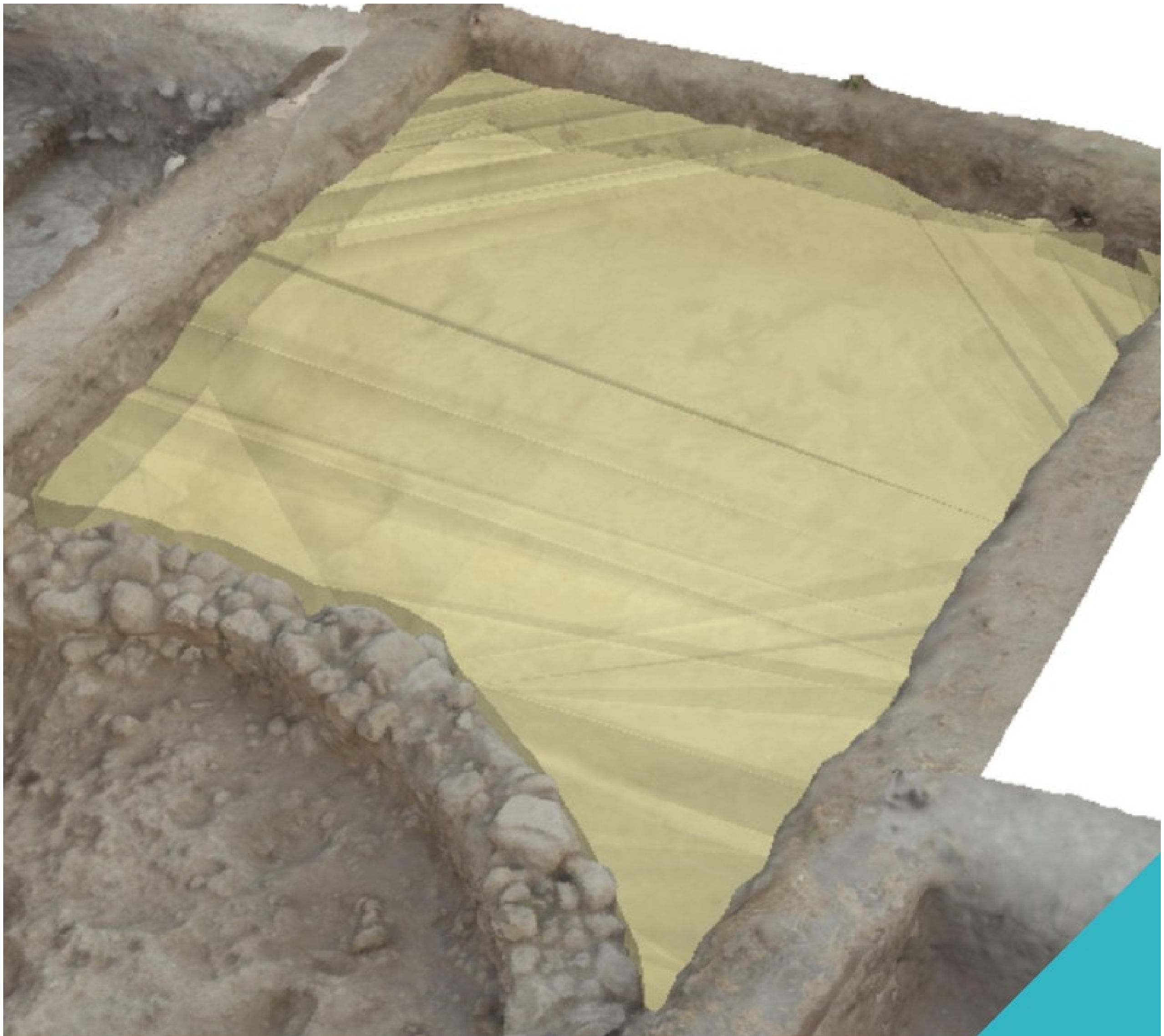

LAYER BY (3D) LAYER

3D GIS STRATIGRAPHIC ANALYSIS OF CHLORAKAS-PALLOURES, CYPRUS

MARINA GAVRYUSHKINA

Universiteit Leiden

Front page figure: Representation of unit BV13_5 created per the Digitizing Section Drawings volumetric modeling method (figure by author).

Layer by (3D) Layer
3D GIS Stratigraphic Analysis of Chlorakas-*Palloures*, Cyprus

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Leiden 15 June 2018: Final Version

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Acknowledgements

It takes a village, and here I would like to take a quick moment to give credit where credit is due. First, thank you to my supervisor, Victor Klinkenberg, for indulging my interest in 3D GIS and giving me access to the *Palloures* dataset. My appreciation for your technical assistance and patience with my countless WhatsApps messages cannot be overstated. This project would also not have been possible without Karsten Lambers, whose invaluable feedback and guidance helped me to be a better scholar.

Thank you to Nicolo Dell'Unto and everyone at the Digital Archaeology Laboratory at Lund University for taking me under your wing during the cold Swedish winter to pass on your expertise in 3D GIS. Your solid advice and technical know-how was incredibly helpful and opened my eyes to new possibilities in Digital Archaeology. On that note, I am very grateful to Chiara Piccoli for connecting me with Nicolo and his team, and for encouraging my interest in 3D modeling.

Moreover, I extend my utmost gratitude to the Leiden University Excellence Scholarship (LExS) committee for granting me the means to pursue my academic ambitions at Leiden University. My experience at Leiden has opened up a world of opportunity and I could not have gotten here without your backing. The LUF International Study Fund (LISF) has also been incredibly instrumental to my research and I want to thank them for awarding me the grant which allowed me to complete my internship in Sweden.

Of course, a special shout-out to Emily Vella and Shannon Mascarenhas with whom I shared an office. Your good humor, memes, and shared love of Pokemon Go kept me sane and motivated through the most stressful of times. Thank you to all of my friends from my OWL group for sharing the Leiden experience with me and a very sincere thank you to my wonderful partner Jerome who put up with me and my deadlines during the past few months.

Last but not least, I would not be here without the support of my friends and my family back home in California, who encouraged me to pursue my academic goals without even really knowing what Digital Archaeology was. Your faith in me constantly inspires me to be better.

Chapter 1: Introduction

Developments in three-dimensional (3D) data acquisition technology and geographic information system (GIS) software capabilities in the past decade have opened up immense potential for improving archaeological documentation practices. As archaeologists are increasingly relying on digital technology to record spatial data during excavation, more research must be done in order to better understand the implications of collecting, visualizing, and analyzing the resulting 3D datasets. This project explores the use of 3D GIS for intra-site stratigraphic analysis using the case study of three excavation trenches uncovered and recorded using a total station and photogrammetry techniques during the 2015-2017 field seasons at Chlorakas-*Palloures*[1]. Henceforth referred to as *Palloures,* this site is a Middle to Late Chalcolithic (early 3rd millennium BC) site located in west Cyprus. Through this project, I propose a workflow for building volumetric 3D GIS models using photogrammtery models and spatial data recorded using a Total Station, then discuss the benefits and limitations of 3D GIS modeling of archaeological excavations in theory and in practice.

1.1 Advances in Excavation Documentation

It is often said that once a context is taken out of the ground, sifted, and discarded, the physical in-situ dataset is essentially obliterated (Morgan and Wright 2018, 1). In this way, excavation is seen as an unrepeatable experiment in which "interpretative drawings, photographs and site records are the only data sources available for post-excavation research" (Dell'Unto 2014, 152). Yet with the rise of digital technologies, the tiresome adage that 'excavation is destruction' has increasingly been called into question.

Digital documentation techniques have the potential to record archaeological stratigraphy faster and more accurately than traditional pen and paper approaches (De Reu *et al.* 2014, 260-261). For instance, laser scanners can be used to accurately model the topography of excavation surfaces by using a large number of individual point measurements to reproduce 3D space (Doneus and Neubauer 2005a, 197; Doneus and Neubauer 2005b, 227). Photogrammetry and computer vision has become exceedingly popular in recent years as the development of software programs, such as AgiSoft Photoscan, has allowed users to automate the entire process of creating 3D models of

[1]The second portion of the site name is italicized as per the naming conventions of the literature on Chalcolithic Cyprus (Papaconstantinou 2013, 130).

material surfaces from photographs. This methodology results in quantitatively precise measurements of archaeological surfaces even faster and more cost-effectively than laser scanning, which is often out of the price range of many excavations (Ducke *et al.* 380; Olsen *et al.* 2013, 244-245; Tschauner and Siveroni Salinas 2007, 274). Moreover, the generated 3D models can be used as important tools for disseminating knowledge by packaging it in a visually engaging format which is legible to the general public (fig.1.1)(De Reu *et al.* 2013, 1119-1120). By providing a means of holistically recording excavation data, digitization techniques improve archaeologists' ability to preserve and communicate archaeological information. Thus, changing our thinking to "excavation is digitization" rather than destruction may prove incredibly beneficial for the discipline as a whole (Roosevelt *et al.* 2015, 325).

Figure 1.1: 3D reconstruction of Late Medieval horse skeletons at Lede "Domein Mesen," Belgium created through computer vision techniques using Agisoft Photoscan (De Reu *et al.* 2013, 1119).

1.2 3D GIS

An emerging field in digital site documentation is 3D GIS, an approach which stems from the larger field of geographic information systems (GIS) research. Generally, GIS is defined as an integrated "database management system designed for the acquisition, manipulation, visualization, management and display of spatially referenced data" (Aldenderfer 1996, 4; Connolly and Lake 2006b, 11). Originally utilized for map-making, users have since embraced and expanded the GIS toolkit to run complex spatial analyses in order to generate new data from existing datasets such as aerial photographs and satellite imagery (Aldenderfer 1996, 4). As the archaeological record consists of a complex web of interconnected artifacts, structures, and features within the landscape, the importance of GIS in the field of archaeology fundamentally lies in its ability to visually represent spatial relationships between data (Lock 2003, 165). Such novel technological capabilities inevitably opened up new directions in archaeological theory and research (Zubrow 2006, 14-15). This is most notable in landscape archaeology which sought to use GIS to better understand human behavior in relation to spatial variables (Richards-Rissetto 2017, 10).

Yet, attempting to represent 3D objects within a real-world context inherently necessitates the use of the third dimension. GIS software has traditionally involved x,y coordinates depicting 2D topology with elevation data stored as a single z-value for every x,y coordinate in the GIS system. This is most notable in commonly used digital elevation models (DEMs) and topographic maps: vertical or overhanging surfaces can not be modeled. Furthermore, if multiple objects (such as artifacts) are located in the same x, y coordinate but at different elevations, they would be plotted as a single overlapping point. Since true 3D spatial relationships are not possible in this system, scholars have dubbed this 2.5D GIS (Fritsch 1996, 2015, Klinkenberg 2016, 39, van Leusen and van Gessel 2016, 33-34; Zlatanova 2002, 27).

Disciplines such as geology and archaeology have a need to depict more complex 3D relationships and volumetric data. Thus, 3D GIS has developed over the past two decades through intensive research and an expansion of software capabilities (Stoter and Zlatanova 2003, 1). Ultimately, 3D GIS combines database and spatial information recorded using photogrammetry, total station, and other techniques into a volumetric model that shows the spatial relationships between layers, features, and objects in full three dimensions (van Leusen and van Gessel 2016, 34). As Klinkenberg points out, a true 3D GIS system is capable of working in three dimensions not only for visualizing spatial data, but also for all other aspects of GIS functionality: data entry, database management, and analysis and manipulation (Klinkenberg 2016, 40).

1.3 Previous Research and Theoretical Implications

Documenting the three-dimensional qualities of excavations is not a new concept as archaeologist have traditionally recorded height data in plan and section drawings. Investigations into laser scanning and photogrammetry techniques for the documentation of 3D data has also been going on for quite some time (Roosevelt *et al.* 2015, 327). However, using 3D GIS for excavation documentation in particular has a shorter history and there are more than a few questions yet to be answered before it could be effectively implemented.

A major issue in the adoption of 3D GIS methodologies is the limit of software capabilities since most GIS programs are still primarily in 2.5D (Stoter and Zlatanova 2003; Rahman *et al.* 2008, 3-4). Furthermore, opening up the possibility of building 3D GIS models necessitates a change in excavation documentation workflows geared toward the collection of 3D data. This is a challenge in and of itself (Huggett 2013, 22). As such, there have a been a number of investigations by various scholars experimenting with various workflows and understanding the theoretical implications of applying digital documentation methods.

One example is the 3D-Digging Project at the site of Çatalhöyük, Turkey in which the researchers investigated various methodologies for 3D data acquisition using various laser scanning and computer vision techniques. The experiments during the 2010 to 2014 field seasons not only sought to test how 3D GIS could be more efficiently integrated into the excavation process but also whether it can offer a reflexive method for improving excavation practices (fig. 1.2)(Forte *et al.* 2012; Forte *et al.* 2015). A similar example is the collaborative excavations of the Iron Age site of Uppåkra, Sweden conducted by the Lund University and Visual Computing Lab in Pisa. Since the spring of 2010, the site has been used to test a variety of digital documentation methods. Like the 3D-Digging Project, the aim of these experiments is to understand the advantages and disadvantages of utilizing 3D documentation methods and to determine how these different methods and workflows affect on-site interpretation (Dell'Unto 2014, 152-153; van Riel 2016, 28-33). Such research is vital for understanding the implications of using digital technologies in the field before such methods become standardized and adopted as an acceptable workflow by the wider archaeological community.

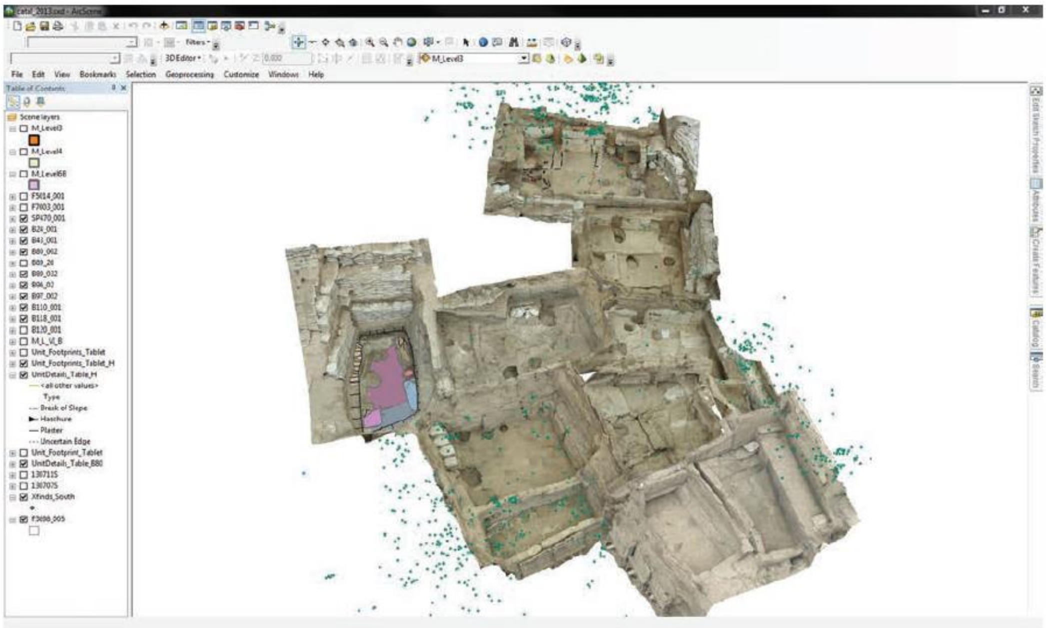

Figure 1.2: 3D GIS model of a portion of the Çatalhöyük archaeological site created from multiple datasets. This model incorporates the spatial location of artifacts with 3D representations of excavation layers (Forte *et al.* 2015, 50).

In addition, it is important to note that digital technologies only work if users know how to use them and apply them properly in the right situations (Bianchini *et al.* 2014, 96; Connolly and Lake 2006a, 1). Indeed, advances in technology must be supported by a solid theoretical underpinning (Zubrow 2006, 19). Without a reflexive approach, scholars may find themselves falling into the trap of throwing new technology at problems which may already be solved using analog methods simply because the technology is available. In order for computerized methodologies to be effective, there must be an added benefit the exceeds the capabilities of traditional approaches (Zubrow 2006, 14; Grosman 2016, 139-40). Most research has focused on the sustainability of 3D GIS approaches for supporting field documentation (Dell'Unto 2016, 310) and much of the literature concerning 3D GIS case studies does not transcend data acquisition and visualization (De Reu *et al.* 2012). Aside from the faster recording and more accurate measurements, is there a greater analytical potential that would justify switching documentation methods? One of the major challenges ahead is pushing the boundaries of current software capabilities to find novel ways of analyzing spatial data in the third dimension.

1.4 Stratigraphic Studies of Chalcolithic Cyprus

That being said, 3D GIS only serves a purpose if there is a purpose to serve. In the case of this project, 3D GIS methodology will be employed to contribute to stratigraphic research of west Cyprus in the Middle and Late Chalcolithic periods using the case study of the *Palloures* excavations. There are few examples of excavated sites in west Cyprus dating to these periods, and even fewer with visible architectural features. Most excavations have been carried out through the Lemba Archaeological Project (LAP) beginning in 1976 (https://www.ed.ac.uk) and in general exhibit a standard arrangement of free-standing roundhouses surrounded by open spaces and pathways. However, at a few sites there are noticeable changes in architecture and the organization of the built environment over time and this necessitates a more thorough investigation into inter-site variability of settlement arrangements (Papaconstantinou 2013, 130-131).

Moreover, LAP director Peltenburg warns of the problematic nature of stratigraphic analysis in Cypriot sites stating that the shallow occupation layers and post-depositional disturbances make it difficult to establish a definitive chronology (Peltenberg 1991, 19). For example, the site of Kissonerga-Mosphilia exhibits similar post-depositional disturbances as nearby *Palloures*: terracing for agricultural development and extensive plowing. Peltenburg's solution to understanding the stratigraphic sequence within this site was to "isolate vertical sets of occupation depositions, to apply a matrix form of analysis and sometimes to extrapolate from the ceramic record" (Peltenberg 1991, 19). This project, on the other hand, will explore whether 3D GIS can assist with visualizing and clarifying the stratigraphic sequence. Moreover, by providing another case study via the excavations at Chlorakas-*Palloures*, it aims to supplement our understanding of the settlement dynamics during the Chalcolithic as *Palloures* exhibits a generally deeper stratigraphy than nearby settlements. Does the site fit with the general settlement pattern evident at nearby sites? Does it deviate, and how?

