for incoming data to be activated. They are always active and choose whether and how to respond to stimuli (Ratey 2002: 110-114). John J. Ratey argues that the brain is: "a powerful prediction machine, continuously making elaborate mental maps of the world that are reliable enough to enable us to predict what lies ahead, both in space and in time" (Ratey 2002: 112). If the material monument represents the tangible remain of Western

Han heritage, the frescos' spatial relations are traces of its intangible one. The map schematizes the themes and simplifies the information.

"Pure Land: Inside the Magao Grottoes at Dunhuang" project is another example on how immersive systems enhance the definition of new strategies for rendering cultural content and heritage landscapes (Kenderdine 2013: 199).

Pure Land immerses visitors in the quintessential heritage of hundreds of Buddhist grotto temples (UNESCO World Heritage site), an art treasury abounding with murals, statues and architectural monuments. Using pioneering virtual reality technology, artists and scientists at City University of Hong Kong have developed an extraordinary new animated 3D experience. Visitors are immersed in a large 360-degree panoramic projection theatre that gives a true-to-life experience of being inside a cave temple and seeing its magnificent Buddhist wall paintings at one-to-one scale. (Fig. 82; https://www.academia. edu/5892049/Pure_Land_Inside_the_Mogao_ Grottoes_at_Dunhuang).

According to Sarah Kenderdine, the *Pure Land* panoramic visualization system allows both allo- and ego-centric interpretations simultaneously, where the "allocentric" perspectives are "those pertaining to a perceived, fixed external framework (that is, a reality that exists 'all around' and is distinct from oneself) and the 'egocentric' contains your relationship with a given object or frame" (Kenderdine 2013: 209).

Immersive visualization systems such as the *Western Han Mural Tomb M27* and *Pure Land* can provide a radically different way of thinking about the past in the present. These immersive display systems promote the visualization of the material/tangible heritage and all the aspects of embedded meanings found within the physical heritage. In fact, virtual space favors the creation of augmented reality visualization where the 3D replica of the real object is supplemented by a set of information (text, picture, video, etc.) that can enhance the understanding of the intangible aspects enclosed in the tangible heritage.

Figure 82. *Pure Land: Inside the Magao Grottoes at Dunhuang* immersive system (Kenderdine 2013).

6.2.2. 3D visualization systems in education

The previous paragraph showed how immersive 3D visualization systems, such as the powerwall, are fundamental instruments for the analysis and interpretation of the archaeological record. It is crucial to understand how these technologies can positively affect not only research but also higher education, representing a bridge from traditional coursework to fieldwork. To this purpose, the project described in this paragraph, "3D Virtual Dig" (Di Giuseppantonio Di Franco et al 2012), demonstrates how 3D interactive visualization systems, and more generally digital approach to laboratory work, can positively affect students learning.

It is quite well recognized that knowledge acquisition can be greatly influenced by students' prior knowledge. A famous study published in *Physics Today* (Wieman and

Perkins 2005) shows how prior knowledge confuses or interferes with academic performance in physics. Social sciences are vexed by similar challenges. In archaeology, for instance, students begin coursework with ideas about the profession that are heavily influenced by mass media (Gale 2002; Russell 2002). Introducing expert ways of organizing knowledge in introductory archaeology courses could help students to recognize more readily how professionals actually work. Perhaps more importantly, this approach to teaching encourages students to master concepts, history, and theory in the discipline, with an emphasis on data analysis and professional methodologies.

A common strategy to engage students in critical professional thinking is problem-based learning, which is one among a few hallmarks of learner-centered teaching, and can be enacted either in a realistic laboratory activity or written exercise (Huba 2000: 37). This technique allows students to apply theories learned in class and demonstrate professional characteristics. When students try to think in archaeological terms, though, they face one challenge: engaging conceptually with excavation methods. In fact, assuming that an archaeological excavation can be described as a sensory and kinaesthetic material experience, it is difficult to communicate the physicality of fieldwork in traditional classroom settings. This initial conceptual struggle suggests that students at the introductory level need active engagement with the materiality of archaeology in order to master important concepts and subsequently to succeed in fieldwork opportunities.

The collaborative research on best practices for student success and digital lab conducted at UC Merced provides a practical challenge of implementing the principles and experiences of fieldwork, with a 3D application to simulate the archaeological excavation process to freshmen students (Di Giuseppantonio Di Franco et al 2012). An archaeological environment was virtually re-created in 3D, and allows users to work with the reconstructed excavation area by means of a virtual reality software application. The archaeological site virtually documented is Çatalhöyük, a Neolithic town in south central Anatolia, Turkey, which, in the 1960s, became the most celebrated Neolithic site in western Asia (Hodder 1997). The excavation is recognized as one of the most important in the world, and currently, Çatalhöyük is on the Turkish proposed list for UNESCO World Heritage Site status. The 3D application allows students to virtually excavate one of the

houses of the town, using the stratigraphic method. The 3D reconstruction is based on real data digitally recorded in the summer of 2010 by a team of students of heritage and archaeology, directed by Professor Maurizio Forte. The archaeological 3D digital data acquisition at Çatalhöyük was possible thanks to an agreement between the University of California Merced and Stanford University.

The advantage of this experimental and innovative project is that it allows lower-division or freshmen students to reflect on data collected during the fieldwork without losing the feel of the immediate, hands-on experience. In other words, the application provides a wide array of students with a simulation of the archaeological process. While a virtual reconstruction cannot activate the kinaesthetic intelligence needed for fieldwork, it can stimulate sensory-motor learning processes, complementary to traditional instruction in textbook or lecture formats (i.e. textual or symbolic-reconstructive learning processes). To put it another way, simulation promises to expand fieldwork experience and professional activities that are normally limited to a few students in upper-division course work. This technology or technical affordance (Gibson 1979) expands our ability to bring expert knowledge and organizing principles to lower-division coursework, ensuring a stronger pathway to success in critical thinking skills. The software was tested in class for teaching the basics of archaeological fieldwork. The application interface is user-friendly and especially intuitive for students, who now have frequent access to technologies such as computers, the internet, email, and mobile phones in everyday life (Waycott *et al* 2010: 1206).

At UC Merced, students of an introductory course are expected to be knowledgeable about two main excavation methods used by archaeologists, the *arbitrary method per levels* and the *stratigraphic method*. An associated learning outcome with this activity is a student solving ill-defined problems, which is characteristic of the high-order thinking in the field. As shown in previous experiences at UC Merced, students have problems with some crucial passages of the stratigraphic method. When looking at a 2D profile or picture paired with lecture notes, students struggle to identify the relationships between each layer in the profile, and subsequently to identify the relative chronology and create the matrix of the stratigraphy, based on Harris' *law of superposition* (Harris 1975). In particular, students struggle to identify a pit and its relationship with the layers that were cut to create the pit.

The application *3D Virtual Dig (3VD)* was grounded on the premises discussed above and realized thanks to a multidisciplinary collaboration between two archaeologists and a computer scientist. 3VD is the first educational application that simulates an archaeological excavation process in 3D. Unlike the other virtual applications available for teaching archaeology, 3VD reproduces a real archaeological excavation area in three dimensions. Students can work on the 3D reproduction of the stratigraphic units excavated in a mud-brick house at Çatalhöyük, Building 86. The excavation area was laser scanned, with highly accurate 3D digital representations that are readily shared, indefinitely reproducible, and cheaply and efficiently stored. This approach favors the preservation and data storage of a very detailed 3D reproduction of the layers that would otherwise be impossible, considering the destructive nature of the archaeological excavation process (see 5.1. fig. 33). 3VD is a real-time application, designed for classroom use to test the individual capacity of students to interact with a 3D representation of the archaeological context and determine the chronological relationships between units of an excavation area. Therefore, 3VD was not conceived for a collaborative environment (e.g. Forte 2008; Forte *et al* 2010) and/or a web-delivered application.

In the application students are asked to use the mouse to excavate layers in the right order (see Screencast). Every time a student fails the task, red colored text appears on the screen and reminds them of the law of superposition (Fig. 83a). Each time the students are able to virtually excavate a unit, green colored text confirms that the task has been accomplished, while on the left side of the screen, the matrix of the excavation area starts to be created (Fig. 83b).

The goal of the 3D application was to teach the basics of archaeological fieldwork and the stratigraphic method in lower-division classes. The software was tested with the students in *Introduction to Anthropological Archaeology*. The class was composed of 120 students, half of whom were freshmen and 20 per cent of whom were declared anthropology majors.
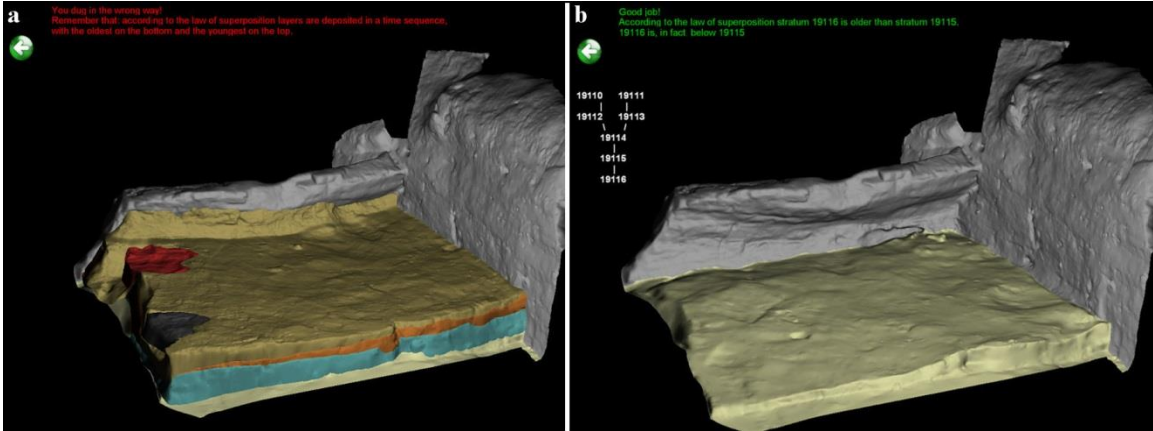
Figure 83. *3D Virtual Dig* application: a. Red colored text explaining why the user was not able to recognize the exact unit; b. Green text showing the user that the right unit was recognized and, therefore, virtually excavated.

Students were divided into two groups:

1. 3D group (60 students). The 3D group was given 40 minutes to work with the 3D application.

2. 2D group (60 students). The 2D group was given 30 minutes to create a matrix from the 2D profile of the same stratigraphic sequence used for 3VD; after 30 minutes they were given 10 minutes to check the key for the assignment, which contained an explanation of the stratigraphic relationship between the various units (same text used for 3VD).

After the training, the students' preparation was tested using an ill-defined problem. All students (2D and 3D groups) were provided with a 2D profile of a stratigraphic sequence and asked to answer multiple-choice and open-ended questions about the relationships between the layers in the stratigraphy and create a matrix based on the sequence.

Students in the 3D group were able to retain the information learned through 3D hands-on activities and use it in the test more than peers in the 2D group when they had to deal with the most challenging task, the identification of a pit and its relationship with the layers that were cut to create the pit, $X2$ $(1, N = 110) = 17.35$, $p < .0001$ (Fig. 84a).

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Moreover, when they were requested to create the matrix of the given stratigraphic profile, the 3D students apparently retained the information, strengthened this learning outcome, and applied it during the test more than their 2D, X^2 (1, N = 111) = 13.6, p < 0.001 (Fig. 84b).

The difference is probably due to the fact that in the 3D application the matrix of the stratigraphic sequence was created step-by-step, while the students recognized and then removed the layers.
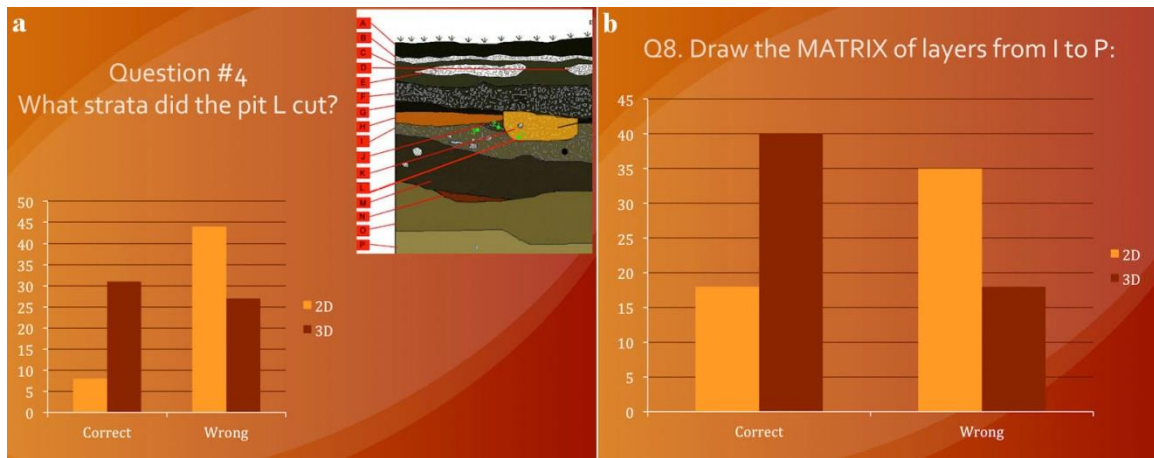
Figure 84. *3D Virtual Dig*: a. This graph shows the results of the test for question 4: *What strata did the pit L cut?*; b. This graph shows the results of the test for question 8: *Draw the MATRIX layers from I to P*.

Through this trial, it was demonstrated how, through a virtual environment, students could understand an archaeological context. The advantage of this experimental and innovative project is that it allows students to reflect on data collected during the fieldwork and grasp the materiality of this process. In addition, the virtual reconstruction of a real archaeological context can be more engaging than pictures and drawings.

There are some limitations to this application, though, such as the difficulty in activating a student's kinaesthetic intelligence. The materiality of archaeology, in fact, starts from a set of gestures that researchers make to interact with material culture. As David Kirsh points out (2010: 124), fieldwork, as well as any lab activity, gives researchers the possibility of interacting with objects and simulating behaviors that past people could have had with those objects. 3VD is not complete in this sense, because it lacks behaviors

(avatars) that could make the experience more immersive (Dell'Unto and Forte 2010). This is why 3VD at this stage should be considered more a work in progress, or a pilot study for a more comprehensive work. While repeating the test with a new set of students would reinforce the results of this research and provide additional information on the learning processes linked to 3VD, implementing the application for a virtual immersive environment would enhance the learning experience. After having demonstrated that 3VD is an effective learning tool, the next step would be to develop it via the powerwall visualization and motion capture facility available at UC Merced.

Even if this 3VD application does not fully provide an immersive experience and cannot activate a kinaesthetic intelligence, it can stimulate sensory-motor learning processes, complementary to textual or symbolic-reconstructive learning processes (Antinucci 2004a: 17; 2004b). In the sensory-motor learning process, students learn through perception and action about a historical reality. In other words, students perceive an event with the senses, act on objects, and change the perception of the event after the action. This second process is augmentative: the action can be seen as a cause producing an effect, which is a new action. In a reconstructed excavation area, students virtually interact with the archaeological layers and act on them (remove the layers). Every action helps students to develop a constructivist process, since they are able to investigate the virtual area and pose questions on the relationships between the units.

As a result, the application can be considered an effective means to teach archaeological excavation and its methods, and in a broader sense the 3D Virtual reconstruction of Çatalhöyük can serve as an important bridge from traditional coursework to fieldwork. More generally, it can be demonstrated that digital lab activities show the value of technological advancement for higher education. They help in the creation of an interactive environment in class, and are particularly engaging for 21st-century students.

6.3. Comparing 2D pictures with 3D Replicas for the digital preservation and analysis of tangible heritage

After comparing different 3D documentation techniques in chapter 5, and discussing the value of 3D replicas and simulations for the preservation and understanding of tangible heritage in chapter 6, this paragraph aims to test 2D and 3D reproductions/images using a set of cognitive experiments. The two experiments described in this paragraph aims to reinforce the discussion on the real value 3D digital reproductions of tangible heritage when compared to 2D digital images (chapter 6.1, 6.2). These experiments are part of a larger research aimed at understanding how media affect the perception of material culture (for a more detailed analysis, especially of experiment n. 2, see Di Giuseppantonio Di Franco 2014; Di Giuseppantonio et al. 2014).

6.3.1. Introduction

Two and three-dimensional images are alternatively used to digitally capture and visualize material heritage; yet scholars have to determine how these visualizations can differentially promote and/or influence deeper understanding of material culture.

According to Colin Wave, visualization can promote deeper understanding by facilitating the understanding of large amounts of data, promoting the perception of unanticipated emergent properties, highlighting problems in data quality, clarifying the relationship between large-scale and small-scale features, as well as helping us to formulate hypotheses (Wave 2004: 3).

Two-dimensional digital pictures are one of the primary methods for visualizing ancient artifacts and creating both off-line and online digital archives for study purposes. Pictures are a fast, simple, and cost-effective way of documenting, preserving and disseminating artifacts that are stored in museums or other remote storage facilities. Although 2D pictures usually provide suitable level of detail for visualizing artifacts, in absence of the real objects pictures cannot be considered an ideal reproduction to

understand innate qualities of objects that are crucial for understanding. For this reason, scholars are exploring the potential of 3D reproduction techniques for the creation of off-line and/or online digital archives of artifacts. Creating 3D digital archives can be time consuming and require multiple facets of expertise. In fact, a digital archive may include: 1. 3D documentation of artifacts; 2. Metadata information (text, pictures, videos, etc.); 3. Synthetic 3D reconstructions of missing data; 4. An online platform to access 3D data.

Based on the latter assumptions, it is important to understand both why and if scholars in the field of heritage should concentrate their efforts on the creation and management of 3D digital archives. In an article on 3D reproductions of prehistoric skeletal collections, anthropologists Susan C. Kuzminsky and museum curator Megan S. Gardiner, highlight the importance of 3D reproductions for preservation purposes. They visited 15 regional and national museums in North and South America and found that many museums still have antiquated or incomplete inventories of both artifact and skeletal remains (Kuzminsky & Gardiner 2012: 2747). Without accurate information on the artifacts, research becomes both difficult and time consuming, since scholars have to be able to locate and find the original artifact in museum storage to facilitate the completion of an accurate report or study of the objects in question.

The benefit of a 3D digital model is that it can be easily stored digitally (on a hard drive for example) and researchers can virtually manipulate the objects over time without the risk of damaging the real artifact due to multiple, sometimes unnecessary manipulations. 3D digital copies of artifacts also have the tremendous advantage of being remotely accessible, making them easier for scholars all over the world to study the same collection and share multiple interpretations of the same artifacts/contexts in real time.

Research on human cognition suggests that pictures are remembered better than words (Tversky 2000: 364), it is our hypothesis that, in the realm of archeological inquiry and examination, 3D media might be preferential to 2D pictures, because interaction with 3D objects mirrors the interactions we have in everyday life. These interactions take advantage of a complex sensory system afforded to researchers everywhere (Levy et al. 1996: 48).

6.3.2. Two and three dimensional archives for preserving tangible heritage: state of the art

Photography, and more often digital photography, is one of the primary methods of documenting, preserving and disseminating artifacts. Photographs are useful for conservation because they provide a fast, simple, and inexpensive way of documenting notable characteristics observed in artifacts. This is perhaps one of the reasons why archaeologists began utilizing photography surprisingly early for recording antiquities. At the end of the 19th century, with a reliable camera using bromide-gelatine emulsions (Dorrell 1989:1), Fox Talbot, British inventor and photography pioneer, but also antiquarian, took photographs of manuscripts, engravings and busts. Soon, in the latter part of the century, photography began, playing a major role in the development of a more scientific, analytical approach to recording and excavation. According to Peter Dorrell (1989:1-2), by the 1850s archaeologists had started to regard photography as a "panacea", mainly for its alleged objectivity.

The practice of photography in archeology was refined in the following years, when Mortimer Wheeler inaugurated the season of large-scale excavations, and pictures became necessary for intra-site comparisons of different excavation areas (Guha 2002: 98). Wheeler imposed a code of rules for site photography, using the camera as a scientific recording device. These regulations included using a measuring scale and removing the names of the photographers from the individual photographs, in the name of objectivity (99).

By the mid-1970s, photography in archaeology became more complex, including aerial photography, underwater photography, and even public audience of technical photographs (Harp 1975). Later, manuals also included infrared and ultra-violet photography, which were considered effective methods in archaeology and museum studies, since they enhance the visibility of material records.

By the early 1980s, archaeological photography had become, for the most part, standardized: the photo scale was now accompanied by an arrow to indicate north and a

photo board with the photograph's locale prominently displayed. Artifacts were photographed in isolation inside labs, with a neutral background.