1.5 The Case Study: Chlorakas-*Palloures*

The case study used for this project is the Middle to Late Chalcolithic (early 3rd millennium BC) site of Chlorakas-*Palloures* located in southwest Cyprus (fig. 1.3). This site was excavated from 2015 to 2017 as part of the *Palloures* Archaeological Project lead by Dr. Bleda Düring of Leiden University. As the plot was scheduled to be developed, the rescue excavation entailed uncovering as much of the site as possible during a limited time frame (Düring *et al.* 2016; Düring 2017; http://Palloures.eu). The 3D GIS visualization workflow study area includes adjacent trenches BU13, BV13, and BX13 (fig. 1.4).

Palloures is well-suited for research into 3D GIS since the excavations have been documented almost entirely using digital methods. This includes a digital database of excavation data in Microsoft Access and recording spatial data (including elevation) of contexts, features, and artifacts using a total station. The trenches and special features, such as burials, were photographed from all angles in order to attain a collection of photographs for creating 3D models using photogrammetry. Additionally, aerial photographs of the site were taken before the start of excavation using a *DJI Phantom vision+* quadcopter drone. The photographs were processed using Agisoft Photoscan in order to create a digital terrain model (DTM) of the site for further GIS analysis (Düring *et al.* 2016, 8, http://Palloures.eu).

Figure 1.3: Location of Chlorakas-*Palloures* (Figure by Author).

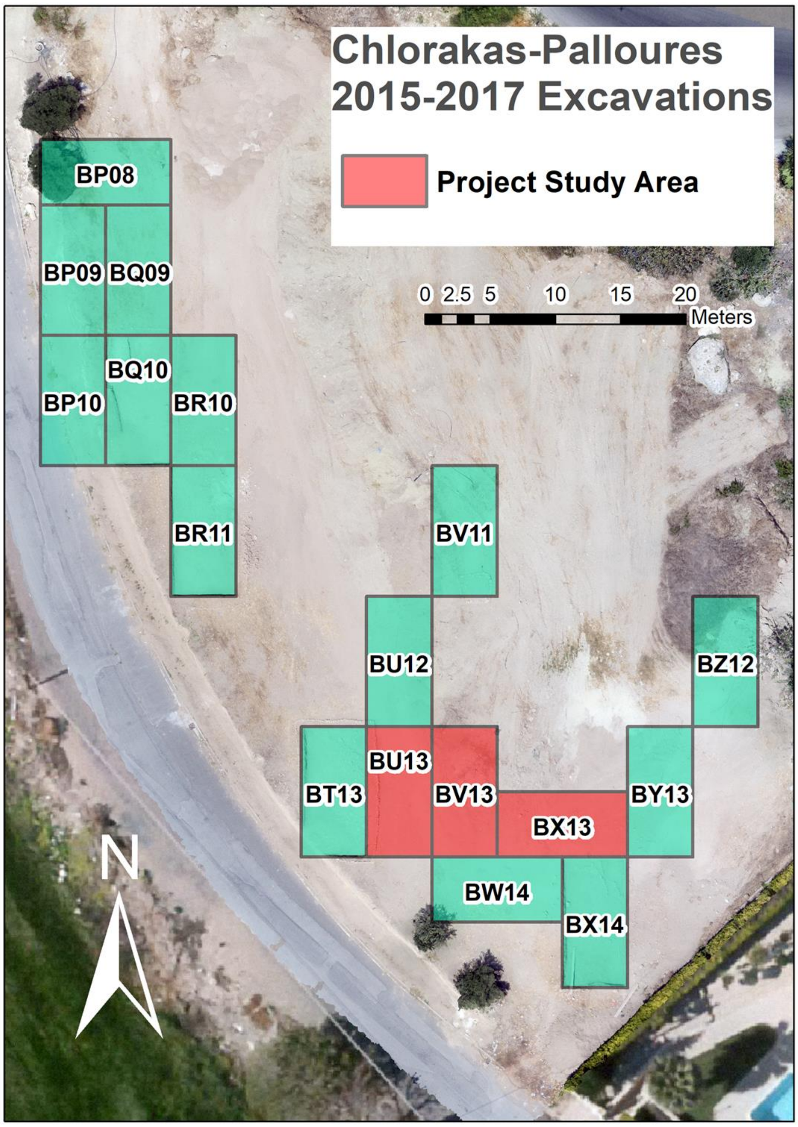

Figure 1.4: Trenches excavated at Chlorakas-*Palloures* during the 2015-2017 field seasons. Trenches modeled using the 3D GIS workflow presented in this project are highlighted in red (Figure by author).

1.6 Research Goals and Questions

The aim of this research has three components. First, I want to offer a reflexive review of current research on 3D GIS methodologies. Next, using *Palloures* as a case study, I plan on proposing a practical and standardized workflow for building a volumetric 3D GIS model of an excavation. I wish to express what the advantages and disadvantages of this workflow are, as well as warn of the potential pitfalls and technical limitations that may arise. Finally, I hope to contribute to stratigraphic research of Chalcolithic Cyprus by reviewing the stratigraphy of the site and discussing the differences between analysis using 3D GIS and 2D analog methods.

Thus, my research questions are:

1. Considering the technological limitations of 3D GIS software, what is a feasible post-excavation workflow for creating a 3D GIS model using total station data and photogrammetric 3D models?
2. What contributions (if any) can 3D GIS modeling make to post-excavation stratigraphic analysis?
    - What is the added value of using 3D GIS in comparison to traditional 2D methods?
3. What can a stratigraphic analysis of Chlorakas-*Palloures* tell us about the settlement dynamics at the site?

1.7 Methodology and Thesis Structure

The methodology employed to answer the questions listed above involves both literature-based research and a practical component. First, I discuss the history of 3D GIS in archaeological research in chapter 2. My intention is not to offer a discussion on the theory behind the various 3D data acquisition techniques such as photogrammetry, laser scanning, and LiDAR. A more thorough evaluation of these techniques can be found in other publications (van Riel 2016, 12-19). As my project focuses on post-processing of 3D spatial data, this research will instead involve a focused discussion of the various 3D GIS model-building workflows proposed by scholars in the past two decades.

In chapter 3, I present a literature-based review of prior excavations of Middle and Late Chalcolithic sites in west Cyprus focusing on the settlement dynamics evident in the archaeological record. This research centers around the sites of Kissonerga-*Mosphilia*, Kissonerga-*Mylouthkia,* and Lemba-*Lakkous,* all excavated under the direction of Peltenburg. Because Peltenburg has been instrumental to the study of Chalcolithic Cyprus, this study is heavily influenced by his work. This chapter also includes a brief discussion of 2D stratigraphic documentation methods as they relate to the case study.

The practical portion of this research involves developing a workflow for combining spatial datasets from the *Palloures* excavation in ESRI ArcScene 10.5.1, a 3D GIS platform with spatial analysis capabilities. Though it is not open-source, ESRI GIS programs are commonly licensed through universities and are thus available for archaeological research projects.

This workflow is described in detail in chapter 4. The chapter begins with an overview of the data acquisition methods employed on-site to document the excavation of Chlorakas-*Palloures*. Because my role in the project begins at the post-processing phase, I begin by organizing and cleaning the total station data of the archaeological contexts recorded in the field. This step involves identifying and digitizing any missing excavation units using the GIS software ESRI ArcMap. The cleaned unit spatial information and photogrammetric models of three trenches (BU13, BV13, and BX13) are then converted into 3D formats compatible with the software and imported into ESRI ArcScene. Next, I propose three different vector-based modeling methods for representing the volumes of stratigraphic units using the capabilities of the 3D Analyst toolkit provided in ArcScene. Finally, the information contained in the excavation database are joined to the resulting volumetric models of the trench stratigraphy.

The final 3D GIS models are presented in chapter 5 along with interpretations of the stratigraphic processes at Palloures as evident within the modeled trenches. This chapter also evaluates the results of the workflow in terms of whether or not it fits the definition of a true 3D GIS and critically compares the results of the three volumetric modeling methods tested during the project.

Overall, the findings of this project have both methodological and socio-cultural implications. In chapter 6, I discuss the challenges encountered during the modeling process and present suggestions for improvement of post-processing and data acquisition techniques for creating 3D GIS systems. This discussion compares the workflow presented in this project with the workflows presented by other scholars. Next, I provide an analysis of the strengths and weaknesses of 3D GIS and 2D plan and section drawings for the purposes of stratigraphic visualization and interpretation. Additionally, I discuss how the stratigraphy of *Palloures* conforms to or deviates from the settlement patterns visible at contemporary sites.

Finally, I present my conclusions in chapter 7 and conclude by offering suggestions for future fieldwork in terms of digital documentation and post-processing strategies for the purpose of intra-site stratigraphic analysis using 3D GIS.

Chapter 2: 3D GIS

3D GIS is not an entirely new concept in the field of archaeology. Indeed, researchers have been experimenting with this technique to aid in archaeological investigation since the advent of GIS itself. This chapter provides a working definition of 3D GIS and presents a history of how this approach was developed. Moreover, it summarizes how it has been applied in recent research contexts and discusses several methods developed by archaeologists to use 3D GIS for site documentation and stratigraphic analysis. These methods will be revisited in chapter 6, where they are compared and contrasted to the workflow introduced in this project. Finally, the chapter concludes with a discussion on the theoretical challenges of implementing 3D GIS workflows to archaeological research.

2.1 Defining 3D GIS

What exactly is 3D GIS? There are many definitions of this method in literature and thus it is necessary to establish what 3D GIS entails for the purposes of this research project. In their discussion of the potential use of 3D GIS in archaeological investigations, van Leusen and van Gessel define a 3D GIS model as “a volumetric model specifying BOTH layers, features and objects in three dimensions AND their spatial relationships” (van Leusen and van Gessel 2016, 34). They differentiate this solid volumetric modeling with 2D surface visualization in regular GIS applications. Instead of visualizing the outside of an object, what 3D GIS is concerned with is on the inside: the volume. The authors offer a geological model as an example (fig. 2.1)(van Leusen and van Gessel 2016, 34).

However, 3D GIS is not simply confined to visualizing volumes in space. Nguyen-Gia and his co-authors state that a 3D GIS system can “present, manage, manipulate, and analyze information linking with 3D phenomena” (Nguyen-Gia *et. al.* 2017, 126). This echoes other scholars’ definitions of 3D GIS which are predicated on its functionality as a GIS system. Rahman *et al.* (2008) argue that the principle functions of GIS are the capture, structuring, manipulation, analysis, and presentation of data (see Rahman et al 2008, 2 for a more detailed description of each function).

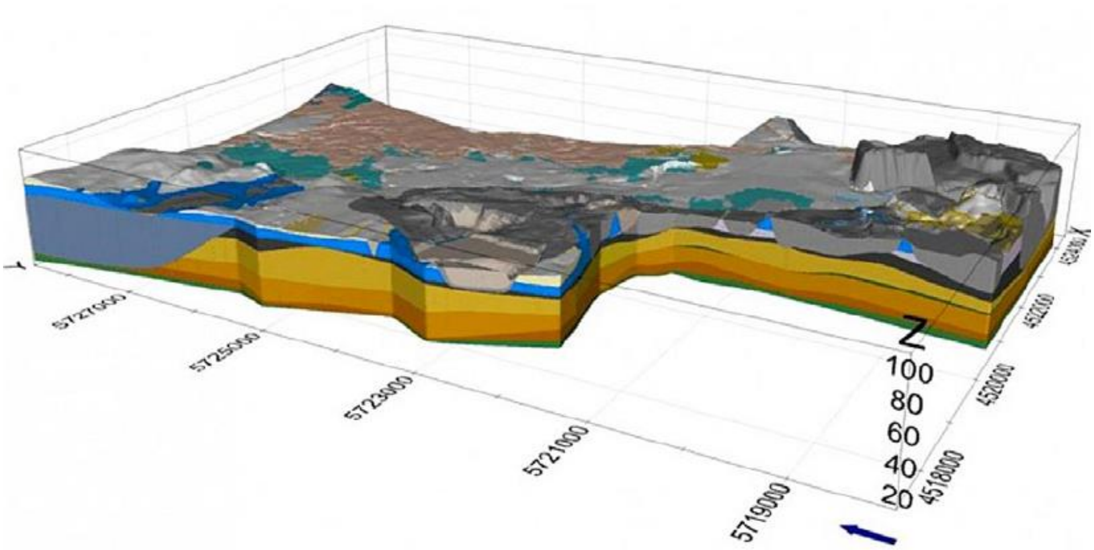

Figure 2.1: Three dimensional geological model of the Bitterfeld area showing geological stratigraphy (http://www.3d-geology.de) (van Leusen and van Gessel 2016, 34 Figure 1, per Martin Luther University Halle-Wittenberg).

Similarly, Klinkenberg cites Wheatley and Gillings who state that a GIS system is composed of four subsystems akin to the ones mentioned above: (1) data entry, (2) spatial database, (3) manipulation and analysis, and (4) reporting and visualization (Klinkenberg 2016, 39; Wheatley and Gillings 2002, 8-9). A true 3D GIS system must therefore be capable of performing all four functions in 3D in order to be considered successful. This definition has far-reaching implications as it opens up opportunities for using this approach for a variety of purposes aside from simply visualizing 3D relationships. Similar to regular GIS applications as discussed further in this chapter, 3D GIS should theoretically allow for the development of new methodological approaches for storing and analysing archaeological data. Thus, this is the definition employed in this project.

2.2 The History of GIS in Archaeological Research

Before delving into how 3D GIS is used in the context of archaeological research, it is necessary to first look at the history of how this method was developed. The advent of 3D GIS is irrevocably tied to the development of Geographic Information Systems (GIS) and its role in modern archaeological theory. Definitions of GIS are diverse and vary both between archaeologists and between disciplines since each discipline utilizes GIS for different purposes (Cowen 1988, 1551). In the most general sense, GIS can be understood as computer or database technology which is primarily used "to store, manipulate, analyze, and present information about geographic space" (Aldenderfer 1996, 4; Wheatley and Gillings 2002, 7-8;). GIS technologies are integrated systems that contain tools which allow the user to interact with and form interpretations of spatial data (Connolly and Lake 2006b, 11).

The history of GIS can be traced back to as early as 1950 when computers were first utilized for cartography. However, it is not until the 1960s when advances in technological capabilities and data storage facilitated the development of specialized computer programs to meet the demand for complex and nuanced spatial analysis and resource management. Commercialized GIS software began to appear in the 1970s, starting with the release of a vector-based software created by the Environmental Systems Research Institute (ESRI) (Wheatley and Gillings 2002, 8-10). Nowadays, both commercial and open-source GIS programs are used by a vast variety of disciplines and are prolific across all computer operating systems.

As early as the 1980s, archaeologists began to adopt GIS into their workflow, mainly for predictive modeling and its potential for cultural resource management (Wheatley and Gillings 2002, 15). Furthermore, by leveraging the functionality of GIS for integrating and analyzing large spatial datasets, researchers have developed a number of approaches to study past human behaviors including viewshed, line of sight, and cost surface analysis (for a detailed description of each, please refer to Lock 2003, 164-182). Thus, archaeologists began tackling research questions dealing not only with archaeological materials, but also environmental and topographical variables. This new direction in academic research had a considerable effect on landscape archaeology which seeks to understand the role of space and spatiality in relation to human behavior in order to offer an "explanation and interpretation of past landscape understandings" (Lock 2003, 164; Richards-Rissetto 2017, 10). However, critics have argued that using GIS technologies has the potential to overstate the effect of environmental variables on human behavior. Most notably, post-processual archaeologists have encouraged efforts to integrate the human perspective back into GIS analysis (Connolly and Lake 2006a, 8; Lock 2003, 173; van Riel 2016, 24; Richards-Rissetto 2017, 10-11).

2.3 2.5D v. 3D

The limitations of the software became more apparent as archaeologists and professionals in other fields began applying GIS methodology to a plethora of spatial problems. One of the major concerns was the lack of three dimensional functionality. This is problematic as the earth's surface is inherently three-dimensional and GIS software represented complex geological formations such as mountains and valleys in a 2D interface (Fritsch 1996, 1). The development of 3D functionality in GIS was, and continues to be, quite slow. Early solutions to this issue involved storing elevation data as an attribute: each x,y coordinate in geographical space was assigned a z-value to represent elevation. The resulting continuous surface with a singe z-value for each point on that surface was dubbed 2.5D (Fritsch 1996, 1). A classic example of 2.5D is a topographical map representing changes in elevation (fig. 2.2).

Figure 2.2: An example of a 2.5D GIS: a topographic map (http://geospatialtraining.com).

Although perfectly satisfactory for most topographical analyses, such as viewshed analysis and predictive modeling, 2.5D lacks the capacity to display more complex 3D shapes and object relationships (Klinkenberg 2016, 39, van Leusen and van Gessel 2016, 33-34; Zlatanova 2002, 27; Lock 2003, 177; Rahman *et al.* 2008, 3). Take, for instance, two artifacts found during an excavation at the same x,y coordinates but at two different elevations. A 2.5D GIS system would plot these two artifacts on top of each other on the map's surface. Moreover, 2.5D does not allows for modeling volumetric solid objects. Stratigraphic deposits, which are inherently three dimensional, are often depicted in GIS programs "with an elevation attribute tagged onto two-dimensional features," thus keeping all spatial analysis confined to a "horizontal plane" without taking into account the volume of the unit (Tschauner and Siveroni Salinas 2007, 274). On the other hand, a true 3D system would take volume into account and display the true spatial relationship between materials (Klinkenberg 2016, 39).

2.4 3D GIS Software Development:

Being able to visualize and analyze materials in three dimensions is critically important for a number of disciplines which deal with spatial information, especially georelated fields such as archaeology, geology, hydrographic survey, and oil exploration (Fritsch 1996, 1; Rahman *et al.* 2008, 3). The pressing need for improved functionality lead various GIS research groups to work on developing 3D software and structures as early as the late 1980s and well into the 1990s.

Rahman *et al.* (2008) succinctly describe the challenges faced by developers, stating that adding a third dimension presents a slough of problems in and of itself and that the development of a 3D GIS environment "needs a thorough investigation of many aspects of GIS including a different concept of modeling, representations and aspects of data structuring" (Rahman *et al.* 2008, 3). Proposed solutions included a variety of data models such as integrating relational databases with a triangulated irregular network (TIN) system and combining CAD with DTM to incorporate topographical information with 3D objects (Rahman *et al.* 2008, 5-6).

A few commercial developers offered 3D capabilities early on, such as ESRI, which released a 3D Analyst (3DA) module in the late 1990s as part of their software package ArcView. However, 3DA was primarily oriented towards 3D display and visualization and lacked essential analytical capabilities (Rahman *et al.* 2008, 8-9;). Another early software package is the Imagine system developed by ERDAS Inc. which included a module called VirtualGIS. This program, originally developed for image processing and remote sensing tasks, was similar to 3DA as it offered a visualization component but the analysis functions were lacking. GeoMedia Terrain created by Integraph Inc. and PAMAP GIS Topographer made by PCI Geomatics Inc. also offered 3D capabilities before the turn of the century yet this was also confined mainly to visualization (Rahman *et al.* 2008, 9-10).

Currently, there are many commercial and open source software packages available which include various degrees of 3D GIS capabilities. These include QGIS, Voxler3D, GSI3D, SGEMS, GRASS GIS, RockWorks, and ArcGIS. However, many of them do not far beyond the capabilities of the early programs mentioned above and lack a great degree of analytical functions (van Leusen and van Gessel 2016, 35). The most widely used and the most developed of these is ESRI's ArcScene which offers a user-friendly interface which does not require the end user to have extensive training in IT. Recent updates to the software have expanded the capabilities of its 3D Analyst extension and improved the memory allocation settings and speed of rendering within the program (Dell'Unto *et al.* 2016, 81).

2.5 3D GIS v. CAD

This discussion necessitates a quick note on the comparison of 3D GIS and CAD drawing methods. Originally intended for engineering and architecture design purposes, Computer-aided design (CAD) software allows for precise and "easy scalability between vector drawing on a computer and a real-world object(s)" (Jensen 2017, 3.1). Not surprisingly, it has been extensively used by archaeologists since the 1990s to aid in excavation documentation. Thus, it is arguable that digitally documentations methods akin to 3D GIS are not new in archaeology. Similar to vector drawings in GIS applications, CAD drawings are scale-able, have accurate spatial measurements, and may be linked to data within attribute tables (Beex 1995, 101). Indeed, early research on developing 3D GIS models integrated spatial data with the high-quality geometric modeling and structuring capabilities of CAD. Some of the first efforts included combining CAD objects with DTM or triangular irregular network (TIN) data structures to incorporate topographical data (Rahman *et al.* 2008, 5).

Although modern CAD programs have more extensive 3D modeling capabilities (for example, see http://www.arctron.de), they were not originally intended to be used for mapping and lack the geographic projection and topographical capabilities of GIS programs (fig. 2.3)(Jensen 2017, 3.1). Thus, CAD programs are often limited to use for intra-site analysis, rather than within the context of the greater landscape as this is far easier to do in GIS programs. As such, most applications of CAD in archaeology involve single-site documentation through the process of digitizing hand-drawn sections and plans created in the field (Beex 1995, 101). Unlike the primary dataset that is produced by measuring units in the field with a TS, this digitization process is considered a secondary step in data acquisition which inherently necessitates an extra time-consuming translation process that may transform the data (Morgan and Wright 2018, 142-143). The resulting 2D vector drawings may be spatially referenced and used in a GIS environment, however these are primarily limited to 2D or 2.5D.

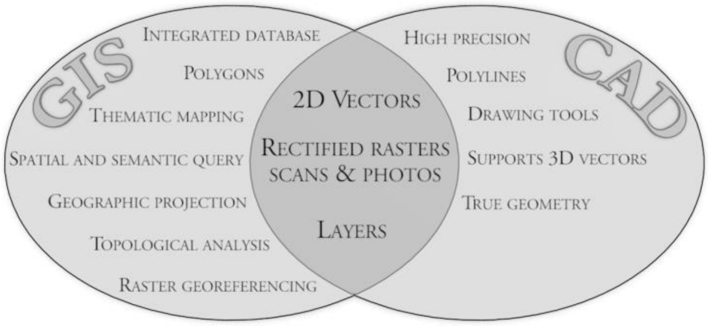

Figure 2.3: GIS v. CAD functionality: similarities and differences (Jensen 2017, 3.1).

2.6 Uses of 3D GIS in Archaeology

Now that I have established the history of 3D GIS development, I turn to how this approach can be applied within the field of archaeology. Indeed, moving beyond looking at sites from the perspective of flat 2D drawings to seeing them in a more intuitive 3D space opens up a variety of possibilities for archaeological research. An in-depth discussion on all the uses of 3D GIS is beyond the scope of this project (for a more nuanced summary of 3D GIS case studies as analytical tools, please refer to Piccoli 2018). However, I would like to highlight a few case studies exploring the analytical potential of this methodology.

First, participants in a session at the 2012 CAA conference discussed a number of uses for 3D GIS. They came up with a variety of possibilities within the realm of cultural resource management such as 3D predictive modeling and comparing differences in material preservation due to geo(morpho-)logical and anthropogenic processes (van Leusen & van Gessel 2016, 35), although these have not been fully explored. On the other hand, the Swedish Pompeii Project focused on architectural analysis by creating a 3D GIS model of the Insula V 1 Pompeian city block (www.pompejiprojektet.se). This endeavour provided scholars with a digital platform for experimenting with various research directions including using 3D GIS as a spatial database for documenting archaeological features (Dell'Unto *et al.* 2016, 82-83), assessing and monitoring the architectural degradation of ancient structures (fig. 2.4)(Campanaro *et al.* 2015, 321; Dell'Unto *et al.* 2016, 76-77), and visibility analysis of decorative elements (Landeschi 2018, 4-6; Landeschi *et al.* 2015). Furthermore, Richards-Rissetto explored using a 3D GIS approach to insert a phenomenological perspective to architectural analysis. Citing MayaArch3D, a 3D webGIS project which aims to document, visualize, and analyze the Mayan archaeological site of Copan, she argues that this methodology can provide a nuanced illustration of the accessibility and visibility of iconographic features in architectural space which may be lost in traditional 2D visualizations (Richards-Rissetto 2017, 12-16). In this way, 3D methodologies can re-insert a human perspective back into GIS analysis.

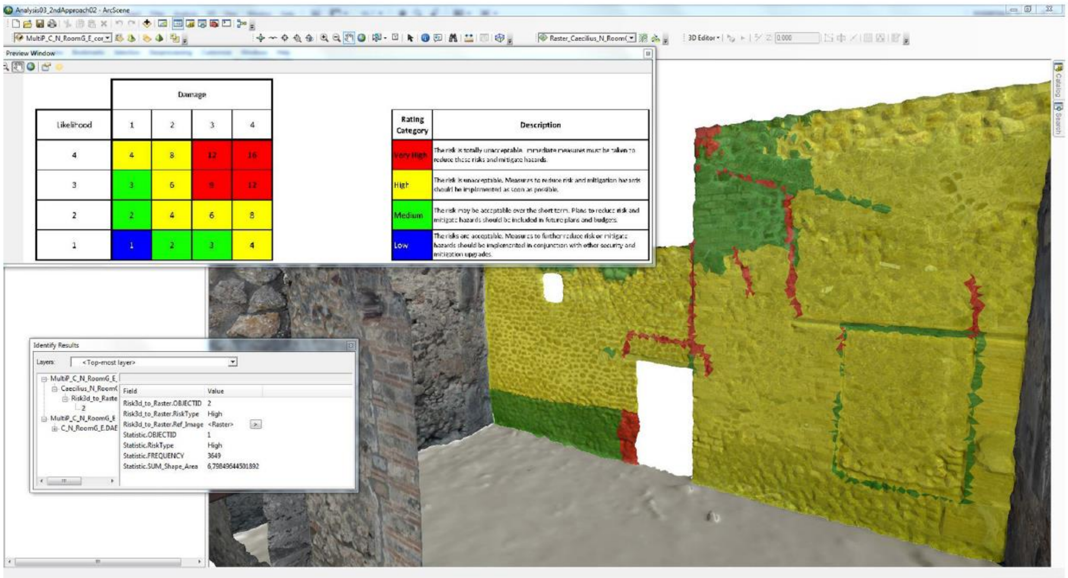

Figure 2.4: A wall within the 3D model of Insula V 1 in Pompeii. Each colored area is linked to a different level of risk for heritage preservation as described by the associated table and matrix (Campanaro *et al.* 2015, 330, figure 10).

Overall, these studies highlight the potential for 3D GIS to supersede the limitations of 2D approaches for spatial analysis. Moreover, they emphasize how expanding our thinking to the three dimensions can benefit our understanding of the past. I now turn to the particular focus of this research project: the use of 3D GIS for the documenting archaeological excavations and for intra-site stratigraphic analysis.

With the advent of 3D digital recording technologies such as laser scanners and photogrammetry software, various workflows have also been presented for a complete digital documentation of archaeological sites and features. Yet, many recent attempts at incorporating digital recording techniques often fall short of true 3D GIS functionality and commonly utilize 3D models merely for "geometrical reference in support of the graphic documentation," which reduces their usefulness for complex spatial analysis (Dell'Unto *et al.* 2017, 632). Take, for instance, the case study of Portonovo in Italy (Barbaro *et al* 2015, 594-598) or that of the megalithic necropolis of Panoría in Spain (Benavides López *et al* 2016, 495-498). In both case studies, 3D models acquired during fieldwork are used mainly for the creation of orthoimages for the purpose of data collection and visualization. The resulting dataset is relegated to 2.5D and 3D spatial relationships between stratigraphic layers are not fully visualized. True 3D GIS workflows, on the other hand, are far more rare in excavation practice. A few important case studies are discussed in the next section.

2.7 Comparative Studies for Developing Effective 3D GIS Workflows

The aim of this paper is to develop a feasible workflow for creating a true 3D GIS system which allows for the analysis of site stratigraphy. Several research projects share a number of similarities with the workflow employed in this endeavor. These projects are summarized here and will be revisited in chapter 6 in order to explore best practices for building 3D GIS models for intra-site stratigraphic analysis.

First, methods for designing a holistic 3D GIS documentation system were explored at the stratigraphically complex Neolithic site of Çatalhöyük in Turkey. During their investigations, researchers experimented with laser scanning, computer vision, and photogrammetry techniques to find the most efficient method of creating 3D models in the field primarily aiming to facilitate a more reflexive system of on-site interpretation (Forte *et al.* 2012, 370-374; Forte *et al.* 2015, 44-47). The project involved integrating various typologies of data including 3D models of the excavation and data collected from previous field seasons within a 3D GIS environment using ESRI ArcScene. The resulting 3D environment was used for a spatial analysis to identify different activity areas within a house (see fig. 1.2)(Forte *et al.* 2015, 50-53). Furthermore, this methodology made it possible to transfer the created model to a virtual reality platforms. This allowed researchers to explore and form interpretations of the site from a completely different perspective as embodied observers within the architectural space (Forte *et al.* 2015, 49). Though the results of this case study are very promising, most archaeological investigations do not have access to as many resources as a famous site like Çatalhöyük. For instance, the virtual reality platform used in this case study may be out of the price range of smaller excavation projects.

Another workflow of interest is the recording system developed for excavating the site of Kaymakçi within the Kaymakçi Archaeological Project (KAP). Along with being "100% digital," this recording system stands out in its focus on volumetric 3D recording (Roosevelt *et al.* 2015, 329). This workflow closely follows a single-context documentation methodology which enables archaeologists to record the volumetric extent of each deposit uncovered during fieldwork using 3D modeling techniques. The processes is as follows: as a new stratigraphic unit is uncovered, a photogrammtertic 3D model of the top surface is created and a corresponding orthoimage is generated using AgiSoft PhotoScan

Pro. This orthoimage is then imported into an ArcMap GIS environment in which the extent of the unit is drawn in as a polygon feature (Roosevelt *et al.* 2015, 334). After this, the entire unit is excavated in its entirety and the bottom of this unit is documented using the aforementioned procedure. Using this dataset, researchers recreate the volume of each stratigraphic deposit by combining the 3D model point clouds of the top and bottom of each unit into a single model in the open-source program CloudCompare (fig. 2.5)(Roosevelt *et al.* 2015, 338-339). This method forces excavators to think volumetrically and be mindful of the stratigraphic relationships identified in the field. However, carefully cleaning and combining point clouds for all units at a large stratigraphically dense site may not be practical as this would require an exceptionally long processing time.

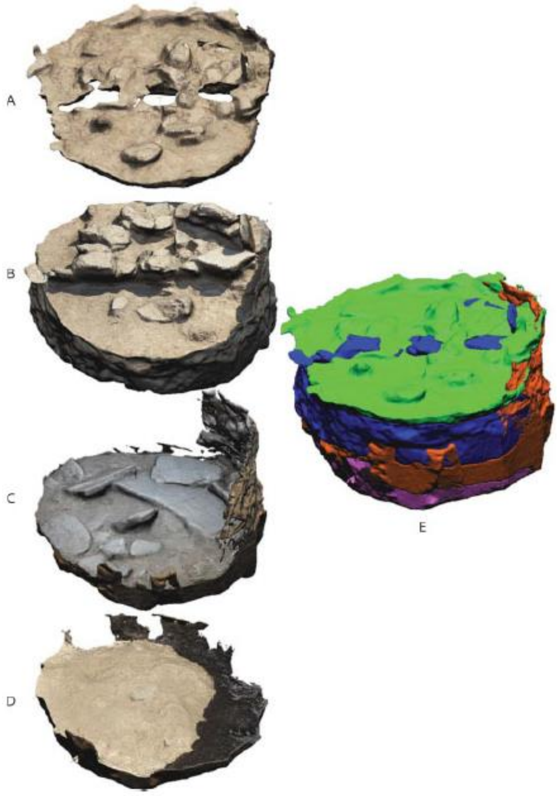

Figure 2.5: Volumetric 3D model of the stratigraphic units of a granary uncovered at Kaymakçi created using the KAP recording system. The end result is a water-tight representation of the stratigraphy of the feature (Roosevelt *et al.* 2015, 338).

Researchers at Lund University in Sweden in collaboration with the Visual Computing Lab in Pisa have also experimented with various acquisition techniques during the course of several field seasons at Uppåkra in Sweden (Dell'Unto 2014; Dell'Unto *et al.* 2017; van Riel 2016). Their most recent published approach leans heavily on the 3D Analyst toolkit within the newest versions of ESRI ArcScene. First, the team creates photogrammtery models of each layer of the excavation using AgiSoft Photoscan on tablet

PCs to process trench photographs and generate 3D models while on-site. These models are georeferenced using ground control points recorded using an RTK Geo Positioning System (GPS). These georeferenced 3D models are then imported into ESRI ArcScene and excavated units are digitally recorded within the 3D GIS interface as 3D polyline features directly on top of the imported trench models. All associated data collected in the field is recorded into the 3D GIS geodatabase, which is structured based on traditional context sheets (Dell'Unto *et al.* 2017, 636-640; van Riel 2016, 33, 44-47). The end result is a comprehensive database management system (DBMS) within the GIS software that combines recorded excavation data and various spatial data sets including vector data and 3D models (fig. 2.6). For future reference within this thesis, this workflow will be dubbed the 'Uppåkra' workflow as per the sites at which it was developed.

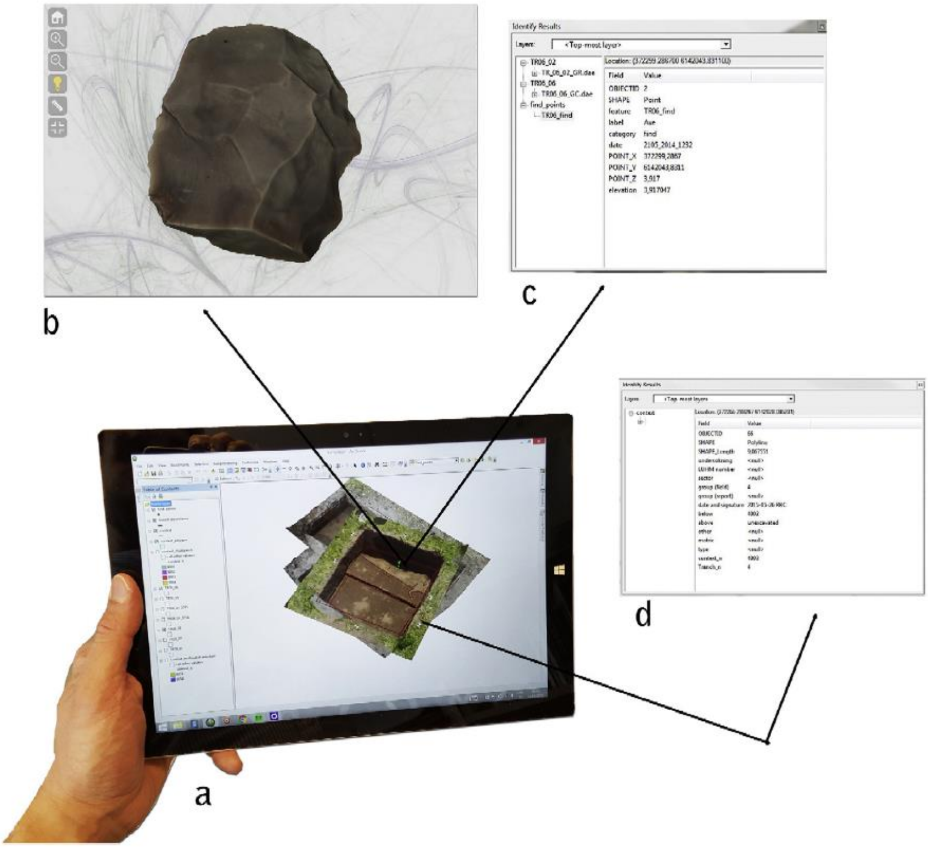

Figure 2.6: Data available through the ArcScene using the Uppåkra workflow, including (a) visualization of the site in 3D; (b) access to three-dimensional models of artifacts found within the trenches; (c) information regarding those artifacts; and (d) context sheets recorded on-site (Dell'Unto *et al.* 2017, 637, figure 5).

Along with providing access to the database and 3D models from previous field seasons, this workflow offers the possibility of using 3D data for real-time interpretations 'at the trowel's edge.' The entire documentation and data processing phases are done on site, thus eliminating the need for any post-processing at the end of the excavation. The authors argue that this method leads to reflexive excavation practices as all the documented data can be queried and referenced during the digging phase (Dell'Unto *et al.* 2017, 638; van Riel 2016, 48). Indeed, the research team was able to import 3D models of retrieved artifacts and situate them in the 3D GIS environment as they were uncovered in-situ. This practice made the spatial relationships between finds readily explicit thus helping to inform the excavation process (Dell'Unto *et al.* 2017, 640-642). The Lund University team further experimented with creating models of each excavation layer in order to reconstruct the stratigraphic composition of the trench and to better understand the spatial distribution of artifacts (Dell'Unto *et al.* 2017, 642-643). The results of this modeling process has not been extensively discussed in publications.