While analogue photography was being standardized in archaeology, in 1969 Willard Boyle and George Smith, working at the Bell Laboratories in the USA, invented the Charge-Coupled-Device (CCD), which became commercially available in 1973. Since then, digital cameras have slowly substituted the analogue variety: Lindsay MacDonald (2006: 189) shows how in 2003 more than 100 million cameras were sold worldwide, of which approximately 46 per cent were digital and 54 per cent were analogue. These numbers seem to indicate that in 2003 for most users digital cameras had reached a level of performance where they could effectively substitute traditional analogue film cameras.

Digital photography provides the advantage of immediate feedback through the display, easy processing, copying and circulating of the digital images compared to images taken using a traditional film camera (for advantages and disadvantages linked to using a digital camera see: Rudolf 2006: 177-209). Moreover, digital photography allows for image editing, such as cutting and scaling, background alteration, or for adding digital scales, symbols, etc.

Another benefit of digital photographs includes their ability to be stored on computer hard drives or other inexpensive external backup devices. This affords material culture experts access to complete archives of archaeological sites and artifacts, as well as the excavation process. From digital models, curators can enhance their data collection procedures by recording information about the material data, sort their collections by site number and/or location, and share the digital records with other researchers. Nonetheless, Rudolf notes that while traditional film can endure more than 100 years if stored in a cool, dry and dark environment, digital photos have drawbacks with regard to longevity, since the technology necessary to read them changes rapidly, therefore digital image data must be duplicated and copied onto new media devices at regular intervals, intervals that usually do not exceed 10 years (Rudolf 2006: 190).

Digital cameras have made it possible to create and manage large collections of digital images and the advent of the Internet has created new opportunities for the use of digital imagery. In the last few years, collections of digital images with appropriate

metadata have been recognized as significant resources for heritage management. The Internet allows immediate access to exemplary corpora of digital images regardless of physical location of the viewer or data source. Some digital collections of pictures integrate information and documentation of excavation projects. A fine example of this technology is the Swedish Pompeii Project (http://www.pompejiprojektet.se/index.php), by the Department of Archaeology and Ancient History at Lund University, and the Çatalhöyük research project (http://www.catalhoyuk.com/) directed by Ian Hodder (Stanford University). Other collections of digital pictures give access to digital representations of artifacts stored in museum facilities: one notable example is the Cuneiform Digital Library Initiative (CDLI; http://cdli.ucla.edu/), which represents the efforts of an international group of Assyriologists, museum curators, and historians of science, made available through the Internet, digital images of cuneiform tablets dating from the beginning of writing, ca. 3350 BC, until the end of the pre-Christian era. More than 290,000 have been catalogued in electronic form by the CDLI, which is directed by researchers at University of California, Los Angeles.

As already discussed in the introduction to this paper, photographs provide images of artifacts that work well for documentation, however some scholars (e.g., Kuzminsky and Gardiner 2012) argue that 2D images are not ideal replacements, especially when the original artifact is unavailable for "hands on" viewing. As a result, 3D reconstructions of real objects have become a common method to analyze and study artifacts when the real objects are located in storage facilities that are difficult to access due to risk of damage of the real objects, physical distance between the object and the researcher, or institutional conflicts that prevent physical object viewing, etc.

Real object models can be reconstructed automatically using both active and passive methods. Laser scanning and structured light are typical examples of the active methods. One of the most significant advantages of laser scanners is their high geometrical accuracy.

The most used passive method, known as Dense Stereo-Matching Techniques (DSM), uses digital cameras located at different viewpoints to reconstruct a 3D model

using a structure-for-motion algorithm (i.e., photoscan). Passive methods are low-cost and useful when direct access to the object is prohibited.

The use of 3D technologies allow for the replication of real objects without the use of molding techniques, that in many cases can be more expensive, more difficult, or too invasive to be performed; particularly in cases where direct contact of the molding substances to the object could harm the surface of the original artifact.

Given all the technological advancements, 3D reproduction techniques offer affordable options to preserve artifacts and other cultural heritage and create large databases to share 3D digital data. An example of a 3D digital archive is provided by the Smithsonian foundation through the Smithsonian X3D initiative (http://3d.si.edu/), a web-based archive of artifacts, ecofacts, bones, etc., which is available for students and scientists to view free of charge.

New databases containing high-resolution 3D digital models are innovative tools that can be used by researchers to collect data tailored to specific research questions. (Kuzminsky and Gardiner 2012: 2749). Indeed, many things can be done with the completed 3D digital models.

Using software packages (such as Scan Studio) researchers can take screen shots of images, record points on objects, calculate surface areas and volumes, or make other precise measurements (Weber and Bookstein 2011).

Scanned images can also be used to reconstruct areas of objects that are structurally incomplete or damaged. For instance, in a recent paper, Sorin Hermon and others (2012), from the STARC Cyprus Institute, describe a case study in which they 3D reconstructed a fragmented vessel starting from the 3D scan of its potsherds found during an excavation in Cyprus.

Another advantage of 3D replicas is that they can be used to calculate surface areas and extract original profiles of an object from potsherds (Tocheri 2009; Karasik and Smilansky 2008). These profiles are indispensable components when studying specific categories of objects, such as wheel-produced ceramic vessels. In fact, through the analysis of 3D profiles, archaeologists can identify the correct axis of rotation of wheels, and this information is of extreme importance, since false positioning

(occasionally occurring through manual drawings) may lead to misinterpretations of objects (Griffiths and Wilson 1991: 51, 58; Joukowsky 1980: 423; Orton et al. 1993: 173; Rice 1987: 222).

Educational research suggests that digital representations are also effective means by which to introduce aspects of artifact study to large numbers of students, when they cannot access collections of original objects. The innovative CONTACT project (Doonan and Boyle 2008) was designed to provide students the opportunity to interact with 3D digital artifacts and enhance material culture studies in Archaeology. Doonan and Boyle (2008: 115) suggest that 3D digital collections of objects should be considered a perceptive aide memoire, which have the ability to partly maintain knowledge engagement beyond the classroom or museum.

A study conducted at the University of California, Merced, the 3D Virtual Dig project (see 6.2.2. *3D visualization in education*), reinforces the idea that 3D replicas enhance student learning. This project was aimed at the 3D reproduction of an archaeological environment, which was incorporated in a virtual reality software application that allowed users to work with a virtually reconstructed excavation area. This project allowed students to reflect on data collected during fieldwork without losing the possibility to interact with the archaeological context in the third dimension. The software was tested in classes with a total of 150 students. The study employed a pre/post-survey design to understand students' previous familiarity with archaeology as well as an examination component to assess student knowledge after the use of the 3D application. These results were then compared with students who studied using 2D reconstructions of the same environment. The results show that students studying with the 3D application demonstrated increased engagement and strengthened abilities to complete ill-defined problem sets (characteristic of the higher-order thinking in the field). Towards this end, here, we designed two experiments where we compared perception of real-life artifacts through either pictures or 3D virtual replicas.

Participants in Experiment 1 were randomly assigned to two condition groups: group 1 viewed digital picture of a statue, while group 2 viewed a snapshot of the 3D point cloud of the same statue. This experiment was aimed at understanding if by augmenting

the reality of an object that is, using different levels of perception of an artifact through digital reproduction, students would perceive this artifact differently. Interaction with digital copies of artifacts was not part of this experiment, since participants only viewed the snapshots/pictures.

Participants in Experiment 2 were divided in three condition groups: participants in group 1 actively interacted with the original artifacts; participants in group 2 viewed pictures of artifacts; and participants in group 3 3D replicas of artifacts. Participants in group 3 could interact with the 3D visualization and also had the option to see the objects with or without original colors applied on it (i.e., texture, mesh, point cloud, wireframe).

Participants' responses were analyzed for speech content, including words emphasizing innate qualities of the artifacts (including shape, material, color, weight, texture, and size). For the second experiment we also analyzed gesture content, including number of iconic gestures, which are depictive of actions, and other key elements in descriptions.

6.3.3. Experiment n. 1

6.3.3.1. Background

In the summer of 2010, a team of students and researchers, directed by Maurizio Forte, travelled to Xi'an, China, to reconstruct, in 3D, archaeological sites and artifacts of the Western Han Dynasty (1 sec BCE circa). The final outcome of this project was the creation of the Virtual Museum of the Western Han Dynasty, which displayed the most representative elements of this dynasty's culture (Di Giuseppantonio Di Franco & Galeazzi 2013, Forte & al. 2010). Our fieldwork included the 3D reconstruction of landscape and artifacts preserved at the Maoling Museum, in Xingping County of Shaanxi Province, where the tomb of the Han Emperor Wu Di (end of the 2nd cent. BC) is located. This museum had an open space area displaying monumental statues. One of these statues, the stone carving "Horse trampling the Xiongnu", particularly struck our

attention. This statue is preserved under a porch and a label reminds the visitors that touching it is forbidden.

The sculpture made using a local stone with a very light yellow texture that partially obscures both its perceived weight and volume, and represents a horse (symbol of the dynasty) fighting against a warrior (symbolizing the enemies of the dynasty) subjugated by the horse. The team particularly struggled to discern the warrior and no text, neither in Chinese or English, described the horse nor explained its importance. Pictures of the statue were taken and then the statue was scanned using a Riegl LMS Z390i. This laser scanner allows acquisitions with an accuracy of 6 mm for a range of 1-400 m.

The statue was scanned using a very high level of detail (8 mm), which allowed obtaining a very detailed point-cloud. After the scan, we noticed that the point cloud alone was able to impart information regarding both volume and detail, two qualities of the statue that were very difficult through real-life visual perception (mainly due to the material colors of the statue). Based on this experience, we decided to design and conduct an experiment to examine the perceptual differences between a picture of the statue with a snapshot of its 3D scanner generated point-cloud. We were interested in if the point-cloud would be able to enhance the perception of a real-life object and how the point-cloud could be used to improve a museum visitors' experience.

6.3.3.2. Participants, materials, and methods

In the first experiment, students at the University of California, Merced were randomly assigned to view one of two images of the Maoling Museum's horse statue: 1. Image 1 was a picture of the statue as exhibited on-site (i.e., in the Mausoleum; fig. 85a). 2. The second image was a snapshot of the 3D point cloud acquired during the 3D laser scanning acquisition campaign (fig. 85b). The level of detail of the point cloud was between 6 and 8 millimeters. In this experiment, students were asked to analyze the 2D images, but they did not really visualize the object in the 3D space.