2.8 Voxel-Based 3D GIS Model Building

Most of the case studies described above and the workflow introduced through this thesis use vector-based modeling to visualize excavation units. Vector-based systems utilizes the principles of constructive solid modeling typically associated with CAD drawing; 3D objects are created by connecting 2D vectors or combining geometrical primitives such as cubes, spheres or cylinders. The resulting models are "boundary representations describing only the surface of a solid" (Tschauner and Siveroni Salinas, 2007, 281). Aside from this data structure, there is another noteworthy volumetric modeling approach which has been explored for the purposes of 3D GIS archaeological investigation: voxel-based modeling.

Instead of vectors, voxel-modeling systems extend a raster surface into the third dimension to create layers of 3D pixels, or voxels (fig. 2.7)(Lieberwirth 2008b, 79). Simply put, a 'voxel' is a volumetric pixel. A simple voxel structure consists of cuboidal elements which contain a given value. A simplified example of voxel structure is LEGO™ models which use blocks of different dimensions to represent objects in space. Yet, voxel structures may not necessarily be constant and symmetrical. Different configurations include the classic uniform structure, as well as regular, irregular, and structured forms which may be used to conform to various geological forms (fig. 2.8)(Fritsch 1996, 4). Voxels may also have more faces than that of a cube in more complex representations (Nguyen-Gia et. al. 2017, 128).

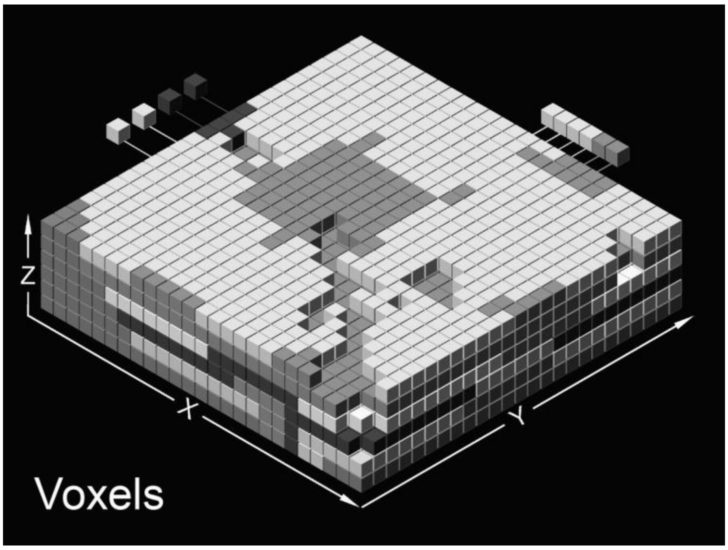

Figure 2.7: Example of a voxel data structure. A solid is modeled using identically-sized cubes thus preserving a uniform resolution throughout (Tschauner and Siveroni Salinas, 2007, 282, figure 12).

In general, voxels are used to represent the three-dimensional volume of objects and are often employed in the field of geology to model geological formations and soil layers (Fritsch 1996, 4; Lieberwirth 2008b, 80; Nguyen-Gia et. al. 2017, 128; Stoter and Zlatanova 2003, 2). Although not a new development (the use of voxels in 3D GIS applications in geological sciences dates back to the 1990s), this data structure is increasingly becoming a more prominent area of interests for 3D GIS modeling in archaeology (Fritsch 1996, 4; Tschauner and Siveroni Salinas 2007, 274).

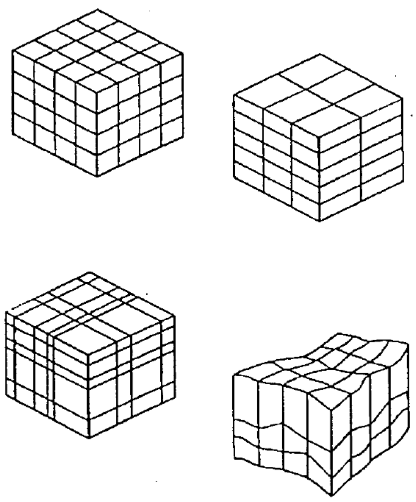

Figure 2.8: Voxel modeling structures: a: unifrom, b: regular; c: irregular, and; d: structured (Fritsch 1996, 4, figure 6).

There are, however, some methodological disadvantages that are important to take into account. First, it requires an incredibly high file size depending on the resolution of the model and thus necessitates high computer memory, storage space, and processing power (Rahman *et al.* 2008, 4-5; Stoter and Zlatanova 2003, 2; van Leusen and van Gessel 2016, 35). The issue of scale poses another challenge in that researchers are often interested in a wider geographical area as well as more localized inter-site research contexts (van Leusen and van Gessel 2016, 37). Even a single excavation level, the memory required to store stratigraphic data is enormous (Tschauner and Siveroni Salinas, 2007, 281). Furthermore, handling uncertainty in representation and the absence of data may pose problems as voxel-based modeling requires one to 'fill in the gaps.' In which case, how would we compare different models with different degrees of uncertainty (van Leusen and van Gessel 2016, 37)? Theoretical implications aside, the main obstacle to using voxel-based 3D GIS remains similar to that of 3D GIS in general: there is little consensus on how to implement it in practice and software capabilities are lacking. After all, modeling solids requires dimensional information of all surfaces which is difficult to accurately attain for archaeological units (Forte *et al.* 2015, 55; http://www.csanet.org).

Nevertheless, Lieberwirth argues that voxel-based modeling could potentially offer significant benefits to stratigraphic analysis. Able to represent continuous overlapping phenomenon, voxels may be used to represent stratigraphic units of excavations (van Leusen and van Gessel 2016, 35). The advantages of this technique are numerous: in a GIS environment, spatial location of artifact finds may be incorporated and volumetric calculations may aid in determining artifact densities for various artifact classes. Lieberwirth offers a possible workflow for making voxel-based modeling a reality using Grass GIS, an open source GIS software (Lieberwirth 2008a, 2).

Her approach involves digitizing two 2D section drawings on opposing sides of a trench using the CAD software AutoDesk Map 2004. As she uses drawings of the north and south sections of the trench, all the pits, walls, and other units found between these sections are disregarded. Next, she connects the units found within each section to create 2.5D raster surfaces (digital elevation models, or DEMs) representing the height values of each layer. She then uses a modified version of the GRASS GIS "flood-filling" algorithm, module r.vol.dem, to interpolate the volume between each DEM. The resulting model depicted a volumetric representation of each layer of the trench (fig. 2.9)(Lieberwirth 2008a, 2-7; Lieberwirth 2008b, 81-82). She then visualizes the resulting model in OSS ParaView which allows for robust visualization functions. Unlike 2D section drawings which only depict a single cross-section, Lieberwirth's volumetric 3D model may be 'cut' in any direction to study the stratigraphy from all sides (Lieberwirth 2008a, 7; Lieberwirth 2008b, 85). Additionally, this program allows her to add vector points to show artifact positions and to measure distances between objects within the model. Lieberwirth concludes that voxel-based modeling may offer the possibility to re-excavate a trench "step by step, disregarding the excavation method, following the natural course of the soil types" (Lieberwirth 2008a, 7).

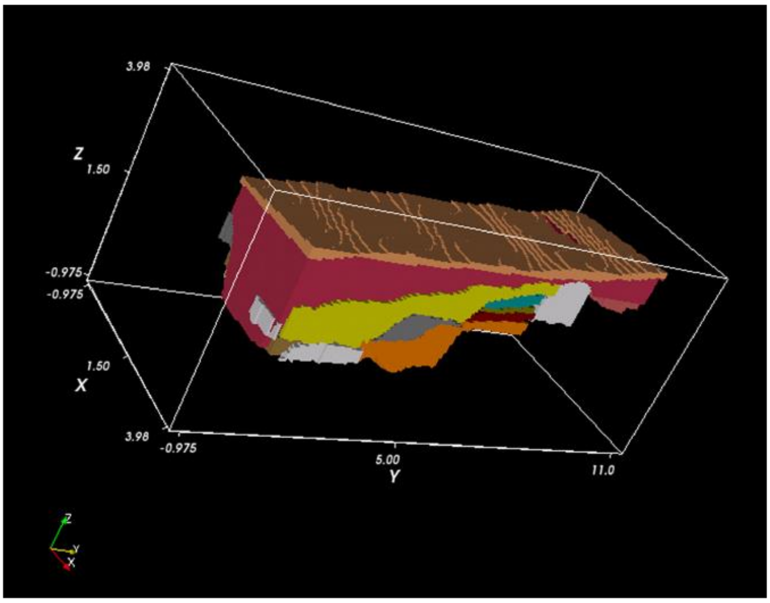

Figure 2.9: The resulting 3D voxel-based model of the stratigraphy of trench IX, Akroterion, Kythera, created in GRASS GIS and visualised in ParaView (Lieberwirth 2008a 6, figure 7).

2.9 Critiques and Theoretical Considerations

I now turn to the theoretical challenges researchers face for employing 3D GIS in archaeological investigations. In order to fully understand the current role of 3D GIS in archaeology, it is important to look deeper into the critiques surrounding its development since the potential of this methodology for furthering archaeological research has been a point of contention since its initial conception. The title of Klinkenberg's article, 'Are we there yet?' (Klinkenberg 2016, 39), is testament to this controversy. As with many other digital techniques introduced since the technological revolution of the 1960s, 3D GIS has been criticised extensively for its limited contribution to the field of archaeology and the implications of the technique on academic research are yet to be fully investigated. The fundamental questions remain: is it useful? And does it work?

First, we turn to the question of utility. Much like other techniques within the realm of digital archaeology, 3D GIS faces the criticism that researchers impulsively latch on to new technologies simply because they are available without fully understanding the ramifications of the software. Indeed, Zubrow warns that archaeologists are in danger of becoming 'technocrats' by applying new software indiscriminately (Zubrow 2006, 14, 26). This critique is common in GIS research and especially in landscape archaeology, which has gone through a theoretical overhaul to incorporate anthropological and cognitive theory in an attempt to mitigate the over-simplification of geographic information presented through GIS computations (Lock 2003, 173; Richards-Rissetto 2017, 10-11).

On the other hand, Zubrow argues that the development of new technologies plays a significant role in advancing archaeological theory as its opens up opportunities to ask questions that could not previously be answered using prior methodologies. However, there must be a tangible archaeological value to justify their use (Piccoli 2018, 74-75; Zubrow 2006, 15-16). For instance, photogrammetry and computer vision techniques have the potential to revolutionize the practice of field documentation by offering an inexpensive and accurate method of capturing the surface of archaeological sites (De Reu *et al.* 2013, 1110-1112). GIS offered novel analytical techniques such as cost surface analysis (Lock 2003, 172-173). Following this pattern, it is important to ask what valuable questions 3D GIS could answer that cannot be answered using an existing methodology.

Thus, the answer to "is it useful?" lies in the ability of 3D GIS to transcend the capabilities of traditional recording, visualization, and analysis methods. As Zubrow points out, there is no sense in applying a new technique on a problem that already has a simple solution (Zubrow 2006, 14, 26). In other words, before archaeologists shift excavation documentation methods to focus on the acquisition of digital data for the creation of 3D GIS models, a retrospective analysis is crucial to identify the added value of this technique upon archaeological practices and interpretations. If the same information can be derived from simple section and plan drawings, then there is no added advantage of using a complex 3D GIS tool requiring high computer processing power and a novel data organization structure.

Additionally, it is important to consider functionality. Does it work? 3D GIS faces the challenge of moving beyond simply a visualization technique. Despite the examples given in this chapter regarding the use of 3D GIS in current research, the old adage that digital models are nothing more than 'pretty pictures' inevitable comes up. Though this critique is more often directed at 3D reconstructions of architectural features, it may also be applied in this case as well. For instance, archaeologists have begun incorporating photogrammetry into the documentation strategy. However, 3D models are rarely used for purposes other than record-keeping and visualization (Dell'Unto 2016, 310; De Reu *et al.* 2013, 1119-1120). This issue primarily stems from the limitations of 3D GIS software. In 2008, Rahman *et al.* stated that at present, there is no true 3D GIS system available on the market. Most software packages have focused on providing a high-quality visual display of 3D features. However, developing analytical functionality commonly found in 2D GIS, such as buffering, intersection, and measurement tools, involves more work (Rahman *et al.* 2008, 1-4).

Unlike Rahman *et al.*, Klinkenberg writes after the release of ESRI ArcScene and improved 3D functionality in open-source GIS software. His evaluation of the 3D GIS offers a few case studies from his own research of Tell Sabi Abyad in Syria, and highlights the existing possibilities for database management and spatial analysis using ESRI ArcScene. Taking a more positive stance than his predecessors, Klinkenberg concludes that 3D GIS can and should be used for more than just visualization and may be leveraged to answer research questions regarding the spatial configuration of features and artifacts at archaeological sites (Klinkenberg 2016, 46). However, more research is necessary in order to explore the analytical possibilities inherent in this approach.

2.10 Data Accessibility and Sustainability

Other essential considerations concerning the implementation of 3D GIS are the issues of data accessibility and sustainability. Data accessibility describes “a user's ability to access or retrieve data stored within a database or other repository” (Richards-Rissetto and von Schwerin 2017, 39). As the functionality between software programs varies, access to 3D GIS models is limited to users with licenses to the programs in which these models were created and computer systems with enough memory and processing power to handle them.

Furthermore, software is constantly evolving and changing. Zubrow warns that computer technology becomes outdated and replaced with new applications every three years. Moreover, “in the more digital world of GIS, it is occurring more frequently” thus highlighting the importance of data sustainability (Zubrow 2006, 22). Richards-Rissetto and von Schwerin provide a rather simplistic definition of sustained data as “data that continues into the future” (Richards-Rissetto and von Schwerin 2017, 38). Although guidelines are available for thinking about sustainability for digital data (for example, see http://guides.archaeologydataservice.ac.uk), exactly how many years into the future is indeterminate and the question remains largely open-ended. In either case, 3D GIS data is incredibly susceptible to technologically obsolescence are this methodology is characterized by large data sets, rapidly-evolving software platforms, and changing data formats. Although a more in-depth examination of the particularities of data sustainability is beyond the scope of this project, moving forward, any discussion on the applicability of 3D GIS should involve thinking about how to make sure that the data collected today is accessible and usable by future researchers.

Overall, there is cause to further investigate the potential use of 3D GIS for archaeological purposes. This chapter summarized the history of 3D GIS development and presented a few examples of how archaeologists are utilizing this method in current research. Several workflows for the documentation and visualization of archaeological excavations were presented. In chapter 6 I will comment on how these workflows compare to the approach utilized during the course of this project in order to help advance the discussion on the use of 3D GIS for the documentation and analysis of archaeological stratigraphy.

Chapter 3: Stratigraphic Studies in West Cyprus (Chalcolithic Period: c. 3800-2500 BC)

This project is concerned with applying 3D GIS methodology in order to better understand the archaeological stratigraphy of Chlorakas-*Palloures*. Thus, this chapter discusses the particular issues involved in stratigraphic analysis of Chalcolithic Cypriot sites and provides an overview of prior research undertaken at three nearby Chalcolithic sites around *Palloures*: Kissonerga-*Mosphilia,* Kissonerga-*Mylouthkia,* and Lemba-*Lakkous.* The excavation at *Palloures* is introduced and some of the issues with traditional 2D documentation strategies are reviewed.

3.1 The Lemba Archaeological Project

Chlorakas-*Palloures* is located in the Paphos district in western Cyprus. This area has been primarily studied by Edgar Peltenburg who served as the director for the Lemba Archaeological Project (LAP), a research effort set up by the Department of Archaeology at the University of Edinburgh in cooperation with the Department of Antiquities of Cyprus. Beginning in 1976, extensive survey and excavation efforts were carried out through LAP at the key Chalcolithic sites in the Lemba region including Kissonerga-*Mosphilia,* Kissonerga-*Mylouthkia,* Souskiou Village, Souskiou-*Laona,* and Lemba-*Lakkous*. The overall aim of the Lemba project was to instigate the prehistory of the region with a particular focus on better understanding the Chalcolithic period (c. 3800-2500 BCE) (https://www.ed.ac.uk). Although the chronological phasing in Cyprus is contested and regional variations exist, in the context of this thesis I will be using subdivisions listed below (Peltenburg et al 2013, 2):

Early Chalcolithic: c. 3800-3400 BCE
Middle Chalcolithic: c. 3400-2900 BCE
Late Chalcolithic: c. 2800-2400 BCE

3.2 Studies of Stratigraphy at Chalcolithic Cypriot Sites

Archaeological evidence of settlements on Cyprus during this period is both patchy and limited in nature. This is partially due to a greater focus on tomb excavation and a geographic and chronological bias resulting from the division of the island in 1974 (Crewe 2014, 137). Only nineteen benchmark sites have been found dating to these periods and they are mainly located in the Paphos district and the Southern Chalk Plateaus regions in the western and southern coasts of the island (Peltenburg et al 2013, 6). Furthermore, sites are often disturbed by extensive post-depositional processes including terracing, plowing, and natural erosion. The effects of these have been exacerbated in modern times due to a growth of the tourism industry and changes in agriculture practice (Croft 2003, xxxi).

The effects of land development in the region had enormous negative impact on the archaeological record because the stratigraphic layers at prehistoric Cypriot sites typically are already shallow (Papaconstantinou 2013, 129; Peltenburg 1991, 19). Some scholars attribute the shallowness of the archaeological layers to the lack of defensive walls around settlements or their geographic position away from hilltops which may promote the accumulation of deposits (Webb and Frankel 2004, 135). Ephemeral sites are susceptible to dispersal as they are “less fixed in space than their Near Eastern counterparts” (Frankel *et al.* 2013, 15). Stratigraphic analysis of these sites is thus further complicated by shifting settlements and a variety of settlement use patterns evident in the archaeological record (fig. 3.1) (Frankel *et al.* 2013, 15-17; Papaconstantinou 2013, 129).

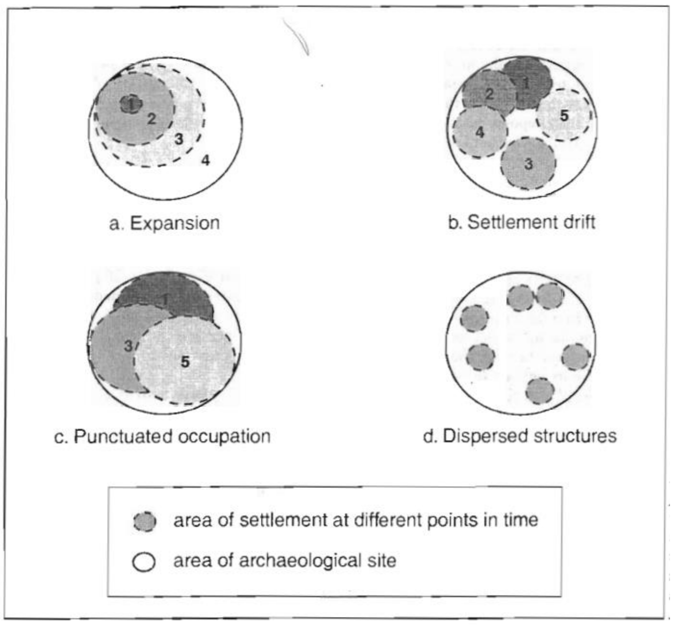

Figure 3.1: Examples of various patterns of settlement use: (a) expansion; (b) settlement drift;(c) punctuated occupation; (d) dispersed structures (Webb and Frankel 2004, 135, fig. 9.10).

The Harris Matrix approach to recording and clarifying the stratigraphic sequence at sites has been used to create intra-site chronological reconstructions. However, some scholars argue that it “has done little to overcome the problems of elucidating macroscale chronologies" (Frankel *et al.* 2013, 17). It is necessary to also link the patterns observed within individual sites to the greater geographic region. Overall, researchers have relied on other lines of evidence, such as ceramic and radiocarbon dating, when comparing chronological sequences between sites (Frankel *et al.* 2013, 15). However, there are a few sites on the island in which the architectural features may provide evidence of a stratigraphic sequence, especially in contexts with multiple layers associated with living floors. The most prominent architectural changes occur in the transition from the Chalcolithic to the Early Bronze Age period in which circular buildings give way to more rectilinear forms. On the other hand, we do not yet have a complete understanding of architectural development within the Chalcolithic period, although it is evident that local and regional variations exist (Bolger 2013, 2). Detecting changes and inter-site variations during the 3rd millenium is quite difficult given the fragmentary nature of the archaeological record (Papaconstantinou 2013, 129-130). Three prominent Chalcolithic sites, Kissonerga-*Mosphilia,* Kissonerga-*Mylouthkia,* and Lemba-*Lakkous* (fig. 3.2)*,* are discussed below.

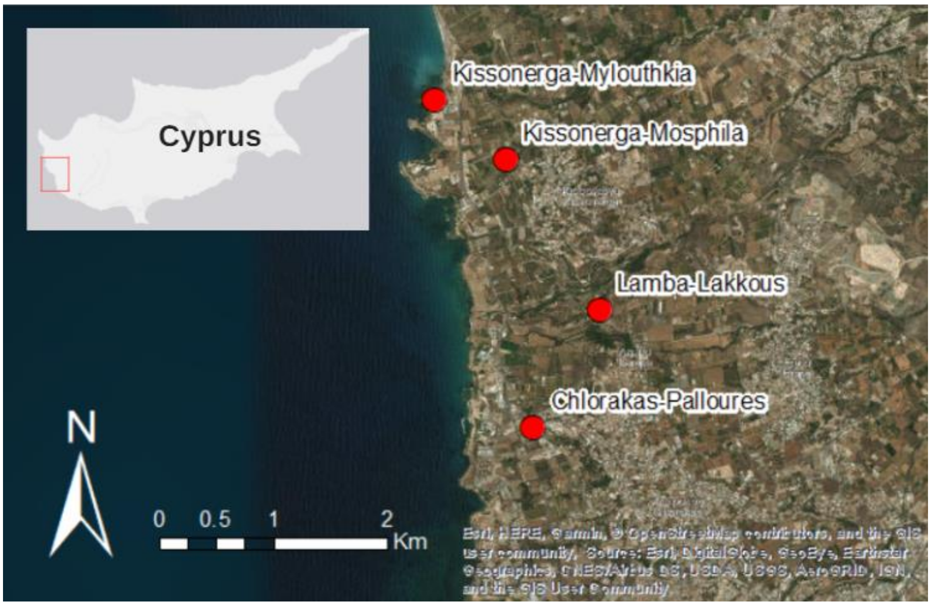

Figure 3.2: Map of Paphos District showing location of major archaeological sites including Chlorakas-*Palloures*, Lemba-*Lakkous*, Kissonerga-*Mosphila* and Kissonerga-*Mylouthkia* (figure by author).

3.2.1 Kissonerga-Mosphilia

Kissonerga-*Mosphilia* is located on the northern bank of the Skotinis stream on a coastal plain of Lemba region of the Paphos district 500m from the modern coastline (see fig. 3.2). The site has been excavated since 1983 and is the longest-lived and most prominent Chalcolithic site of the region. Evidence of occupation phases spans from the earliest prehistoric periods to the beginning of the Bronze Age (c. 4500-2300 BCE). At 12 hectares, the site is characterized by its exceptional size as other contemporaneous sites are significantly smaller, usually averaging around 3 hectares (Papaconstantinou 2013, 131; Peltenburg 1991, 19-20). Due to its large size, the site is referred to as Kissonerga. Other sites of the Lemba cluster, such as Kissonerga-*Mylouthkia*, are thus differentiated by their secondary name. Excavations from 1979 to 1992 opened up two areas of the site for investigation: the Main Area and the Upper Terrace in the north of the site (Frankel *et al.* 2013, 21). As with many other Cypriot sites, the stratigraphy is characteristically shallow with most deposits less than one meter deep and consisting primarily of superimposed architectural units. Kissonerga has also been subject to severe post-depositional damage due to erosion, plowing, and terracing (Peltenburg 1991, 19). Chronology of the site has therefore been derived from radiocarbon dating and material finds (mainly ceramics) associated with "securely stratified local sequences" (Frankel *et al.* 2013, 23).

The Middle Chalcolithic settlement (termed period 3B in publications) appears to be a single occupational episode based on the fact that the structures do not overlap and seem to be constructed from similar masonry (Frankel *et al.* 2013, 23; Papaconstantinou 2013, 131). The free-standing circular structures are surrounded by communal pathways (fig. 3.3)(Peltenburg 1991, 21-22). The settlement appears to be divided into two areas: a "high sector" in the center and north and a "lower sector" to the south characterized by differentiation in "the size and construction type of the buildings"(Papaconstantinou 2013, 133; Peltenburg *et al.* 2006, 1). The lower sector contains standard circular structures with floor space divided by ridges and walls constructed from plaster-covered rubble. The upper sector is marked by a communal ceremonial area surrounded by a few larger structures with a diameter of over 8.5 meters built from local calcarenite stone. These sectors are separated by a ditch and paved track running north-south (Peltenburg *et al.* 2006, 1). Small rectilinear structures are also present and show variety in size and function. Evidence of destruction and the abundance of archaeological materials from this period may point to a sudden abandonment of the settlement (Papaconstantinou 2013, 13, Peltenburg 1991, 22).

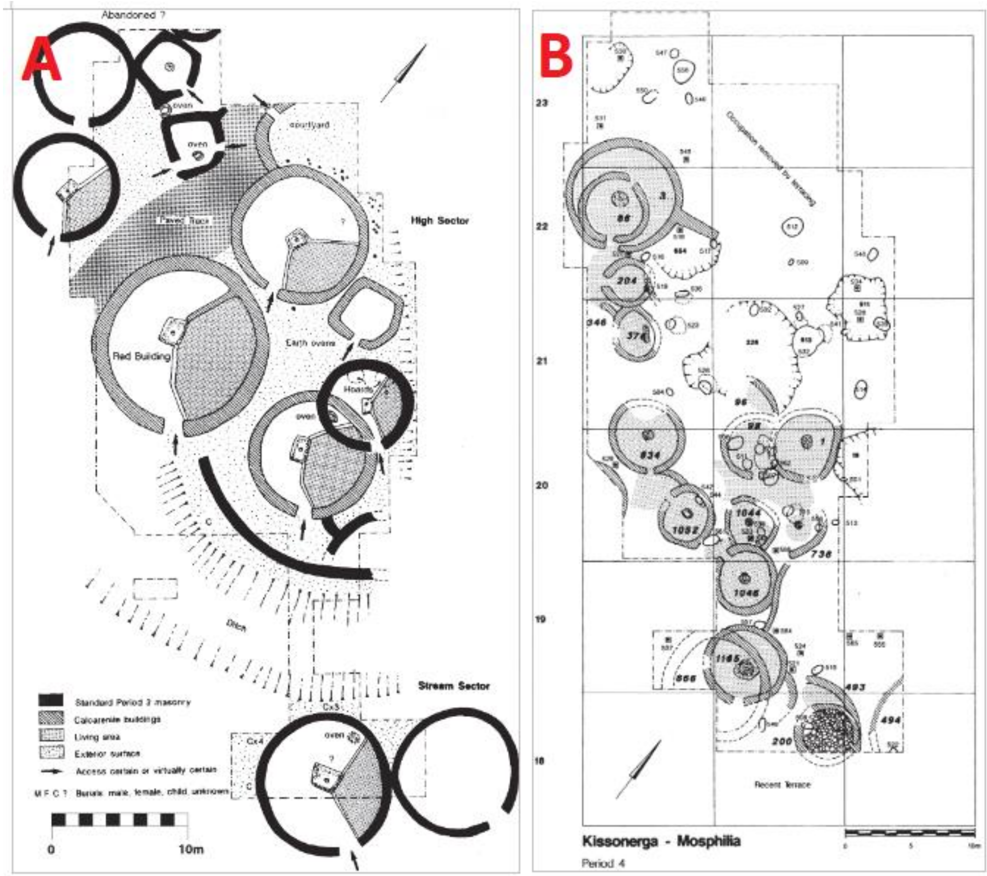

Figure 3.3: Single-phase plans of Kissonerga-Mosphilia: (A) Early-Middle Chalcolithic; (B) Late Chalcolithic (Peltenburg et al. 1998, fig. 31 in: Papaconstantinou 2013, 132, fig. 4.1; Peltenburg et al. 1998, fig. 39 in: Papaconstantinou 2013, 134, fig. 4.2).

The Late Chalcolithic phase at Kissonerga begins after a period of cultural break in which no evidence of occupation could be discerned (Papaconstantinou 2013, 133). The Late Chalcolithic phase spans roughly 200 years and is characterized by two periods of occupation: period 4A and 4B. Period 4B contained clusters of smaller structures and was divided into "three discrete zones...lacking communal facilities, public works and dominant structures" (Frankel *et al.* 2013, 23-24). Unlike period 3B, buildings are simply built and there is no evidence of ridges used within buildings to delineate internal divisions of space nor paved paths and communal walls within the settlement. Furthermore, there are more hearths within buildings rather than in communal spaces and more burials associated with structures (Papaconstantinou 2013, 133). Unfortunately, the erosion between the architectural features, a lack of differentiation in the ceramic materials, and problematic 14C dating prevented researchers from making interpretations concerning the relationships between the three zones with certainty (Frankel *et al.* 2013, 24). This settlement arrangement adjoining structures and clusters of buildings with associated intramural burials is considered typical for the Late Chalcolithic (Papaconstantinou 2013, 130).

3.2.2 Kissonerga-*Mylouthkia*

Located just one kilometer northwest of Kissonerga-Mosphilia, the site of Kissonerga-*Mylouthkia* is an eroded coastal site which is considered a part of the Lemba cluster of Chalcolithic sites in the Kitma Lowlands of west Cyprus. Henceforth referred to as *Mylouthkia*, the site was excavated from 1976 to 1996 by the LAP. Much like other sites in the region, it has been extensively affected by agricultural and housing development (Peltenburg e*t al.* 2003, xxxiii-xxxiv).

Excavations revealed two distinct types of buildings at Mylouthkia which correlate to the Early Chalcolithic and Middle Chalcolithic periods. Examples of the Early Chalcolithic house type consist of highly eroded circular hollows in the ground surrounded by multiple post-holes. Evidence of a plaster-lined floor surface and structural mud ridges lead scholars to infer that these structures were likely constructed from timber and mud walls of indeterminate height (Croft and Thomas 2003, 123). The Middle Chalcolithic houses are similar to those found at Kissonerga period 3B and are best exemplified by building 200 which showed evidence of four consecutive phases of construction, occupation, destruction, and collapse (fig. 3.4)(Croft and Thomas 2003, 119). The walls of this structure are built from plastered rubble and there is evidence of continued re-plastering of the interior. Postholes within the structure point to a wooden roof construction and there may be some evidence of spatial partitioning in the earlier phases. The hearth consists of a firebowl in the center of the building, a common Chalcolithic feature (Croft and Thomas 2003, 125-126).

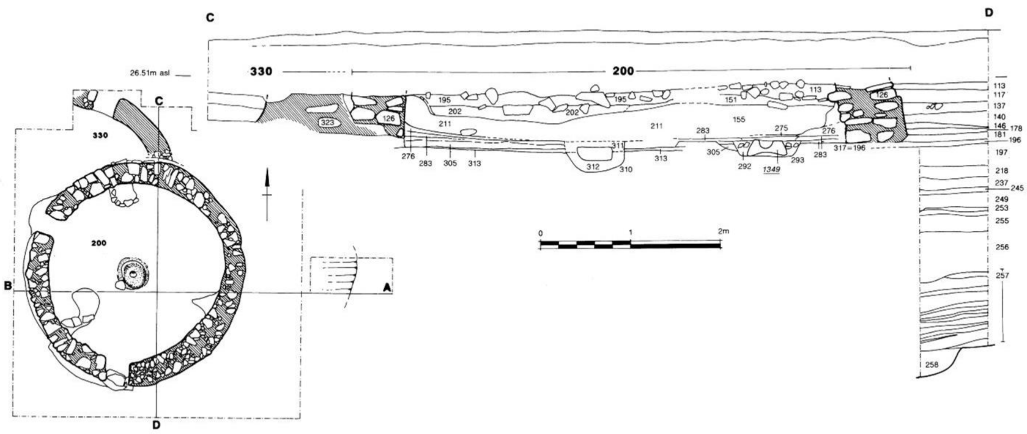

Figure 3.4: Plan and section of building 200 at Kissonerga-Mylouthkia, period 3 (after Peltenburg *et al.* 2003, fig. 42).

3.2.3 Lemba-Lakkous

Lemba-Lakkous is located in the foothills of the low Paphos Plateau ca. 4km north of the town of Paphos in the Lemba region and around 2 km south of Kissonerga. It is a small elongated settlement of around 3 hectares nestled between two streams on its northern and southern sides. Excavated from 1976 to 1983 by the LAP (Peltenburg and Baird 1985, 1-4), the site was predicted to span a greater part of the Chalcolithic period. Unfortunately, the stratigraphy was difficult to establish due to a variety of issues including the shallow depth of ancient remains, irregular bedrock deposits, and complex post-depositional disturbances. The scarce evidence of structures that were found indicates that the site was in use from the middle of the 4th to the early 3rd millennium BCE and was organized similar to the settlement found at Mosphilia. The Middle Chalcolithic phase was characterized by several uniform buildings clustered together with a circular hearth and ridges dividing the floor space. Burials were grouped together in large open communal areas between buildings (fig. 3.5)(Papaconstantinou 2013, 135).

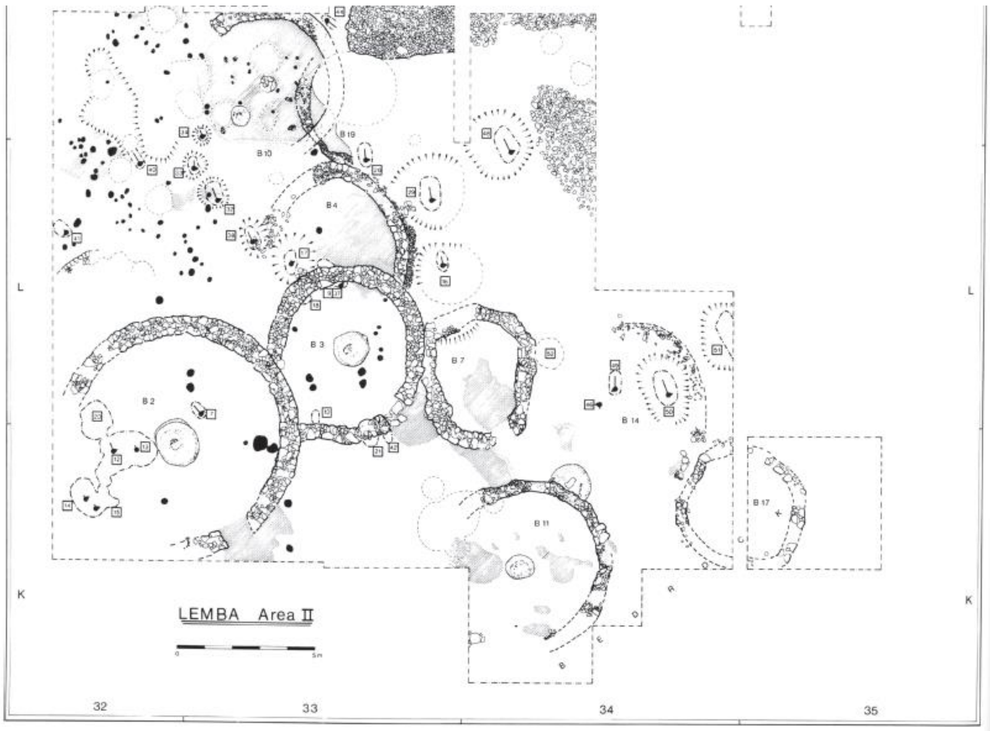

Figure 3.5: Plan of Area II at Lemba-Lakkous (after Peltenburg and Baird 1985, fig. 122 in: Papaconstantinou 2013, 136, fig. 4.4).

The architectural elements dating to the second phase of occupation (late 4th to early 3rd millenium BCE) are patchy, but do contain some evidence for buildings of various sizes with stone masonry and hard plaster floors. Overall there is a greater presence of storage areas between buildings. The final occupation phase (middle 3rd millennium) contains tight clusters of structures and intensive storage within structures as well as in communal areas (Papaconstantinou 2013, 135-137). There appears to be some settlement drift toward the south along the slope of the hillside. Much like other sites in the area, the chronology was reconstructed based on ceramics and ^{14}C dates (Frankel *et al.* 2013, 25-26).

3.3 Chlorakas-*Palloures*

The site of Chlorakas-*Palloures* is located 1 km south of Lemba-Lakkous and 2.3km south of Kissonerga within the Lemba cluster of Chalcolithic sites in the Kitma lowlands of the Paphos District (Düring *et al.* 2018, 12). In 2015, the *Palloures* Archaeological Project was set up to investigate the site by Leiden University in collaboration with the Department of Antiquities of the Republic of Cyprus in Nicosia. During the 2015 to 2017 field season, the project focused on a rescue excavation of a field with land registry number 568 which was expropriated from the owners as it was scheduled for development (Düring 2017, 1). As with other prehisotric sites in west Cyprus, *Palloures* was expected to be heavily influenced by post-depositional disturbances and had been greatly disturbed by agricultural and urban development since the 1970s (Düring *et al.* 2016, 1; Düring 2017, 5). Ceramic evidence from survey and excavations dates the site to the Middle and Late Chalcolithic periods. Thus, further research may contribute to a better understand of the transition between these two periods (Düring 2017, 12-13).