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Figure 85. Maoling Museum (Xi'an, China). The horse statue: a. Picture; b. Point cloud.

One-hundred-fifteen UC Merced, undergraduate students volunteered to participate in this study for course related extra credit. All were proficient speakers of English, either native speakers of English or bilinguals with dominant English experience. All had normal or corrected vision. Data was collected online using Survey Monkey, one of the most popular tool for online surveys. After consenting to participate and reading the instructions (see text below) displayed on the computer screen, the students pressed a START button on the screen to start the experiment. Participants were randomly assigned to either the real-life picture condition (58 students) or to the 3D point cloud condition (57 students). The task was presented as follows: "In this task, your job is to look at the picture and answer the questions below. Take as much time as you need. Thank you for your cooperation". All participants answered 14 questions while viewing the associated image (either picture or point-cloud snapshot). All questions focused on innate qualities of objects (materiality, shape, texture and spatiality) in the attempt to understand if the perception of these qualities differed between the two conditions.

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6.3.3.3. Results

For this experiment, we conducted a preliminary analysis of verbal responses for each of the following questions:

Q1. What is the figure?

Question 1 aimed at understanding if the participants were able to recognize all features characterizing the sculpture. The results showed that most subjects (95.7%) were able to recognize the horse, but no one described the figure underneath it, with no difference between the 2 groups: X^2 (4, $N = 115$) = 5.14, $p = .27$

Q2. Please use the scale provided (1-7) to answer the question. How easy is it to recognize the image in this sculpture (1 being difficult; 7 being easy)?

On average, the majority of students felt confident about their level of perception and understanding of the artifact as a whole. In fact, the difference between the two groups was not statistically significant, $t(115) = 1.91$, $p = 0.06$. Participant judgments in the point-cloud condition (*M*=5.74, *SD*=1.55) did not reliably differ from participant judgments in the photograph condition (*M*=6.24, *SD*=1.275).

Q3. What is the figure made out of?

This question was aimed at understanding how participants in the point-cloud condition would overcome the absence of texture (color) to elaborate upon the material of the statue. The result was surprising, 63.2% of students who viewed the point cloud wrote that the statue was made of stone; this percentage was very close to the participant responses in the photograph condition (69%): X^2 (6, $N = 115$) = 19.57, $p = 0.003$. Even if the majority of participants in the point-cloud condition recognized the stone, 25.9% of them indicated that the statue could be made of cement, since they were visually influenced by the color of the limestone. Interestingly, the second most frequent response of the point-cloud group was clay (24.6%); this suggests that in absence original colors, students participants made reference to their background knowledge and real-life

experience (indirect perception) with this type of representation (horse-statues) to provide an answer to Q3. In other words, it seems that background knowledge influences the perception/description of material culture, when the medium limits the sensorial experience of people with objects.

Q4. Hedging about the material. How sure are you that this is the right material?
To calculate hedging about the material, all cases in which students gave multiple answers were considered, since they were not sure about the material.

Results of this question show a statistical difference between picture and point-cloud groups (93.1% vs 78.9): X^2 (1, N = 115) = 4.81, p 0.028. This statistical difference was to be expected, since the point-cloud group worked with an image lacking original colors. What is surprising, though, is that almost 80% of the students in the point-cloud group felt confident about their answers and this result is even more impressive if compared to the result of the previous question, reinforcing the idea that background knowledge influences the way people perceive material culture, in absence of a limited sensorial experience with it (e.g., the absence of original colors limits the visual experience with the statue).

Q5. Please use the scale provided (1-7) to answer the question. What is your impression of the image? (1 being weak; 7 being strong)
(Point-cloud students M=4.53, SD=1.197; picture students M=4.93, SD=1.543) t(115)=1.57, p=0.12.

Q6. Please use the scale (1-7) provided to answer the question. What is your impression of the image? (1 being passive; 7 being aggressive)
(Point-cloud students M=3.56, SD=1.524; picture students M=3.67, SD=1.49) t(115)=0.395, p=0.69.

Q8. Please use the scale provided (1-7) to answer the question. What is your impression of the image? (1 being cowardly; 7 being brave)

(Point-cloud students M=4.82, SD=1.571; picture students M=5.6, SD=1.256) t(115)=2.94, p=0.004.

Even if a significant difference was registered in Q8, it is possible to observe a trend, the picture group describes the statue as stronger, more aggressive and braver than the point-cloud group. This result could be interpreted in two different ways: 1. the point-cloud group, which seems to better recognize the warrior under the horse (as we will better understand with the following questions), focuses more on the whole representation, without favoring the dominant figure of the horse. On the contrary, the picture group, which mainly focuses on the horse in the description, define the statue with adjectives that are more related to this dominant figure and/or to a common idea we have on the horse as symbol of wildness, freedom, regality, and power. 2. The other explanation could be that since the picture is more realistic than the point-cloud, it enhances force, aggressiveness, and bravery of the horse that, as already pointed out, are characteristics commonly associated to this animal.

Q7. Please use the scale provided (1-7) to answer the question. What is your impression of the image? (1 being light; 7 being heavy)

Using a Likert scale this research wanted to understand which medium better enhanced the perception of density and weight of this artifact in question. The results show that both groups expressed their preference toward the adjective heavy (point-cloud: *M*=4.33, *SD*=1.618; picture: *M*=5.03, *SD*=1.747). This result has two possible explanations: this could reinforce the idea that students' answers are influenced by their material understanding idea of the statue; alternatively, this result could refer to point-clouds as effective means to stress not only texture and physical details, but also density and solidity of artifacts. Nonetheless, participants in the point-cloud condition perceived the statue as significantly heavier when compared to the participants in the picture condition, $t(115) = 2.232, p = 0.03$.

Q9. Please use the scale provided (1-7) to answer the question. What is your impression of the image? (1 being Lifeless; 7 being lively)

Examination of these data show a significant difference between the two groups (point-cloud: *M*=3.96, *SD*=1.57; picture: *M*=3.24, *SD*=1.58), $t(115) = 2.46, p = 0.015$. Participants in the point-cloud condition judged the statue as more lively, compared to the participants in the photograph condition. This result could be explained by the fact that the point-cloud better highlights the physical details of the horse (e.g., muscular structure) emphasizing the action represented by the statue (i.e., the horse prevailing over the warrior).

After reading the results of the last question, all descriptions of the statue were analyze, to see if the provided figures were described with an emphasis on space. As a result, the participants in the point-cloud condition exhibited an increased sense of spatiality in describing the statue when compared to participants in the photograph group (76.9% of the VR described the object stressing its spatiality versus just 23.1% of the R; fig. 86): X^2 (1, N = 115) = 10.059, p 0.002.

Q10. What do you see under the horse? Is what you see easy to recognize?

In Q10 students were requested to recognize the figure under the horse: most of the participants in the point-cloud condition were able to recognize the human figure (70.2%), while less than a quarter of the participants in the photograph condition readily recognized the figure under the horse (24.1%), X^2 (1, N = 115) = 24.46, p < 0.001. When asked if it was easy to recognize this figure, most of students, regardless of condition answered that they were unsure (point-cloud: 78.9% unsure, photograph: 72.4% unsure): $X^2(1, N = 115) = 0.666$, p = 0.41. This demonstrates that, participants in both point-cloud and photograph conditions easily recognized the horse and felt confident about their level of understanding of the statue (see Q2), when challenged by Q10, which requested an in-depth description, participants indicated that they felt more insecure. This insecurity seems independent from the medium used to visualize the statue and linked to the complexity of the artifact. Indeed, it seems that the virtual representation helped students to overcome their insecurity.

Emphasis on spatiality
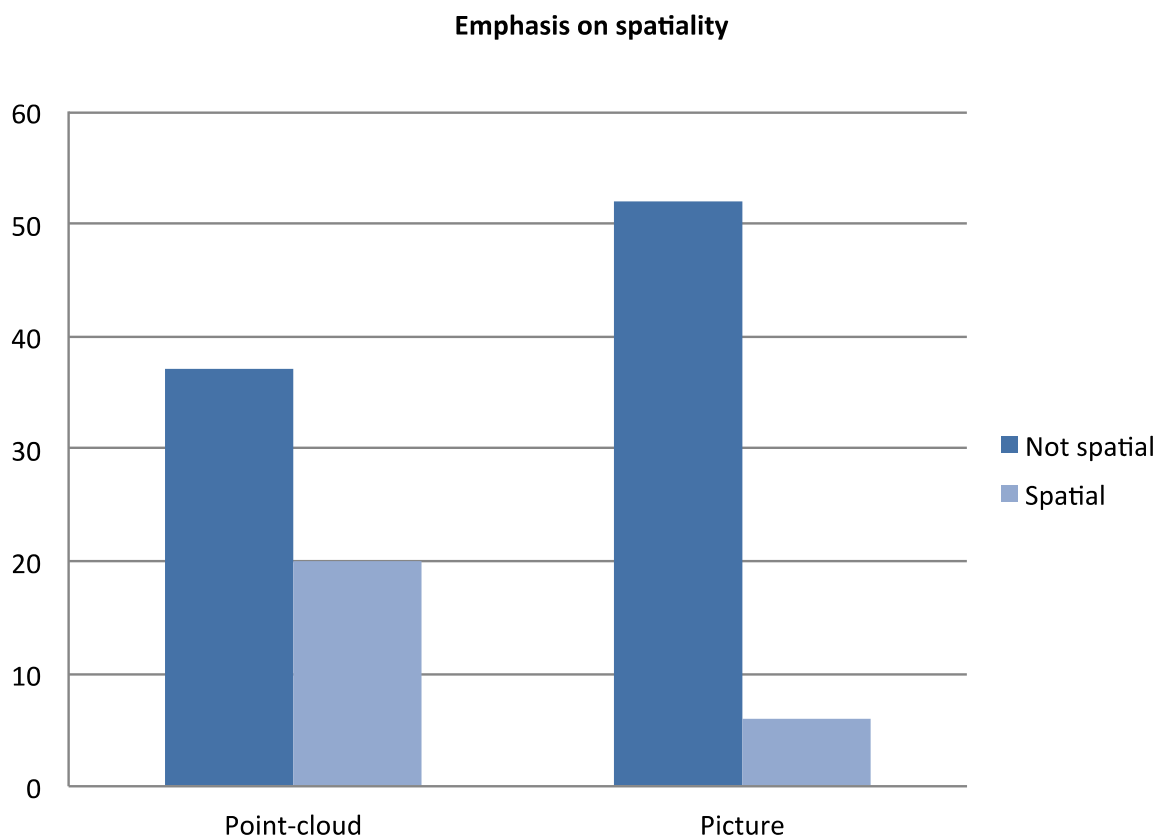
Figure 86. Sense of spatiality: point-cloud versus picture.