As demonstrated above, there is great variation in settlement size and settlement arrangements during the Chalcolothic period (Papaconstantinou 2013, 130). There are also few sites available for study and much difficulty involved in creating relative chronologies between them even with the support from ceramic analyses (Crewe 2014, 138). Unlike the three sites discussed above, the stratigraphy of *Palloures* is exceptionally deep and thus, research into the stratigraphic nature of the site may benefit our understanding of the chronological sequence and regional variations in settlement patterns during this period.

The excavations revealed architectural features in the northern and the southern parts of plot 568 with a distinct lack of archaeological materials in the central area. The northern section contains an unusually large and well-constructed building with a monumental hearth platform in the interior. This section generally contains larger structures than those found in the southern portion of the plot although the chronological relationship between them is not clear (Düring 2017, 18). This project will focus on three trenches in the southern half of the site: BU13, BX13, and BV13. Along with a deep stratigraphy of over one meter in trench BU13, trenches BV13 and BU13 contain large structures and several plaster floor layers. The intention of this project is to determine whether a 3D GIS model could clarify the stratigraphic relationships between these features.

3.4 2D Stratigraphic Documentation

In order to aid in a stratigraphic analysis of *Palloures*, it is also important to review the methods with which stratigraphy is traditionally documented at archaeological sites. Harris states that the stratigraphy of a site "is an unconsciously compiled record of past societies and their activities" (Harris 1989, 20). Therefore, the careful study of this stratigraphy would lead to an informed interpretation of past human activity. However, stratigraphic information is commonly recorded and published as 2D plan and section drawing which are prone to methodological issues inherent to the medium. First, projecting 3D information onto a 2D plane inevitably reduces its effectiveness to present complex 3D data. Section drawings are also often difficult to interpret for non-archaeologists (Reilly 1990, 133). Moreover, spatial data is often published as separate drawings and figures which leads to "notoriously selective and inaccessible collections of spatial data," thus "rewarding creative interpretation rather than "mere" collection of evidence" (Tschauner and Siveroni Salinas 2007, 273-274). This section reviews the issues within 2D section and plan drawing and asks the question: could 3D GIS provide a solution?

Section drawings are utilized to visualize the stratigraphic sequence of a site and to record the vertical dimension of deposits. As such, they provide a pseudo-3D reconstruction of the site's taphonomic processes and clarify stratigraphic relationships between units (Harris 1989, 72; Roskams 2001, 143-144). Roskams identifies two different types of section drawings: balk and cumulative. Balk sections are usually drawn at the end of an excavation by directly recording the stratigraphic sequence evident in trench walls or balks (Roskams 2001, 144-145). Cumulative sections are created by sequentially recording underlying units as they are uncovered, usually along a predetermined line across a specific area of interest. Unlike balk sections, the entire sequence is never seen in its entirety as units are removed before the next deposit is recorded (Roskams 2001, 145).

The most considerable drawback to both section drawing methods is that they are only able to record units found along an arbitrary line across the site. Any units found within the interior of a trench are not captured within the final drawing and thus section drawings never contain a complete stratigraphic sequence evident at the site or even within a single trench (Harris 1989, 71; Roskams 2001, 145; Tschauner and Siveroni Salinas 2007, 274). This is problematic for sites with ephemeral and irregular architectural features such as those found at Chalcolithic sites in Cyprus. This problem is compounded by the fact that cutting two adjacent deposits at different angles results in different interpretations of the data (fig. 3.6). Hence, additional individual sections of specific stratigraphic problems must be drawn in order to faithfully convey the spatial relationships between deposits. Yet, unless all unit relationships are detailed in this manner, the result of this documentation strategy is a "biased and partial record, which is potentially misleading." (Reilly 1990, 133).

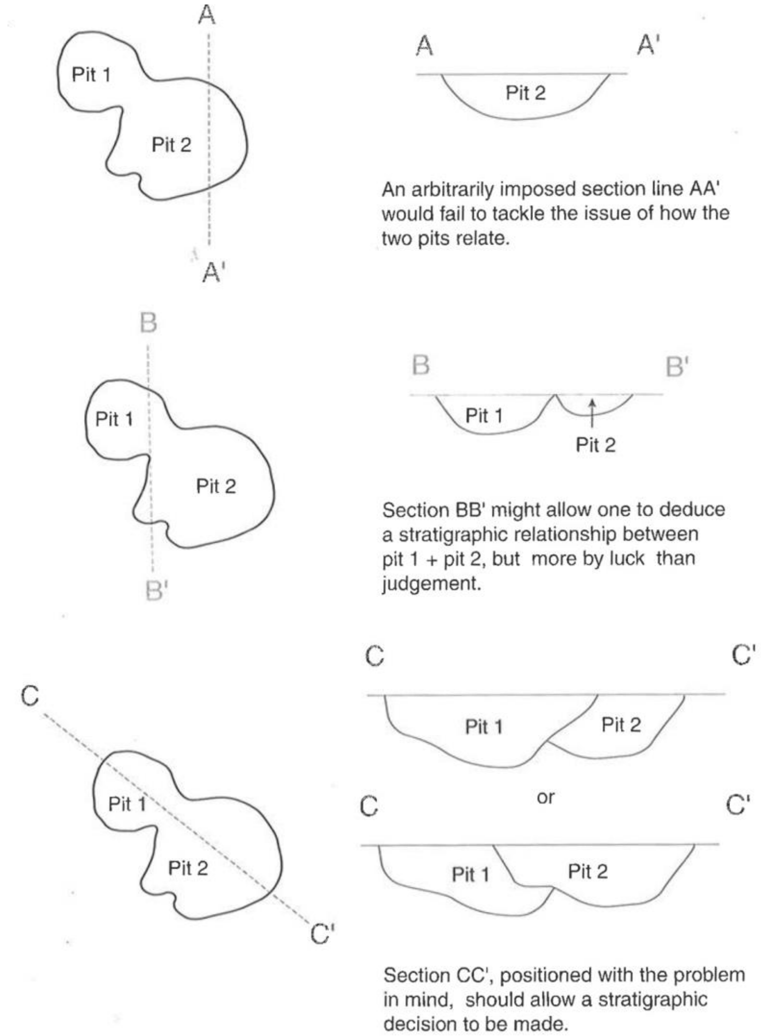

Figure 3.6: Section drawings show different unit relationships depending on the line of intersection (Roskams 2001, 148).

Along with section drawings, archaeologists employ several types of horizontal plan drawing methods each with their own theoretical underpinnings. These are top plans, single-phase plans, and single-context plans (fig. 3.7)(Roskams 2001, 137).

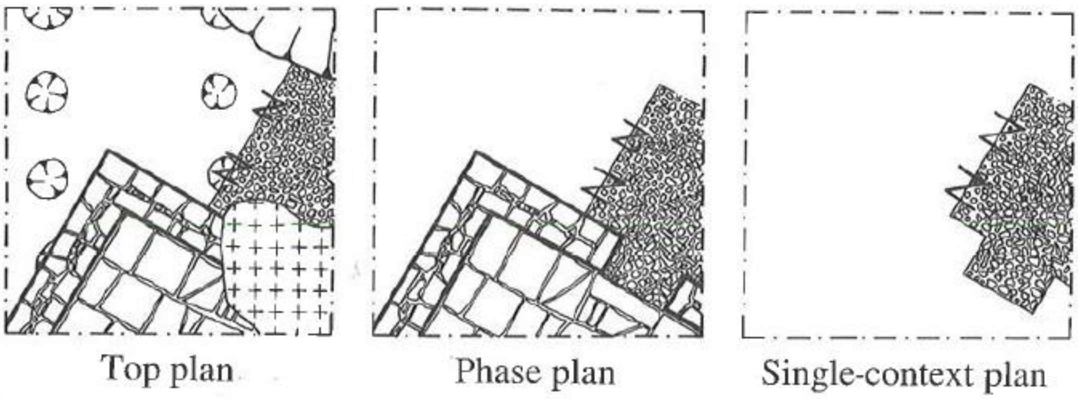

Figure 3.7: Examples of three types of plan drawings (after Roskams 2001, 138).

Top plans are drawings of the horizontal extent of an excavated area, drafted at a specified point in the excavation process. This method is inherently arbitrary; features are included in the drawing regardless of whether they belong to the same period. The resulting visualization thus do not represent an actual moment in the development of the site, but rather a snap-shot of the excavation process (Roskams 2001, 139). On the other hand, single-phase plans provide a horizontal visualization of only those features interpreted as belonging to a single point in time (Roskams 2001, 139). Yet, the value of this kind of drawing "depends on the validity of the phasing interpretation, which is at the discretion of the excavators (van Riel 2016, 61). Düring further critiques this approach stating that such phase interpretations often over-simplify past occupational processes into discrete periods in which all similar architectural features are represented as having been constructed, used, and abandoned at roughly the same time. In actuality, each architectural unit has its own life history that may not be easily correlated to other stratigraphic layers within the site. Settlements are "in a state of constant flux" and thus looking for overarching continuous occupational phases will often prove ineffectual (Düring 2012, 331). Düring suggests that focusing on a micro-stratigraphy of specific areas of excavations which may most reliably linked to other strata "if direct stratigraphic relationships exist or by means of a good series of radiocarbon dates" (Düring 2012, 331). Such micro-stratigraphies may serve as a more reliable means of depicting the nuances of complex site formation processes.

Thus, Single-context recording is the most suitable method for accomplishing this task. Indeed, *Palloures* is documented using the single-context method "in which each stratigraphic unit (layer, feature, or cut) is described separately and linked to adjacent stratigraphic units by means of a Harris Matrix" (Düring 2012, 325). As such, the Harris Matrix serves as a conceptual tool for mapping out spatial relationships between archaeological strata. Yet, single-context recording is not without its critiques. Roskam points out that this method may reduce the possibility of on-site interpretations as "each unit seem(s) to float free of any of its associates" (Roskams 2001, 1). On the other hand, I would argue that this approach actually facilitates stratigraphic interpretations in the field rather than detracts from it as the excavator becomes hyper aware of the relationships between the unit in question in comparison to other deposits (Harris 1989, 34). This is evident in the KAP recording system laid out by Roosevelt *et al.* (2015) which is geared toward single-context excavation and is highly focused on recording the top and bottom interfaces between deposits. This method "encourages best practices of material collection and stratigraphic separation because it prevents contexts that physically overlap whatsoever from simultaneous excavation" (Roosevelt *et al.* 2015, 334).

Overall, van Riel suggests that "a good practice could be to document single-context where possible, and a composite drawing where necessary" to ensure complete documentation of the archaeological record (van Riel 2016, 60). 3D GIS models of site stratigraphy may additionally offer a solution to some of these critiques.

In the next few chapters, I present a workflow for creating a 3D GIS model of three trenches from the *Palloures* excavation and discuss how this technique compares to traditional documentation approaches describes here.

Chapter 4: Methods

To generate a three-dimensional dataset for stratigraphic analysis, it is important to convert all spatial data collected in the field to a 3D format for use in ArcScene. In this chapter, I review the documentation methods used at *Palloures* and then describe the workflow I used to create a 3D GIS system following the definition presented in chapter 2: a volumetric model representing the spatial relationships of materials in the third dimension. As per Klinkenberg, this model must be capable of data entry, can serve as a spatial database, and should allow for analysis and visualization of spatial relationships (Klinkenberg 2016, 39). The aim of this research is to present an effective and feasible workflow which may be applied to future archaeological projects.

It is important to note that the dataset utilized for this research has been provided by Klinkenberg and has been partially post-processed by other members of the *Palloures* team. This work affects the subsequent steps in the 3D GIS workflow. The data acquisition practices and the post-processing done before the start of this research is outlined below.

4.1 *Palloures* Documentation Methods

Before describing the workflow used for post-processing, I summarize how the dataset was collected in the field. With a few minor exceptions, excavations at *Palloures* followed the same documentation methods during the 2015-2017 field seasons.

The *Palloures* excavation used a predefined grid of 5x10 meter excavation trenches based on the WGS coordinate system (fig. 4.1). Section balks were preserved only when adjacent trenches were excavated in the same excavation season. Trenches were named using the grid system, combining letters for the x axis and numbers for the y axis. The excavation was documented using the single-context recording method in which each stratigraphic unit is recorded individually. During the course of the excavation, the top interface of each unit was recorded using a Robotic Total Station (RTS) in 2015 and a regular Total Station in 2016 and 2017 (tab. 4.1). Each unit was assigned a number within the trench it is located in to ensure unit numbers are not duplicated. Thus, the units numbering follows the naming convention: 'trench number_unit number.' For example, unit 1 in trench BX13 is labeled BX13_1. Collections of artifact locations were also recorded using the TS as individual lots. Unlike the stratigraphic units, the bottom of each lot was measured. Data from the TS was exported at the end of each day.

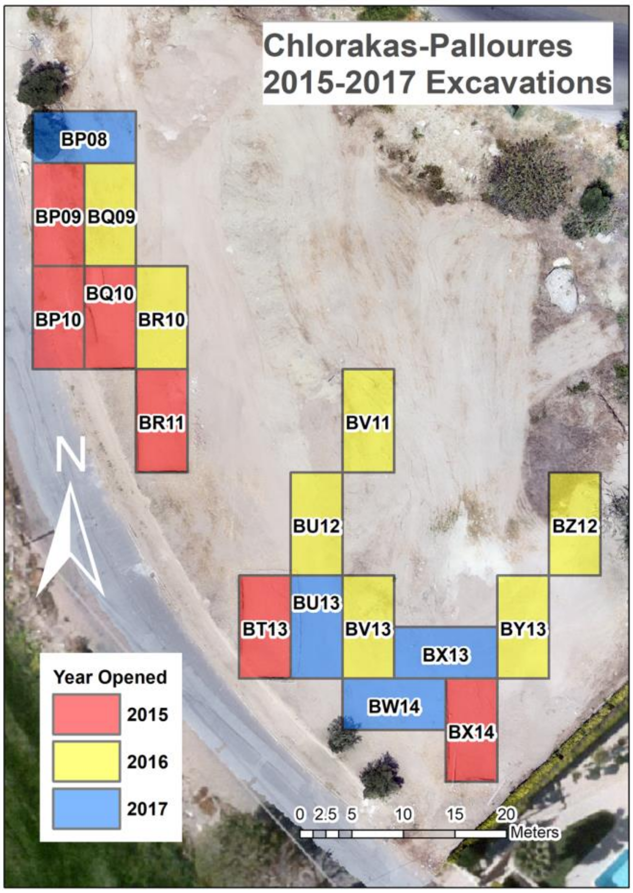

Figure 4.1: Trenches excavated at Chlorakas-*Palloures* during the 2015-2017 field seasons (figure by author).

Using different Total Stations each year lead to slight technical differences in the data collected. This is important to note because different post-processing procedures were necessary for each dataset in order to arrive at the final 3D GIS model. Budget constraints and issues in availability of resources commonly lead to differences in equipment between field seasons at many excavations. The intent of the workflow presented later in this chapter is to demonstrate how a 3D GIS system can be set up despite such changes.

Table 4.1: Differences in Total Stations used each year (table by author).

Year	Total Station Type	Recording Process	Output	Conversion to shapefile Required?
2015	Robotic (RTS)	Automatic, can follow the complex geometry of unit contours	3D Polygon Shapefile	No
2016-2017	Regular	Records one point at a time, unit contours are simplified	spreadsheet (.xlsx format) including x,y,z coordinates for each recorded point.	Yes

A *DJI Phantom vision+* quadcopter drone was used to take daily aerial photographs of trenches. Units were drawn directly on the aerial photographs and these annotations served as documentation of the day to day progress of the fieldwork. Furthermore, digital

3D models were created with photogrammetry techniques by processing ground-based photographs of features and trenches in the software AgiSoft Photoscan. Models were made for each special feature, including burials, architectural remains, and complex find contexts such as floors with multiple layers. Additionally, photogrammetry models were created for each trench at the end of its excavation. These trench models were used to generate orthophotos of the plan and of each section of each trench. These orthophotos were then annotated by the trench supervisor to depict the stratigraphic sequence within the sections and to create a composite plan of the units visible at the bottom of each trench.

Additionally, an excavation database was set up in Microsoft Access (fig. 4.2). Instead of using paper context sheets, information regarding each unit and lot was recorded in the field directly into the database using a tablet assigned to each trench. Along with descriptive data, the recorded information includes the stratigraphic relations between units identified in the field. A list of possible unit relations can be found in table 4.2.

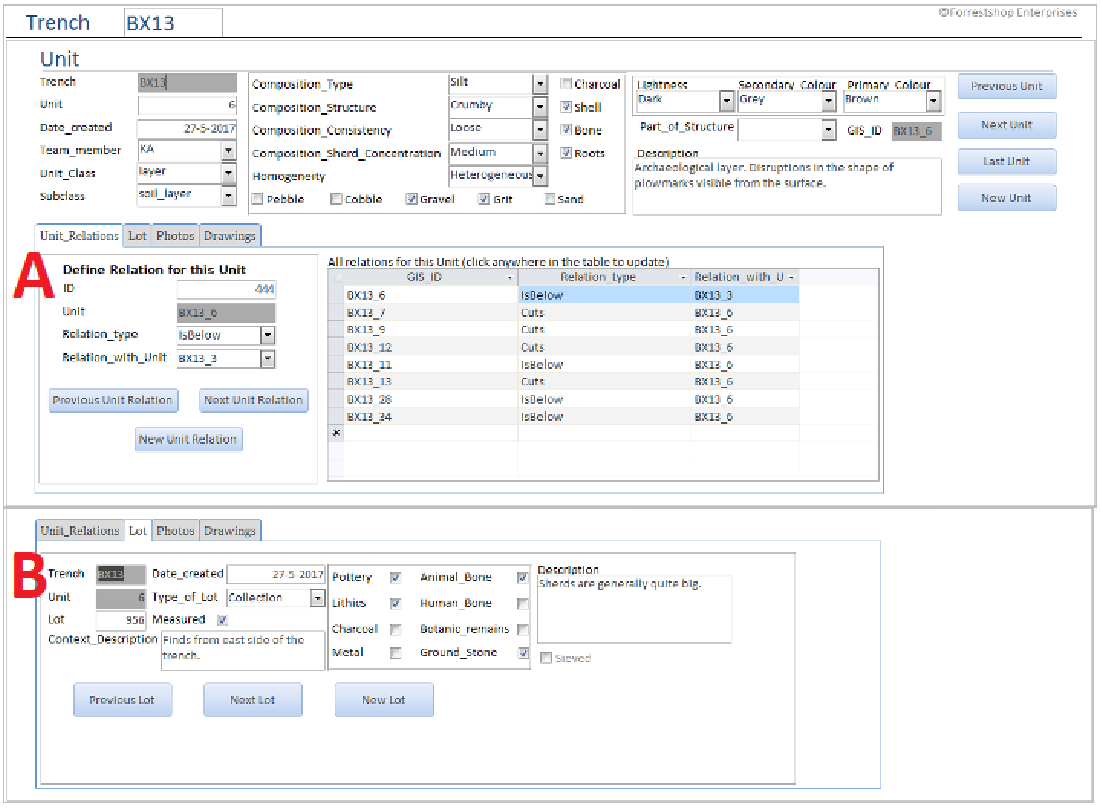

Figure 4.2: Excavation database interface in Microsoft Access: (A) unit data and (B) lot data for unit BX13_6.