Q11. Does the figure under the horse looks like it is moving?

Answers to this questions show that the majority of students independent of condition did not recognize any motion in the figure (point-cloud: 58.3%, photograph: 41.7%; fig. 87): X^2 (1, $N = 115$) = 0.93, p = 0.334.

This result can be explained in two possible ways: first since generally speaking, all students struggled to describe bodily parts of the warrior, they did not really focus on the detail of the arm, which is lifted, suggesting a fight against the horse (thus motion). The second reason could still be related to the dominant figure of the horse that imposes itself over the warrior, impeding his movements.
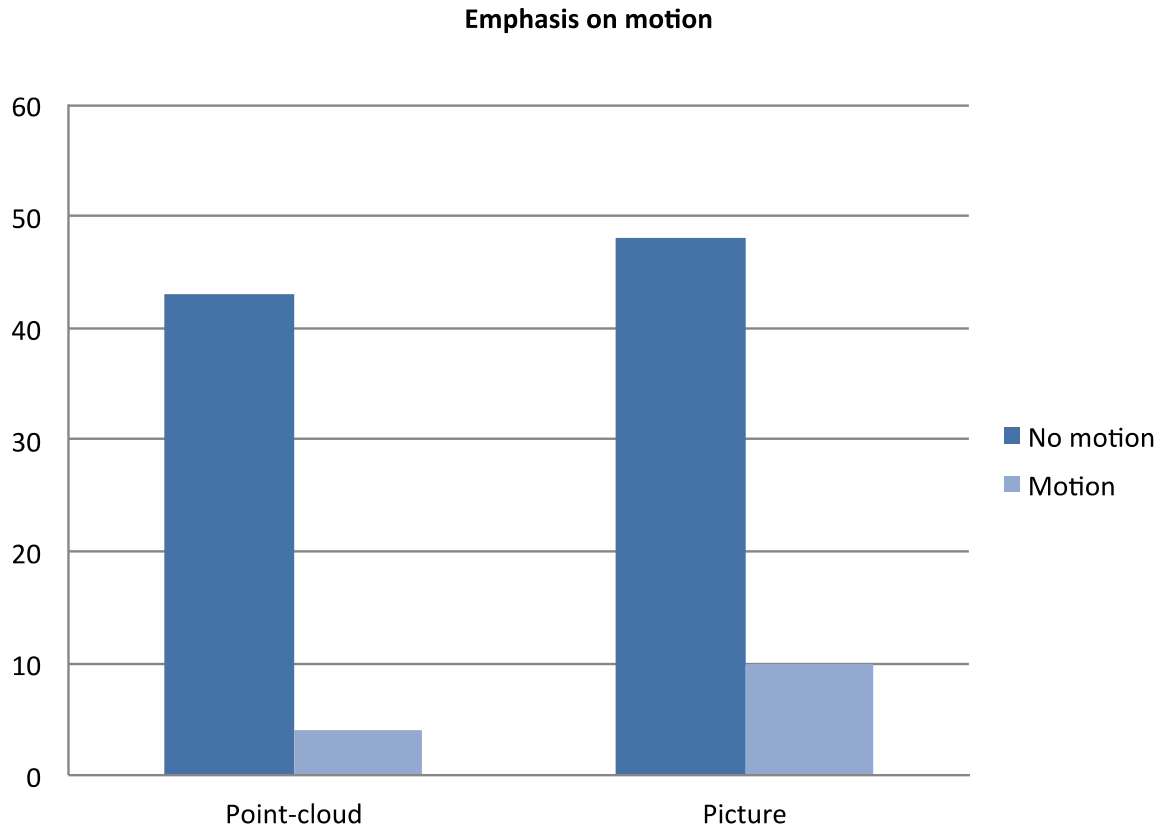
Figure 87. Motion: point-cloud versus picture.

6.3.4. Experiment 2

6.3.4.1. Background

In Experiment 2, participants were videotaped while they interacted with selected artifacts through different forms of media. This experiment aimed to understand how medium (e.g. tactile experience, interaction with 3D virtual copies, and 2D pictures) influences the way people describe and understand objects. This section provides a summary of research finding. For a complete analysis of participants responses see Di Giuseppantonio et al. (in preparation).

6.3.4.2. Participants, materials, and methods

Thirty-two participants volunteered to take part in this study. Half were University of California, Merced, undergraduate students, who received extra course credit in exchange for their involvement; the other half were expert archaeologists (i.e., either academics or contract archaeologists) who also volunteered for the study. All were proficient speakers of English, either native speakers of English or bilinguals with dominant English experience. All had normal or corrected vision.

All students were videotaped in a large, well lit laboratory room at UC Merced and after signing a consent form they were asked to stand in front of either real objects or their reproductions (made using different media), located on a table together with a succinct caption providing information of the object's provenience and age (See Table 1). A video camera, fixed to a tripod, was positioned opposite the participant on the other side of the table, about 120 inches (3 m) from participants. Some archaeologists were also interviewed in the lab at UC Merced, but most were interviewed, based on their availability, in their personal offices or labs, where the authors of this paper reproduced, to the best of their ability, the conditions and atmosphere experienced by the participants at UC Merced. Participants were given verbal instructions by a researcher. The researcher then left the lab leaving the participant alone during the experiment, this was done to prevent undue nervousness of the participants.

Participants were randomly assigned to the following conditions: 1. Real-life Haptic (touching the real objects, 8 participants); 2. 2D Visual (looking at pictures, 8 participants); 3. 3D Virtual: (interacting with the 3D copies of objects displayed on a computer, 8 participants). Once they finished describing the objects, participants were given specific instructions to either open the door of the lab and let the researcher enter, or call the researcher, so that the researcher could enter and stop the video recording.

For this study we analyzed and compared all interviews in the three conditions, to see how 2D and 3D digital reproductions differentially enhance and/or influence the understanding of ancient material culture in absent of tactile experience with real-life objects. The task for the tactile group (Touch) was presented as follows "Here you have the pictures of four archaeological artifacts and a brief explanation on the place where these

objects were found, approximate chronology, and size. Imagine you are an archaeologist who found this objects and is studying them to understand their use in the past. One at a time, please hold an object, and while looking at the camera, describe it in as much detail as you can. Then try to guess its function in the past. I am going to leave you alone now. When you talk about the objects please remember to stay in view of the camera".

6.3.4.3. Results

First, we compared the total average number of words produced in the touch condition with the picture and 3D to see if there was some difference in the length of discourse produced by both students and archaeologists. Overall, the comparison between touch and picture shows a significant difference (Touch: $M = 250.15$, $SD = 222.07$; Picture: $M = 145.81$, $SD = 34.19$) $t(14) = 1.23$, $p = 0.0001$. However, if we examine students and archaeologists separately, we find a significant difference just between archaeologists (Touch archaeologists: $M = 322.62$, $SD = 286.99$; Picture archaeologists: $M = 160.625$, $SD = 32.1$) $t(6) = 0.97$, $p = 0.0023$; (Touch students: $M = 177.69$, $SD = 75.94$; Picture students: $M = 131$, $SD = 29.48$) $t(6) = 0.99$, $p = 0.07$.

When comparing touch and 3D conditions, we find no statistical significance (Touch: $M = 250.15$, $SD = 222.07$; 3D: $M = 308.84$, $SD = 164.53$) $t(14) = 0.56$, $p = 0.22$.

These findings show that touch and 3D participants produce a very similar amount of words, which is higher than the amount of words used from participants in the picture condition. The difference between the amount of words produced in the pictures condition and that produced in the 3D is noteworthy (Picture: $M = 145.81$, $SD = 34.19$; 3D: $M = 308.8$, $SD = 164.52$) $t(14) = 2.57$, $p = 0.02$. When comparing students to archaeologists, results show that while no significant statistical difference can be registered for students (Picture: $M = 131$, $SD = 29.48$; 3D: $M = 217.7$, $SD = 129.66$) $t(6) = 1.13$, $p = 0.3$, archeologists in the 3D condition use more words (Picture: $M = 160.6$, $SD = 32.09$; 3D: $M = 400$, $SD = 143.90$), $t(6) = 2.81$, $p = 0.03$. Archaeologists, who are professionals who study artifacts as a daily practice, are quite critical with 3D technologies and spend a considerable amount of words talking about the medium, and its potentials and limits.

The three groups were then compared to see how differently participants perceived innate qualities of objects, such as shape, weight, color, etc. The analysis was also aimed at understanding if specific media would better stress some qualities over others, and how media would influence the overall perception of ancient artifacts and their functions in the past. The analysis included: material, color, shape, size, and weight. For this, we decided to compare Pictures and 3D (combined) to the tactile group with the original objects. This aimed to get a sense of how pictures and 3D differ from real life experience.

As for the material, four categories of analysis were created: correct, incorrect, uncertain, and absent. The uncertain category included all cases in which participants were not sure about the material of an object, but eventually indicated the correct one (see table 13). The *absent* response was not considered as an incorrect answer, since multiple factors could explain why people did not mentioned material or other characteristics of an object: for instance, it could be that the medium does not stress/afford/enhance a specific characteristic; or that some people do not consider a specific characteristic crucial for their description of an object. In addition, some participants might have felt that the perception of a characteristic is so obvious, that they did not need to provide a description of it. For all other categories, correct vs incorrect answers were not considered, since determining weight and size of an object, for instance, could be challenging in any given condition; the analysis thus aimed at examining when participants either mentioned or did not mention each characteristic and the frequency with which they did. All graphs and tables include answers for all objects described.

Material

No reliable differences were found between the touch, pictures, and 3D conditions: X^2 (2, $N = 96$) = 2.4, p = 0.3. Therefore, we analyzed archeologists and students independently and found reliable difference between conditions controlling for participant type: Archaeologists, X^2 (2, $N = 48$) = 1.79, p = 0.4; Students, X^2 (2, $N = 48$) = 10.14, p = 0.006.

Further, Touch with Picture and 3D were compared respectively and it was found how students in the picture and 3D conditions mentioned the material of the objects more frequently than their touch peers (with no statistical difference between picture and 3D):

- Touch vs Picture: general X^2 (1, $N = 64$) = 5.46, p = 0.06; archaeologists X^2 (1, $N = 32$), p = 1; students X^2 (1, $N = 32$), p = 0.015.
- Touch vs 3D: X^2 (1, $N = 64$) = 0.19, p = 0.12; archaeologists X^2 (1, $N = 32$) = p = 0.6; students X^2 (1, $N = 32$) = 5.24, p = 0.02.
- Picture vs 3D: X^2 (1, $N = 64$) = 0.99, p = 0.3; archaeologists, X^2 (1, $N = 32$), p = 0.6; students, X^2 (1, $N = 32$), p = 1.

The previous results show how using 3D replicas and 2D pictures tend to increase the interest toward *material*. This could be explained by the challenge experienced by participants in both categories to recognize the exact material of an object. As shown in the following graphs, in fact, the level of uncertainty in determining an object's material is higher in picture and 3D than in touch, and this can lead to an incorrect interpretation of material.

The challenges associated with material understanding experienced by 3D and picture participants increases examining students and archaeologists separately, suggesting that, while archaeologists have more background knowledge to decode object material, students, who are not trained to analyze ancient artifacts, encounter problems when they are not allowed to touch real-life objects. Research finding suggests that in absence of the real-life object, 3D replicas seem more effective than pictures in conveying information about the material.

The qualitative analyses performed here reinforces the idea that both students and archaeologists struggle when asked to describe 3D objects, even if with differences in frequency. It's interesting that in absence of direct tactile experience, participants use several other visual cues to discern the material of an object, such as color, texture, and shape.

Texture

A reliable difference was found in how participants mentioned texture across the three categories of analysis (touch, pictures, and 3D): X^2 (2, $N = 96$) = 8.59, p = 0.01. Comparing touch participants with each of the two categories, a reliable difference with pictures emerges, but not with 3D:

- Touch vs Picture: general X^2 (1, $N = 64$) = 3.92, p = 0.047; archaeologists X^2 (1, $N = 32$) = 0.53, p = 0.46; students (1, $N = 64$), p = 0.17
- Touch vs 3D: X^2 (1, $N = 64$) = 1.02, p = 0.3; archaeologists X^2 (1, $N = 32$) = 2.03, p = 0.15; students X^2 (1, $N = 32$) = 0, p = 1.

Analyses also showed a noteworthy difference between picture and 3D, suggesting that the interaction with 3D objects facilitates participants mentioning texture more often than pictures: X^2 (1, $N = 64$) = 6.93, p = 0.008. The statistical difference remains significant if we compare archaeologists, X^2 (1, $N = 32$) = 6.15, p = 0.01, but not if we compare students, X^2 (1, $N = 32$), p. = 0.17.

The last result can be expanded upon using a qualitative analysis of participant responses since quite a few participants (both students and archaeologists) in the 3D group focused on texture while describing the artifact. The participants stressed the importance of removing original colors from the 3D digital replicas, to better understand texture and detail of the objects under analysis. Particularly, some examples point to the possibility of removing original colors from the digital artifacts as an added value for the perception of specific physical cues that facilitate the inquiry process.

Color

A reliable difference was found in how participants mentioned color across the three conditions (touch, pictures, and 3D): X^2 (2, $N = 96$) = 7.93, p. = 0.02. Individual comparisons of touch participants with respectively picture and 3D participants clearly:

- Touch vs Picture: general X^2 (1, $N = 64$) = 6.35, p. 0.01; archaeologists X^2 (1, $N = 32$) = 10.16, p. <.0001; students (1, $N = 64$) = 0.14, p = 0.71.

- Touch vs 3D: X^2 (1, $N = 64$) = 5.11, p = 0.02; archaeologists X^2 (1, $N = 32$) = 4.8, p = 0.03; students X^2 (1, $N = 32$), p = 0.43.
- Picture vs 3D: General: X^2 (1, $N = 32$) = 0.07, p = 0.8; archaeologists: X^2 (1, $N = 32$) = 1.25, p = 0.26; students: X^2 (1, $N = 32$), p = 0.68.

As expected, these results show how both pictures and 3D replicas elicit similar responses from participants while they describe color.

Shape

As expected, no reliable difference in participant responses were found with regard to shape across the three conditions: touch, pictures, and 3D replicas: X^2 (2, $N = 96$) = 5.59, p = 0.06. This means that the three conditions elicit similar descriptions regarding object shape. Due to the marginal effect, we decided to further investigate how touch relates to pictures and 3D independently and if there were differences in responses between P and 3D participants:

- Touch vs Picture: general X^2 (1, $N = 64$) = 3.09, p = 0.08; archaeologists X^2 (1, $N = 32$) = 2, p 0.16; students X^2 (1, $N = 32$) = 1.17, p = 0.28.
- Touch vs 3D: general X^2 (1, $N = 64$) = 0.26, p = 0.6; archaeologists X^2 (1, $N = 32$) = 0, p = 1; X^2 (1, $N = 32$) = 0.51, p = 0.47.
- Picture vs 3D: X^2 (1, $N = 64$) = 5.07, p = 0.02; archaeologists X^2 (1, $N = 32$) = 2, p = 0.16; students X^2 (1, $N = 32$) = 3.14, p = 0.08.

This additional comparison showed a significant difference in how participants described objects when presented with pictures or 3D replicas (in favor of 3D), but this difference disappears if we consider archaeologists and students separately (suggesting how further analysis with a higher number of participants could clarify and/or reinforce this result).

This qualitative analysis helps clarify the importance of 3D multi-visualization for the analysis of artifacts' digital replicas. More than one participant underlined the

importance of geometric properties with no colors applied to better understand the shape of the objects.

Interestingly, focusing on specific objects, it was possible to notice that both archeologists and students find it difficult recognizing the internal part of the pot (Fig. 88). While archaeologists have both the professional experience and background knowledge to overcome this challenge and recognize exact shape and function of the pot, students can be misled and can make incorrect assumptions about object details concerning shape, function, and even material.
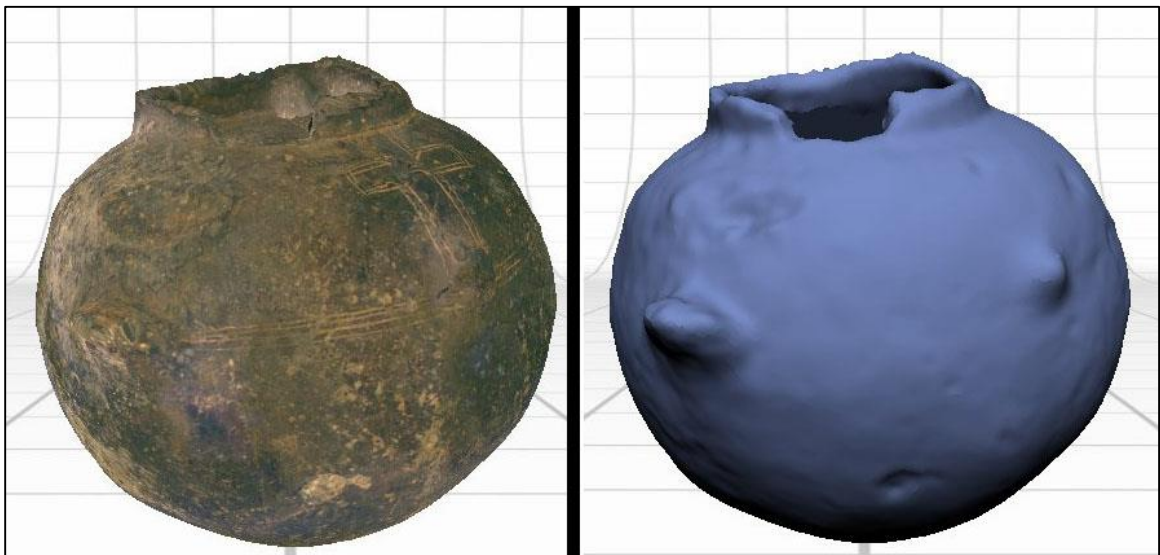
Figure 88. Motion: Virtual Reality (VR) versus Real (R); from Di Giuseppantonio Di Franco et al. 2014.

Size

A reliable difference was found in how participants mentioned size across the three conditions (touch, pictures, and 3D): X^2 (2, $N = 96$) = 6.34, p = 0.04. Further comparisons show a significant difference with pictures, but not with 3D:

- Touch vs Picture: general X^2 (1, $N = 64$) = 6.27, p = 0.01; archaeologists X^2 (1, $N = 32$) = 2.13, p = 0.14; students X^2 (1, $N = 32$) = 5.24, p = 0.02.
- Touch vs 3D: X^2 (1, $N = 64$) = 1.02, p = 0.31; archaeologists X^2 (1, $N = 32$), p 0.65; X^2 (1, $N = 32$) = 5.24, p 0.02.

Archaeologists who interacted with 3D replicas mentioned the size of the objects marginally more frequently than participants who viewed pictures, but this difference is not statistically significant: general X^2 (1, $N = 49$) = 0.44, p = 0.5; archaeologists X^2 (1, $N = 25$), p = 0.07; students X^2 (1, $N = 24$), p = 1.

More interestingly, when examining the way participants mention object size, it was noticed that, while T participants used adjectives and exact measures to provide size information, participants in the picture and 3D conditions often used gestures to relay this information.

6.3.5. Discussion and conclusions

Two experiments were conducted to investigate how modality of presentation influences participant understanding of artifacts. Specifically, how do people, interact with, understand, and describe objects differently when presented in three unique modalities: 2D pictures, 3D digital reconstructions, and 3D replicas. In both studies, participants were asked to describe ancient artifacts in detail. In the first experiment, participant descriptions were elicited using self-guided question sets including a combination of multiple choice, Likert scale, and open ended questions. In the second experiment, participants (students and professionals in the field of archaeology), were asked to freely describe objects, alone, in front of a video camera.

Results from Experiment 1 reveal insights into how people perceive artifacts through digital copies and how they cope with the absence of authentic, real-life, objects. In general, it was found that background knowledge guided some of the students' answers. In particular, when point-cloud students were asked to determine the material of an object, in absence of original colors (Q3), they relied on their personal conceptualization, which was most likely influenced by their real-life experience with these types of representations (statue of a horse). Even more surprisingly, most students who experienced objects through point-cloud felt confident about their answers on the material of the statues, suggesting that background knowledge can influence perceptual and interpretative processes.