Table 4.2: Possibilities of unit relations as recorded in the *Palloures* excavation database (table by author).

Relation	Description	Example
isAbove	Unit was formed after another unit	BU13_1 isAbove BU13_2
isBelow	Unit was formed before another unit	BX13_6 isBelow BX13_3
Cuts/IsCutBy	Unit is cutting into another unit	BX13_12 Cuts BX13_6
IsAdjacentTo	Unit is stratigraphically next to another unit	BU13_3 IsAdjacentTo BU13_2
IsContemporaryWith	Unit was formed at the same time as another unit	BU13_7 IsContemporaryWith BU13_6
IsFillOf	Unit is a fill of a pit unit	BU13_27 IsFillOf BU13_26
IsPartOf	Unit considered part of another unit	BU13_21 IsPartOf BU13_20

4.2 *Palloures* Dataset

All data recorded during the excavation and used for the purposes of this thesis is listed in table 4.3. As per the methodology described above, the resulting dataset it entirely digital. This includes the unit and lot spatial datasets, annotated drawings, 3D computer vision models of all trenches and special features, orthophotos, DEMs, and the excavation database. As mentioned earlier, there were some post-processing steps undertaken before the dataset was given to the author for the purposes of this research. Notably, the raw unit spatial data recorded by the TS was converted to shapefiles for visualization in ArcMap. However, the data from each year was converted using a different method[2]. For example, the 2016 unit data was converted to a 2D polygon shapefile feature class which did not include elevation data. The 2017 unit data, on the other hand, was converted to a 3D format but as a polyline shapefile feature class. The implications of this work is that different data cleaning and 3D conversion strategies were necessary during subsequent steps in order to integrate each dataset into the 3D GIS system.

[2]Since the original raw TS data for unit boundaries was mixed in with lot spatial data, it was more efficient to work with the already processed dataset despite differences in data formats.

Table 4.3: Dataset utilized for this project as provided by Victor Klinkenberg (table by author).

Dataset	Type	Geometry Type	3D?	Acquisition Method
2015 Units	Shapefile	Polygon Z	Yes	RTS
2016 Units	Shapefile	Polygon Z	No	TS
2017 Units	Shapefile	Polyline ZM	No	TS
2015 Lots	Shapefile	Point ZM	Yes	RTS
2016 Lots	Shapefile	Point ZM	Yes	TS
2017 Lots	Shapefile	Point ZM	Yes	TS
Trench Boundaries	Shapefile	Polygon	No	Digitized
Photogrammetry Models (all trenches and special features)	Collada (.dae)	Multipatch	Yes	Photographs/Computer Vision Software
Georeferenced Orthophotos (all trenches and special features)	TIFF	N/A	No	Photogrammtery Models
Georeferenced DEMs (all trenches and special features)	TIFF	N/A	N/A	Photogrammtery Models
Excavation Database	Miscrosoft Access	N/A	N/A	Field recording
Annotated Aerial Photographs	PDF	N/A	N/A	Field recording
Annotated Plan Drawings	PDF	N/A	N/A	Orthopohotos
Annotated Section Drawings	PDF	N/A	N/A	Orthopohotos
Trench Reports	Word documents	N/A	N/A	Field recording

4.3 Software

The software chosen for this project is listed in table 4.4. ESRI products ArcMap and ArcScene are used for all GIS processing. ESRI ArcScene comes with the 3D analyst toolkit which offers the most robust 3D capabilities for any GIS package currently available. On a personal level, the author of this thesis is more familiar with ESRI ArcMap than any other GIS software package and has a free 1-year student license for ArcMAp 10.5.1 on her personal laptop. On a practical level, Leiden University computers are equipped with licenses for ArcMap and ArcScene version 10.2.2. Both versions of ArcMap were used interchangeably throughout the project since the majority of the dataset was stored on university computers while the newer version of the software was installed on the personal laptop. ArcScene is particularly useful because recent updates to the software has allowed multiple different spatial data formats, such as 3D models created in Photoscan and multipatch features, to be imported and combined in the same environment (Dell'Unto 2016, 310-311). As it is open-source thus more-freely available, an alternative software package for the GIS processing may include QGIS. However, the three-dimensional capabilities of QGIS are limited to visualization and thus do not offer as many possibilities for analysis as the commercial software package provided by ESRI. Most open-source GIS software is limited to 3D visualization and thus ArcScene was chosen due to both availability and technological capability (van Leusen and van Gessel 2016, 35; Rahman et al 2008, 8-11).

Table 4.4: Chosen software (table by author).

Program Name	Manufacturer	Version	Type	Website	Open-Source
ArcMap	Esri	10.5.1	GIS Software	https://www.esri.com/en-us/home	No
ArcMap	Esri	10.2.2	GIS Software	https://www.esri.com/en-us/home	No
ArcScene	Esri	10.5.1	3D GIS Software	https://www.esri.com/en-us/home	No
XTools Pro	Xtools, Inc.	17	ArcMap Add-on	https://xtools.pro/en/	Yes
PhotoScan Professional	AgiSoft	1.4.0.5650	Computer Vision Software	http://www.agisoft.com/	No

Additionally, this workflow required the use of XTools Pro, an add-on for ArcMap which contains shapefile conversion tools that exceed the capabilities of the ArcMap toolkit. The benefits of this add-on will be discussed in more detail in the procedures below. AgiSoft Photoscan was used to generate 3D models using structure from motion (SFM) techniques. The software is also provides the possibility of generating DEMs and orthophotos from the 3D models themselves and to georeference all outputs. This software package is also licensed by Leiden University and is available for the purposes of this project.

4.4: 3D GIS Workflow

The remainder of this chapter outlines the workflow used to create the final 3D GIS model using the dataset listed above. It is the author's intention that this workflow could be applied on other projects with a similar dataset no matter the time period or geographic area investigated.

4.4.1 Importing 3D Models into ArcScene

Photogrammetric models of each trench were available in my dataset since they were created during the excavations. These models have already been generated and georeferenced using ten ground control points before the start of this thesis project. However, due to the high processing power required to render the models and textures within ArcScene, the file sizes for each model had to be reduced within AgiSoft Photoscan in order to be usable in further processing steps. The Lund University research team suggests that a low quality trench model with a small file size (as low as 20,000 vertices) is sufficient for the purpose of visualizing the spatial location of excavation units (Dell'Unto *et al.* 2017, 636). Thus, I decimated each model to 100,000 vertices as this preserved data quality and allowed for fast user experience while working within the software.

Next, each trench model was exported twice as in a Collada (.DAE) file format. The first export included geographic coordinates using the coordinate system utilized for the site: WGS 1984 UTM Zone 36N. The second export was done specifying a local coordinate system. This process is necessary due to the particularities of the ArcScene software. The "Import 3D Files" within the 3D Analyst module in ArcScene tool was used to import the geographic coordinate model which determines the x,y,z midpoint of the multipatch feature. This model was then replaced with the local coordinates model using the 3D Editor toolkit because the local coordinate model contains the geometry and texture. The results of the import can be seen in figure 4.3.

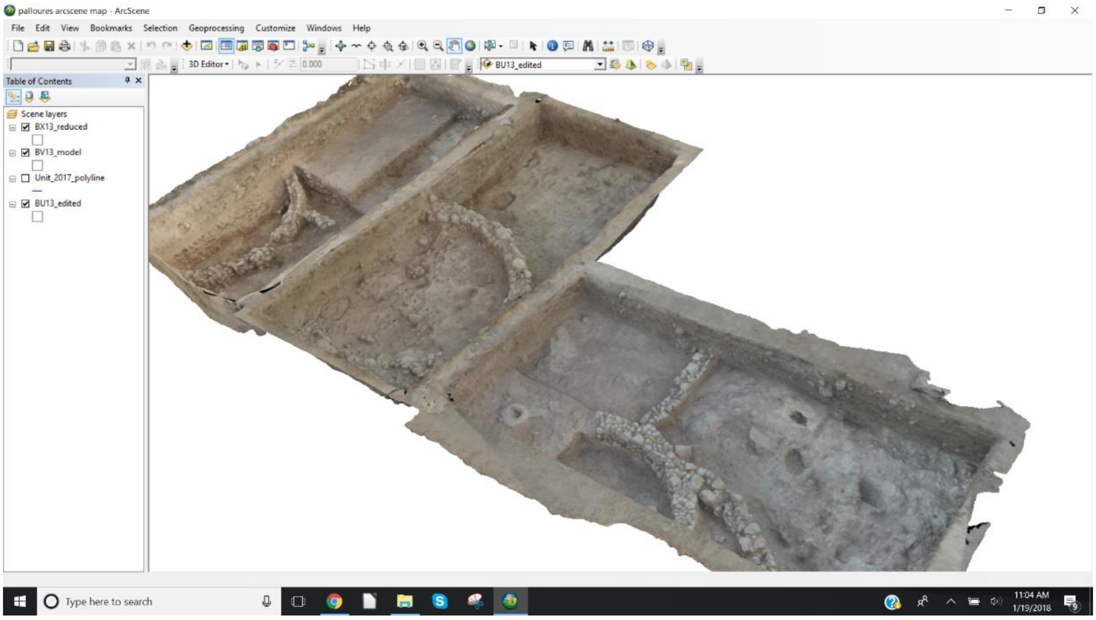

Figure 4.3: Overview of 3D photogrammetric models of trench BU13, BV13, and BX13 at Chlorakas-*Palloures* within a 3D GIS environment using the software ESRI ArcScene (figure by author).

4.4.2 Cleaning Total Station Data

Since the unit spatial data was recorded and converted using different methodologies for each year, it was important to evaluate whether any discrepancies exist in the recording methods and to determine how each dataset would need to be converted to 3D. Thus, the next step in the workflow was to review the spatial data exported from the TS, make any corrections necessary, and determine whether there are any units missing from the dataset. To organize this processes, I created an Excel spreadsheet by exporting the unit list from the excavation database (fig. 4.4; see supplementary materials for the full list). This sheet includes columns for trench number, the excavation year, and for inputting corrections which need to be made (or have been made). It also includes space for notes regarding the composition or spatial location of missing units and can be easily queried and filtered. The spreadsheet acts as a dynamic record for keeping track of changes and is therefore vital for organizing a large excavation dataset.

	A	B	C	D	E	F	G	H	I
1	Chlorakas-Palloures (2015-2017)								
2	List of Units								
5									
6	Trench	Year	Unit	Trench_Unit	SHAPE *	Amou	Dataset	Corrections?	Notes
107	BQ09	2016	BQ09_33	BQ09 _33	Polygon Z	1	Unit 2016		
108	BQ09	2016	BQ09_34	BQ09 _34	Polygon Z	1	Unit 2016		
109	BQ09	2016	BQ09_35	BQ09 _35	Polygon Z	1	Unit 2016		
110	BQ09	2016	BQ09_36	BQ09 _36	Polygon Z	1	Unit 2016		
111	BQ09	2016	BQ09_37	BQ09 _37	Polygon Z	1	Unit 2016		
112	BQ09	2016	BQ09_38	BQ09 _38	Polygon Z	1	Unit 2016		
113	BQ09	2017	BQ09_39	BQ09 _39	Polygon Z	1	Marina	Created	Cut of unit 40
114	BQ09	2017	BQ09_40	BQ09_U40	Polyline ZM	2	Unit 2017 Polyline		
115	BQ09	2017	BQ09_41	BQ09_U41	Polyline ZM	1	Unit 2017 Polyline		
116	BQ09	2017	BQ09_42	BQ09_U42	Polyline ZM	1	Unit 2017 Polyline		

Figure 4.4: Excel spreadsheet used to keep track of unit information (figure by author).

A systematic approach was used to review the TS data: the three unit shapefiles from each field season were imported into a map document in ArcMap. A supplementary shapefile containing the boundaries and labels of each trench was added for reference. Each trench was individually evaluated for completion starting from the northeast corner of the plot with trench BP08 and working down in a southwest direction (fig. 4.5). Any missing or mislabeled units were noted in the spreadsheet and any mislabeled units were corrected. This review revealed that 154 of 545 total units were missing from the shapefiles. Due to the large amount of absent units, it was likely that some TS raw data was not converted to shapefile format and may contain much of the missing data. Furthermore, each fill and cut of pit features were recorded as separate units and often only one feature was measured during the excavation.

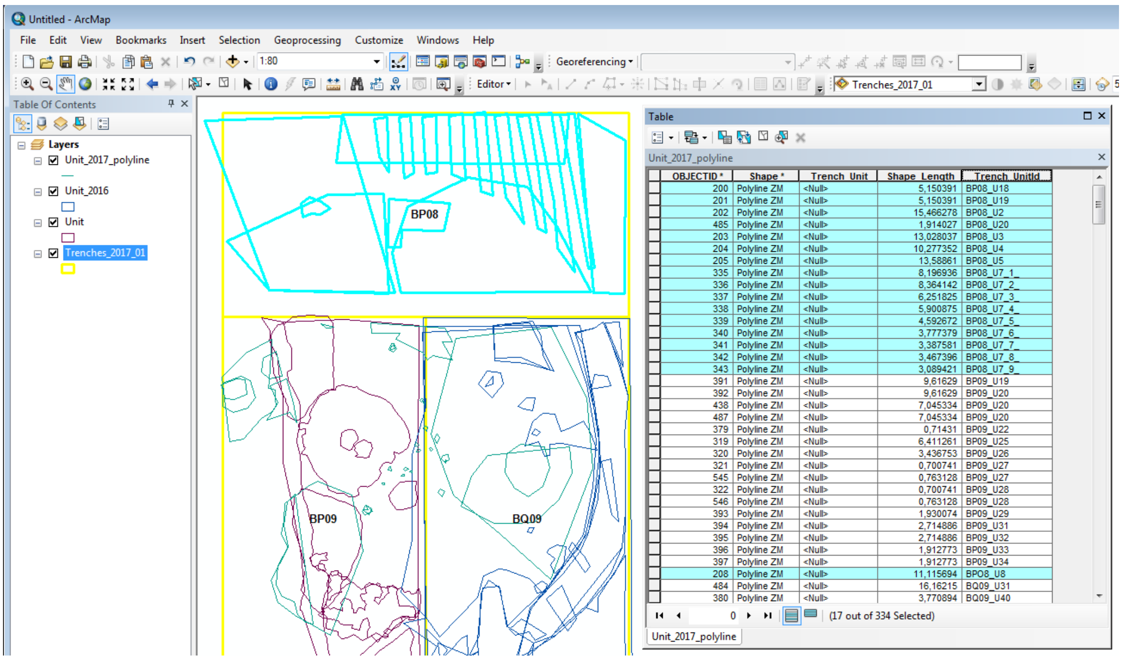

Figure 4.5: Analyzing trench BP08 for missing units (figure by author).

4.4.3 Digitizing Missing Unit Data

The next step in the process of recreating the 3D spatial properties of the units was to recreate the missing data. First, the description of each missing unit was copied from the Access database into a “notes” column in the spreadsheet. This allowed for easy identification of cut/fill units and provided important descriptive information necessary to digitize other units completely absent from the dataset. For the thirty-five missing pit units mentioned above, the single recorded unit was duplicated to attain the corresponding cut or fill. Next, the backup TS data from each year was compared to the corresponding shapefiles to locate any units that were not converted during the post-processing phase. Twenty missing units were located using this method: three units from 2016 and seventeen units from 2017. The unit coordinates found in the raw data files were saved in a separate Excel list named ‘Total Station Units.’

These approaches left ninety-one units unaccounted for to be digitized manually. The trench reports, excavation database, annotated aerial photographs, and final annotated drawings provided crucial information needed to determine the contours of the majority of missing units. Furthermore, the georeferenced orthophotos of the plan of each trench were imported to the map document and served as an accurate spatial reference. The approximate 2D extent of each unit was drawn using the ‘create features’ tool in ArcMap and stored within a new unique polygon shapefile named ‘Marina units’ after the author of this thesis (fig. 4.6). Sixty-five units were digitized using this methodology.

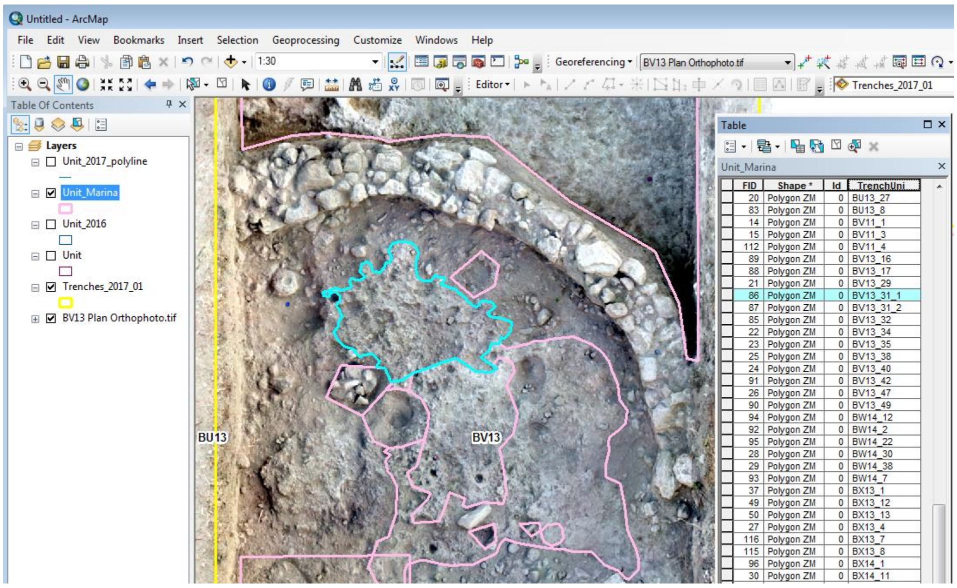

Figure 4.6: Manually Digitizing missing units in trench BV13 using a georeferenced orthophoto for reference (figure by author).