With regard to the use of different media types, results show that overall, students in the virtual reality condition demonstrated a better understanding of particular details of the statue (Q10, Q12), including features of the warrior underneath the horse, suggesting participants in this condition had a more complete understanding of statue texture and shape through the use of point clouds. Moreover, with regard to emotional qualities elicited by the artifacts, students in the point-cloud group perceived the statue as more lively (Q9), indicating that something as simple as media type can highlight tension represented in the scene of the fight (muscular structure of the horse, horse prevailing over the warrior, etc.). Experiencing the artifact as a point-cloud seems to enhance the sense of spatiality that the statue physically convey. Interestingly, participants in neither conditions perceived a sense of motion that the representation of the fight seems to suggest.

Results from Experiment 2 compliment results from Experiment 1, giving important insights on how people perceive artifacts in absence of a real-life tactile experience. While Experiment 1 showed that point clouds of 3D digital replicas improve the perception of physical details and increase the sense of spatiality of complex shapes, Experiment 2 further clarifies how individuals perceive important physical characteristics of objects; characteristics such as material, texture, color, shape, and size. Examining individual characteristics reveals that while pictures and 3D digital copies invoke similar participant responses for material, color, and size, we cannot say the same for shape and texture. A significant number of participants in the 3D group stressed the importance of multi-visualizations (i.e., object with or without original colors) to grasp textural information, a detail highly associated with tactile experience. Texture cues can help participants successfully determine both object material and function. In the case of the grinding stone, people often look at signs of wear to determine its function. For many participants, the Buddhist object's material was only identifiable through the use of texture to determine its material.

With regard to shape, both students and archaeologists interacting with 3D replicas mentioned and described the shape of the object more consistently and frequently than those in other experimental conditions. As noted earlier, the shape of 3D replicas can be difficult to recognize when color information is applied to the model. For this reason, the visualization

of 3D models with no colors applied can be crucial for recognizing *shape* information. The importance of removing original colors from the 3D models was highlighted by several participants, but this observation is usually only made following second, or sometimes even third, 3D model they interact with over time. This observation is not trivial, since it indicates that 3D model users needed experience to understand the tool and to fully benefit from the 3D model medium. Once participants in the 3D model condition understood how the tool functioned, the possibility to remove colors from the 3D model was seen as a disclosure (Heiddegar 1972: 70), which originated from a constructivist experience with the 3D digital object. The experience with multiple layers of the 3D digital models activated a constructivist sensory-motor learning sequence that allowed participants to actively create knowledge about the artifacts while simultaneously interacting with their environment (i.e., 3D copies) in seek for meanings (Huba, 2000, p. 37).

In summary the results of these experiments point to 3D digital replicas of artifacts as more effective means to digitally preserve tangible cultural heritage since 3D multi-visualization augments the perception of physical characteristics of the artifacts allowing a more embodied experience with these objects. Real-time 3D experiences using multiple informational layers (texture, mesh, vertexes, wireframe) simulate, to some extent, real-life experiences better than 2D digital pictures, since the perception of texture/surface compensate for the lack of a tactile experience with original artifacts.

Chapter 7

Conclusions

The work presented in this dissertation research shows how the last decade has seen the exponential growth of the three dimensional technologies in archaeology and heritage studies. Three dimensional technologies are changing archaeological excavation practices, but the definition of methodology and standards is still far to come. This research has defined a methodology that starts with the integration of 3D technologies for the onsite documentation, and proposes new strategies for the simulation and visualization of past landscapes.

The complete 3D documentation of archaeological sites such as Las Cuevas should be an added value to the traditional documentation practice by providing the opportunity to visualize the 3D data not only in Geographic Information System, but also more complex and immersive visualization, such as the powerwall visualization and motion capture facility described in chapter 6.

Three dimensional documentation made on site is a fundamental instrument for preservation and analysis. The great advantage of having high-resolution three-dimensional model of the site context and features is the ability to visualize, study and extract 2D and 3D information from various points of view and at different scales. Horizontal and vertical sections, as well as plans of the excavation area and cave system can be easily generated from the 3D models. The use of two-dimensional representations of the 3D data collected can be an important instrument to monitor interventions.

One major problem encountered during the 3D data post-processing was the sheer amount of data, especially for the laser scanner acquisitions. It is important to carefully plan in advance how the data should be used and decide what resolution really is needed. If there is a need for extra high-resolution, then it is necessary to make sure there is enough computing power in the post-processing procedures. It is important to design strategies that consider the preservation of the 3D data at different resolution giving the opportunity to

use and visualize the 3D contents at increased resolutions with the advancement of available machines.

For this reason the geometry comparison, described in chapter 5, was done between PST high-resolution 3D models and DSM 3D models of the same archaeological unit acquired at different resolutions to understand if at a lower resolution corresponds a lower accuracy of the DSM models. The comparison between PST and DSM models acquired at different resolution (2 M, 5 M, 10 M) was contained (2-4 mm), showing the potential in the acquisition and preservation of the unit at different resolutions for future interpretation and visualization.

In this particular environment DSM showed to be a reliable technique for the metric representation of archaeological stratigraphy. In fact, DSM allows fastening the 3D documentation process, reducing both data acquisition and processing time. However, the accuracy deviation between PST and DSM (5-8 mm based on the dimension of the acquired area) shows that the use of laser scanner techniques is more appropriate for the 3D reproduction of micro-stratigraphy. For this reason the integration of laser scanner and dense stereo matching techniques seems the appropriate approach when the acquisition of millimetric features contained in the stratigraphy is mandatory.

The integration of the two techniques was strategic also for the reproduction of the units' color information. In fact, for all the units acquired, except for the acquisition in cave environment where the low quality of both PST and DSM color information required the use of perspective projection methods (application of high-resolution images acquired through digital camera) for the mapping of the 3D models, the DSM models' color information was applied to the PST high-resolution geometry using the Meshlab's color projection tool (see chapter 4.5).

The geometry comparisons conducted on the 3D data acquired in two fieldwork seasons at Las Cuevas (2011-12) through laser scanning, TLS and PST, and DSM techniques represent an unprecedented accuracy test of these 3D technologies onsite. In fact, according to Dellepiane et al.,

although someone claims that dense stereo reconstruction is a mature alternative to 3D scanning, no convincing comparison has been presented until now. Recently, some initial effort has been made in this direction, but an overall methodological definition and accurate data assessment are still missing (Dellepiane et al 2012: 203).

This research fills the gap providing an accurate data assessment for the Las Cuevas archaeological site, and representing a concrete starting point for the definition of a sharable and overall methodology. However, at Las Cuevas the 3D technologies were compared in the different environmental and lighting conditions of the same archaeological site and context. For the definition of a reliable and overall methodology the same 3D documentation techniques need to be tested in sites/contexts characterized by different climates and light exposure conditions. For this reason future improvements to this research will consist in applying the methodology used at Las Cuevas in other archaeological sites and contexts.

The results of this research led to the opening of a new discussion on the real value of micro-accuracy in the 3D documentation of archaeological stratigraphy. What kind of accuracy is really needed for documenting the archaeological stratigraphic record? Is the centimetric accuracy that it is possible to obtain from DSM technique sufficient to archaeologists needs? Or is the reproduction of millimetric 3D models mandatory for a correct analysis and interpretation of the archaeological record?

These are central questions for the definition of best 3D archaeological documentation practices to which scholars have given different answers over the last ten years. Some scholars believe that the reproduction of micro-accuracy is always a crucial aspect for the documentation of archaeological stratigraphy supporting the use of laser scanner technologies, others researchers see in DSM a faster and reliable method and do not consider micro-accuracy a compulsory aspect for the understanding of the archaeological sequence. Probably the best approach would be to reach a compromise between the two visions choosing the methodology considering the single case study. Some archaeological contexts require more accurate data acquisitions than others (e.g. Güth 2010: 3105-3114; Mc Pherron et al. 2009: 19-24).

The second important aspect analyzed in this research is the 3D reconstruction/simulation of archaeological sites/monuments. The preservation of cultural heritage includes not just the physicality of the material culture acquired through 3D documentation techniques, but all the information connected with its cultural and historical background, as well. In this sense 3D reconstructions and virtual environments can be challenging in the simulation of the original context of ancient remains. The use of these innovative tools allows, working on the creation of as many interpretations as possible, to increase the objectivity in the interpretation and reconstruction process.

Using digital technologies, we can avoid the alteration of our physical heritage sites and artifacts by creating another level of perception of the monument that is completely virtual. In this way the shape that we can modify and interpret is not real, but a 3D digital reproduction. Moreover thanks to these tools it is possible to create metric reproductions of the monument, preserving it in the process so as to have the possibility to analyze its decay over time.

A dispute is still ongoing between different schools of thought on the preservation and reconstruction process. Is it really necessary to preserve and reconstruct our heritage in an invasive way or is it possible and desirable to start thinking of a new approach that through the use of new technologies could digitally record it, and simulate its original nature and cultural context, avoiding a destructive intervention of the monument? Moreover is it possible to preserve not just the heritage site's physical aspects (tangible) but its meaning too (intangible), thanks to the use of new technologies?

According to Svetlana Boym "we don't need a computer to get access to the virtualities of our imagination: reflective nostalgia has a capacity to awaken multiple planes of consciousness" (2002: 49), because machines are just a tool. They have to be used as containers and displays of the virtualities created from our imagination. The computer cannot be a substitute for the human brain, but at the same time virtual reconstructions and new technologies in general are powerful visualization tools for our mental interpretations of the past.

The discussion about the value of virtual reconstruction for the preservation and interpretation of cultural heritage has just started. Should these virtual simulations be

considered original digital representations of our cultural heritage or just virtual 'fakes'? They can be probably considered subjective virtual interpretations (a relative 'authentic') that aim to get as close as possible to the absolute 'authentic' thanks the activation of a multi-simulation process. This kind of process can allow users to compare virtually and in real-time different reconstructed worlds coming from diverse interpretations of the same cultural heritage.

The multi-simulation and visualization process is possible thanks to 3D visualization systems that allow the easy switch between different 3D contents. These visualization systems can be offline immersive, offline non-immersive and online non-immersive (Fig. 89). As shown in chapter 6.2.1, at UC Merced 3D immersive applications for the analysis and understanding of heritage monuments/sites were developed and implemented in the powerwall visualization and motion capture facility ("Virtual Museum of the Livia's Villa", "Virtual Museum of the Western Han Dynasty"). These immersive visualization systems gave students the opportunity to interact with the reconstructed sites/monuments and increase their understanding through a cybernetic presence.

This research explored also the potential of offline not immersive 3D visualization systems in education. A 3D application (3D Virtual Dig, see 6.2.2.) was created to teach the archaeological excavation process to freshman students, showing how a 3D digital approach to laboratory work can positively affect student learning, and serves as an important bridge from traditional coursework to fieldwork.

This dissertation research demonstrated how 3D contents can enhance the understanding and interpretation of tangible heritage better than 2D traditional media such as pictures and drawings, thanks to cognitive experiments conducted at UC Merced with students interacting with 3D and 2D reproduction of tangible heritage (see 5. 3). 3D digital replicas of tangible heritage can, in fact, give users a multi-visualization experience with the artifact which augments the perception of physical characteristics of the object such as texture (surface). The visualization of multiple layers of the 3D models (texture, mesh, vertexes, wireframe), allows a more embodied experience with the object compensating for the lack of tactile experience with original artifacts. These results seem to stress the

importance of giving access to 3D replicas to multiple users for supporting the interpretation of material culture in absence of the real-life object.
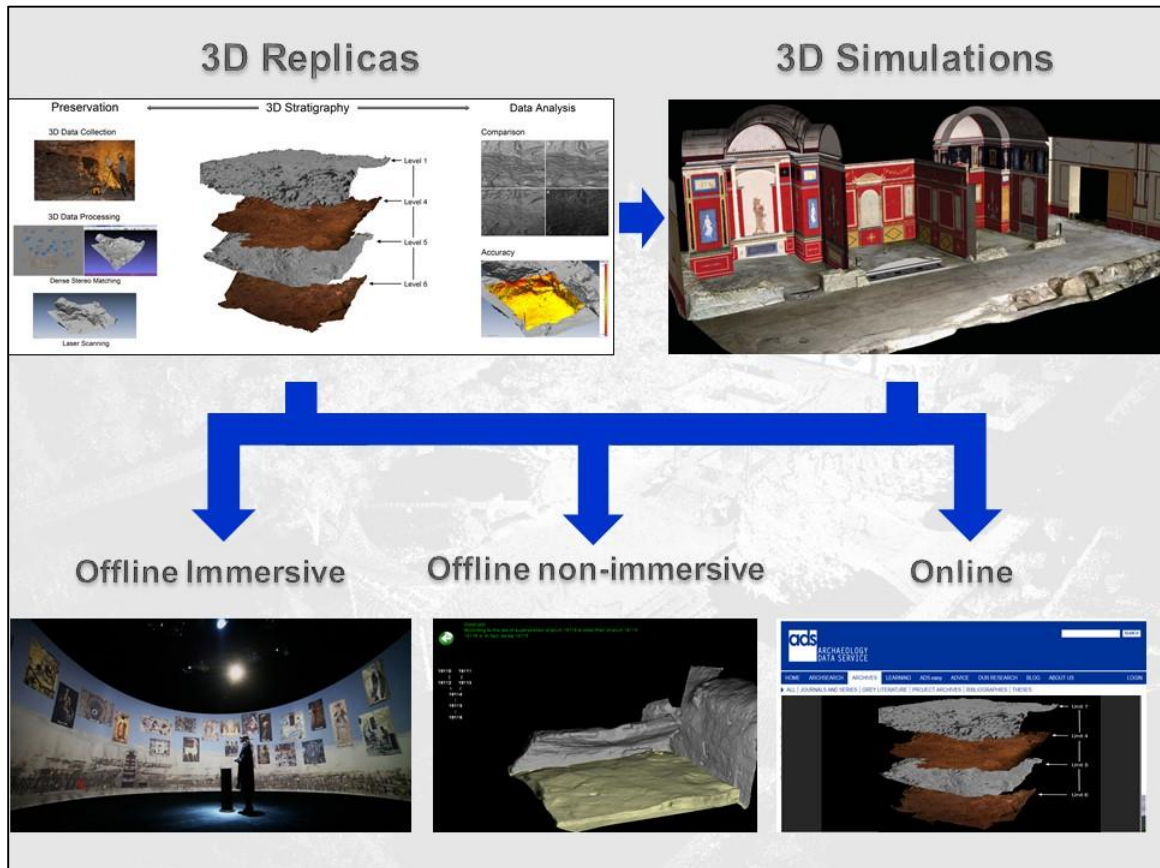
Figure 89. 3D visualization systems.

For this reason, future research should explore the possibility to develop a 3D real-time visualization system (3D viewer) that will allow the management and analysis of the acquired 3D data. This 3D viewer should integrate new datasets coming from fieldwork campaigns and hyperlinks (i.e. links to pictures, 3D models, text, etc.) that provide various audiences with extra information on the layers detected, excavation area, and methodologies used during fieldwork, and, in addition, links between the layers and artefacts or other material remains found on site etc. As argued by Mark Aldenderfer, 3D viewers allow simultaneous visualization of 3D contents and all inferences enhanced by 3D replicas and simulations:

What I have in mind as a set of tools for visualization in service of archaeological simulation doesn't really exist yet in our field. We must develop tools and approaches that allow us to simultaneously 'see' (i.e., to create images that may represent a wide variety of information content across a variety of media types) and to 'know' (i.e., to be able to connect these disparate images to other kinds of data) such that inference is enhanced and enabled (Aldenderfer 2010: 55).

In other words, this kind of interactive applications will give scholars and general public the opportunity to access and visualize various dataset, favoring multiple interpretations of the same archaeological context.

This 3D viewer will strengthen the work done in the studies presented in chapter 3.3, developing a complex real-time system for the data management, analysis, and visualization of archeological stratigraphy, using 3D realistic and metric reproduction of the archaeological units instead of schematic graphic representation. This research is more challenging than the projects already discussed in term of data management. In fact, the complexity of the 3D models represents a node point for the creation of a usable and accessible visualization program.

The second phase of this continuing research will be the integration of the 3D real-time visualization system in online information brokers and aggregators for different resources, giving users the possibility to access archaeological data to ground-truth interpretations. The 3D viewer will provide a web-based means of visualizing a site in 3D and using the 3D model as a means of interrogating the underlying data.

The visualization of 3D contents was one of the main goals of the European funded project CARARE (http://www.carare.eu/). CARARE gave users the opportunity to visualize 3D models in real-time, but the information on these models can only be seen separately from the 3D models. In other words it is not possible to visualize 3D models and excavation information simultaneously.

The real-time system that will be developed in this continuing research is a complex application that will allow the analysis and visualization of 3D realistic and metric reproduction of the archaeological contexts. The application will be developed using a game development platform, such us Unity. Up to now, game development platforms have

mainly been used for communication purposes, such as virtual museums. This research will explore the potential of game development platforms for the creation of interactive systems focused on data sharing and the analysis of archaeological record. Thanks to interactive hyperlinks, different layers of information (pictures, text, video, stratigraphic unit sheets, etc.) will be linked to the 3D models of the site's reconstructed units and contest directly in the 3D view. Unity Web Player Streaming allows users to view the content almost immediately and start the analysis of the 3D environment in real-time instead of waiting for the files to download from the web page.

The methodology to be used in obtaining the 3D viewer is characterized by four main objectives:

1. *3D model optimization.* To provide a visualization that can be used to access supporting data in the 3D view, it is first necessary to optimize the 3D models. The optimization and management of complex 3D models acquired through laser scanning and dense stereo matching techniques is, in fact, the first challenge to be overcome for the creation of usable and accessible visualization programs.

2. *3D viewer development.* The optimized 3D models will be imported into the game development platform for the development of the offline infrastructure. After a preliminary analysis of the potential layers of information to be linked to the 3D models, interactive hyperlinks will be applied to the models and tested offline to understand their effectiveness.

3. *Standardization of structures and formats.* This part of the project will be crucial for the integration and visualization of the 3D contents in the online aggregator. After the design of the viewer, a set of pilot tests will be run to optimize it and facilitate its integration in the existing online aggregator's cyber-infrastructure. Moreover different formats will be tested with the viewer to find an appropriate standard.

4. *Implementation of the 3D viewer in online journals.* The applicant and the host institution will explore the opportunity of including the 3D viewer within an online peer-reviewed journal.

To date, specialists in the field of digital archaeology and heritage have mainly focused their efforts on two main aspects:

1. *The development of 3D interactive visualization systems characterized by the high-resolution of the geometric information.* There are several examples of real-time visualization systems, both off and online, mainly focused on the preservation of the geometric information of the simulated sites (Antinucci 2007; Pietroni et al. 2008: 225-234). Most of them are virtual museums principally directed to the communication of monuments and archaeological sites to the general public. Thanks to interactive hyperlinks these 3D virtual simulation, when seen as supplements to and not replacement of the real context, can increase the understanding of cultural heritage and help users to retain more information related to the real site.

2. *The creation of standardized and complex databases for the preservation and sharing of the archaeological record.* Two of the most important and successful examples of data services supporting research and education in archaeology are ADS (Archaeology Data Service) and tDAR (the Digital Archaeological Record: http://www.tdar.org/). ADS was established in September 1996 at the University of York, while tDAR was developed at Arizona State University in 2008 due to the Digital Antiquity initiative.

These two aspects have never been successfully integrated in projects concerned with preservation and data sharing. In the past ten years, in fact, scholars have tried to develop databases linked to complex 3D simulations of the archaeological sites during and after the excavation process, but most of the examples have not produced durable, standardized and complete databases for accessing the archaeological record, very often for lack of resources (Galeazzi et al. 2007). The 3D Viewer developed by this continuing research will demonstrate originality and innovation in the attempt to integrate a 3D real-time visualization system for high-resolution 3D reproductions of the archaeological record with online archives for digital outputs for archaeological research.

Thanks to this 3D viewer, users will be able to analyze and interpret the archaeological record not just from text information and 2D representation of the archaeological excavation or site, but interacting in real-time with its millimetric 3D reproduction. The interaction with the 3D model and the activation of hyperlinks will be an incredible opportunity of data sharing with a large number of users through the internet. This will promote the creation of multiple interpretations of the same archaeological context, encouraging discussion between scholars.

The possibility to share complex 3D reproductions of archaeological site and monuments with all the information related to the interpretation made by archaeologists represents a revolutionary change in the discipline.

The challenge to add the 3D real-time component in existing databases will allow to build an online infrastructure unavailable elsewhere in the world, giving scholars from all continents the opportunity to have access to 3D data coming from different research projects.

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