The remaining thirty-four units left unaccounted have been dealt with as follows. Five units were skeletons or large pottery assemblages which were not recorded using the total station but have been digitized into shapefiles by tracing orthophotos generated of the special features in which they were found. These are found in the shapefiles 'Pottery' and 'Bones.' Three additional skeleton units were not digitized but could be derived from the 3D models created of the burial features. Sixteen units pertaining to the cuts and fills of stakeholes in trench BW14 were measured with the total station but mislabeled upon recording. No annotations of this layer exist and therefore identifying the unit numbers for each stakeholes has proved impossible. Finally, ten units were removed from the documentation and not digitized as they were deemed irrelevant by the field director, Klinkenberg. The final result was a complete 2D dataset of all excavated units (fig. 4.7). A summary of unit counts per acquisition method can be found in table 4.5.

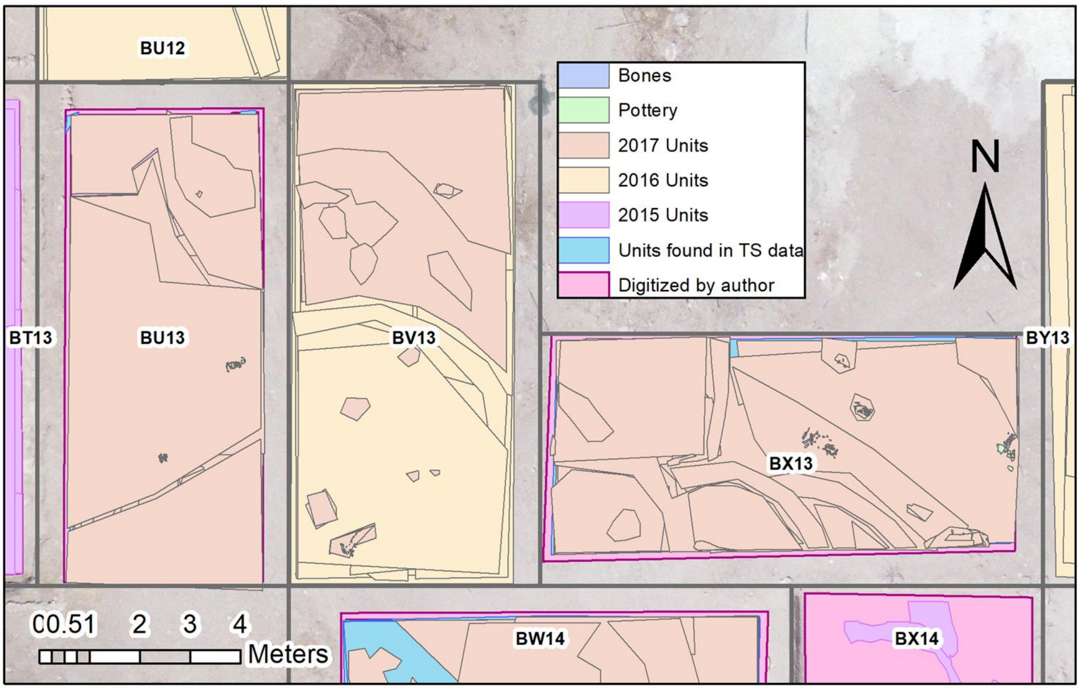

Figure 4.7: Units within the project study area visualized as 2D polygons in ArcMap (figure by author).

Table 4.5: Table containing the breakdown of how each unit was acquired and 3D conversion strategies (figure by author).

Name	File Format	Units (amt)	Acquisition Method	3D Conversion Required?	3D Conversion Process
Unit 2015	3D Polygon Shapefile	74	Robotic Total Station (RTS)	No	None
Unit 2016	2D Polygon Shapefile	113	Total Station	Yes	Polygon shapefile decimated into points. Height data extracted from original 2016 TS measurements and appended to points shapefile using Spatial Join, converted to 3D, then converted to 3D polygon feature class
Unit 2017 Polyline	3D Polyline Shapefile	239	Total Station	No	Converted to 3D polygons using XToolsPro 'Polygons from Polylines' tool
Total Station	Excel Spreadsheet	20	Total Station	Yes	Converted to 3D points shapefile, then converted to 3D polygon feature class
Unit Marina	2D Polygon Shapefile	65	Manually Digitized	Yes	Polygon shapefile decimated into points. Height data extracted from DEMs of trench and special features and appended to points shapefile using Extract Value to Points tool, converted to 3D, then converted to 3D polygon feature class
Pottery Shapefile	2D Polygon Shapefile	1	Orthophoto annotations	Yes	Same as 'Unit Marina' shapefile (see above)
Bones Shapefile	2D Polygon Shapefile	4	Orthophoto annotations	Yes	Same as 'Unit Marina' shapefile (see above)
Skeleton Units	2D Polygon Shapefile	3	Orthophoto annotations	Yes	Same as 'Unit Marina' shapefile (see above)
BW14 Stakeholes	N/A	16	N/A	N/A	N/A
Not Digitized	N/A	10	N/A	N/A	N/A
		545	**Total**		

4.4.4 3D Conversion

Once the horizontal extent of each unit was finalized, all shapefiles were converted to a 3D format. Each method of acquisition listed in figure x necessitated a different conversion strategy and therefore were treated as separate entities in the workflow described below.

As previously mentioned, the original TS unit data was exported and converted to shapefiles before the start of this project. The conversion was done using different procedures thus resulting in different shapefile types for each excavation year. These discrepancies in the dataset complicate the post-processing phase as each shapefile type requires a different workflow for 3D conversion. As the RTS exports data directly into a 3D shapefile format, there are no additional post-processing steps needed for the 2015 unit dataset. Similarly, the 2017 shapefile was already in a 3D format. However, it was saved as a polyline shapefile. The 'Polygons from Polylines' tool in the ArcMap add-on XtoolsPro was used to convert this dataset to a polygon feature class.

The 2016 data required a far more complex post-processing workflow since the TS output was initially converted into a 2D polygon shapefile without preserving the height attributes (z-value) of each coordinate. The original point shapefiles containing all TS measurements from each excavation day was available. Unfortunately, these shapefiles contain both lot locations and unit coordinates and the labeling needed extensive cleaning. Thus it was decided to pursue a more efficient workflow[3]. The 2016 2D polygon shapefile was decimated into individual points using the 'Features to Points' tool in XToolsPro. Next, the TS point shapefiles were imported into the map document and merged into a single layer. The 'Spatial Join' tool in ArcMap was used to join the height values from the attribute table of the TS point shapefile to the points created from the 2D polygon shapefile. The resulting points shapefile was converted to 3D using the 'Feature to 3D using Attributes' tool in the 3D Analyst toolkit and then converted to polygons using the 'Polygons from Points' tool in XToolsPro.

The missing units found within the raw TS data were imported to ArcMap and converted to 3D points, then converted to polygons using the 'Polygons from Points' tool in XtoolsPro. The sixty-five units which were manually digitized also lacked elevation data. Converting these units to 3D thus required evaluating each unit individually to determine possible sources of height information. For example, height data units which lay along the bottom of the trench could be extracted from the photogrammetry models created of those trenches. In these cases, the 'Extract Values to Points' tool was used to take the elevation values from the georeferenced DEMs created from the photogrammetry models and to append these values to the associated units.

These processing and cleaning steps were performed on all units within the given dataset. The result of this conversion process was 3D polygon shapefiles of all recorded units that could be imported into ArcScene along with the 3D points representing lot locations and photogrammetry models for spatial reference (fig. 4.8). However, the 3D modeling procedures outlined in the next section were applied only to three adjacent trenches within the excavated area: BU13, BV13, and BX13. This was a deliberate choice as focusing on three trenches proved to be sufficient to determine the efficacy of the modeling methods described below. Moreover, time constraints within the project limited the scope of the area under investigation.

[3]The original raw TS data was also mixed in with spatial data on lot locations which would have taken a long time to clean. Thus, it would not have been more efficient to re-do the entire conversion process starting from the raw dataset.

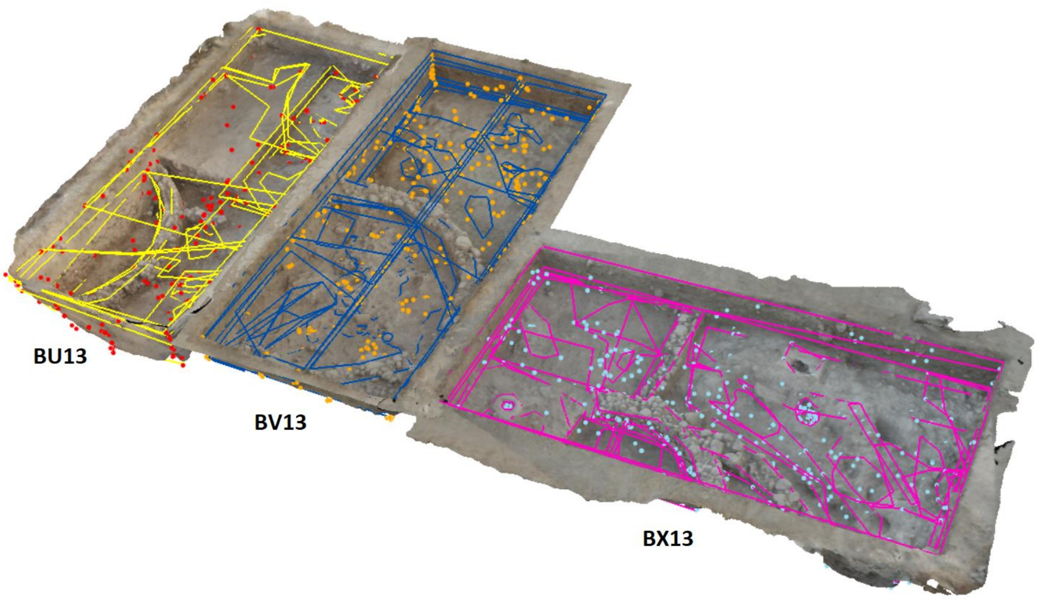

Figure 4.8: Units symbolized as hollow 3D polygons within photogrammetry models of trenches BU13, BV13, and BX13, visualized in ArcScene. Points denote lot locations (figure by author).

4.5 Modeling Unit Volumes

Although the elevation data is preserved, cleaning the datasets and converting all unit shapefiles to 3D polygons resulted in flat representations of the contours of each unit (fig. 4.7). This visualization lacks depth and clarity as the stratigraphic relationships between the units are not immediately apparent. Thus, in order to better understand the spatial relations between the units, I chose to use vector-based 3D GIS modeling approaches to create volumetric representations of the units within ArcMap.

To do this, I utilized three different methods: (1) converting each unit polygon to a TIN and then using the 'Extrude Between' tool to derive the volume between each TIN (Method 1); (2) using the 'Minimum Bounding Volume' tool to create a representation of the boundary surrounding the 3D point shapefile of the unit contours and the lot locations recorded by the TS (Method 2); and (3) digitizing the annotated sections drawings as 3D polylines directly onto the 3D models of each trench based on annotated drawings, converting the polylines to TINs, and extruding between them (Method 3). These volumetric modeling methods were applied to trenches BU13, BV13, and BX 13. The workflow involved in each method are as followed:

4.5.1 Method 1: Extrude Between TINs

The first method that I employed was utilizing the 'Extrude Between' tool to model the volume between overlapping units (fig. 4.9). The theory behind this approach is that in single-context recording, each unit is recorded as a separate entity. A series of these layers can then be consolidated based on the stratigraphic sequence noted during fieldwork. In the case of the *Palloures* investigation, the top interface of each unit was recorded digitally as a polygon feature. Therefore, the volume of each unit could potentially be determined by extruding this polygon down to the subsequent underlying unit.

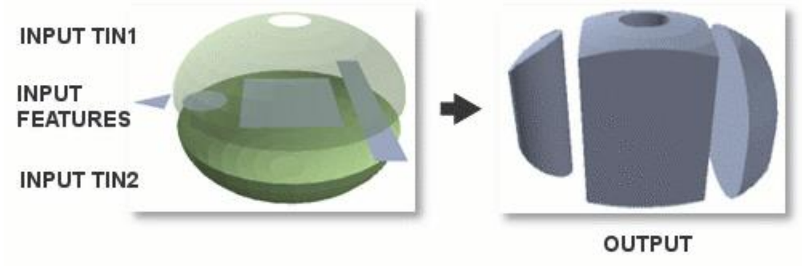

Figure 4.9: Illustration of the function of the 'Extrude Between' tool. Input features (polygon shapefiles) are extruded between two overlapping TINs (http://pro.arcgis.com).

In order to do this, I needed to create TINs from each stratigraphic unit within each trench. After merging all units from every dataset for each of the three chosen trenches, I used the 'Split by Attribute' tool to derive a unique 3D polygon shapefile for every unit as a separate shapefile which I stored in a separate folder. To create TINs for each unit, I utilized the iterator functionality of the Model Builder in ArcMap to run the "Create TIN" tool for each unit shapefile (fig. 4.10). This workflow resulted in a folder containing all unit TINs.

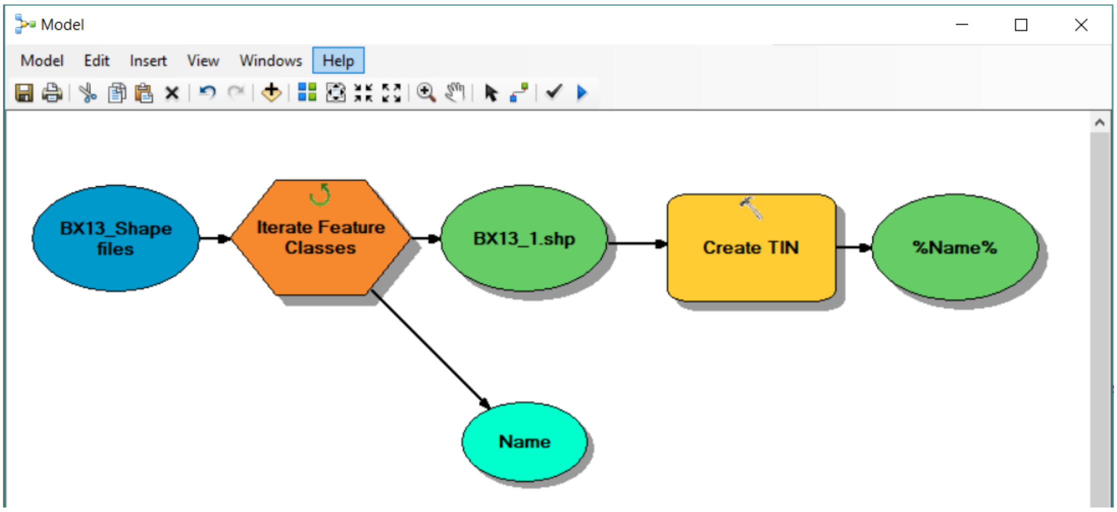

Figure 4.10: Workflow used to create a TIN for every unit within trench BX13 using the iterate function of ArcMap's model builder (figure and model by author).

In order to model the volumes of deep stratigraphic units, I also created TINs of the bottom of each trench from the DEMs derived from the 3D photogrammetric models created at the end of the excavation period. Additionally, I created TINs of two burial features within BX13: unit 11 and unit 15. The challenge was to generate a high-resolution TIN from the 3D mode with a low-enough file size to enable fast processing for use within the 'Extrude Between' tool. Thus, I created models within Model Builder which could be applied to each trench (fig. 4.11). This processing workflow involved deriving the elevation value from the DEM to a point shapefile that covered each DEM at an interval of 2cm. This shapefile was then used as an input to create a TIN.

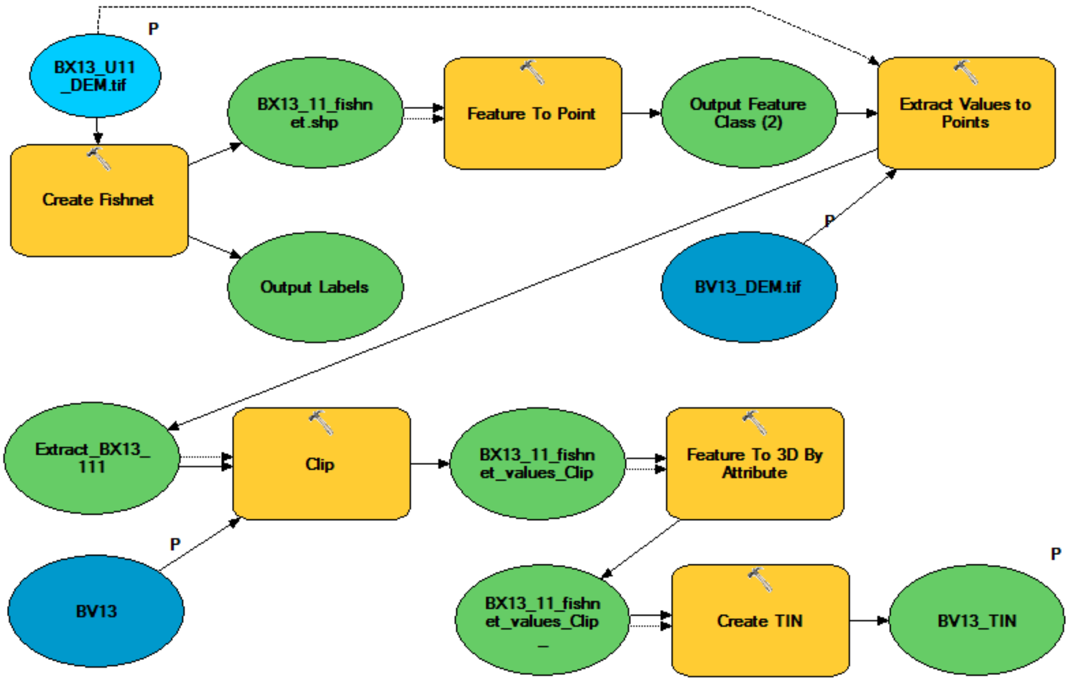

Figure 4.11: Model builder workflow for creating a TIN from DEMs derived from 3D photogrammetric models (figure and model by author).

Once all TINs have been created, I used the 'Extrude Between' tool within the 3D Analyst toolkit to model the volume of each unit based on the stratigraphic relationships recorded in the excavation database. This tool requires two input TINs and one input feature (fig. 4.9). For example, the model of BV13_5 was created by extruding the 3D polygon shapefiles for the two polygons recorded for the unit between the two BV13_5 TINs and the underlying layer BV13_22 (fig. 4.12 (A)). Only the geometry which overlaps both TINs is extruded, the geometry not constrained by the underlying TIN is removed. Thus, if a unit lay on top of the boundary between two different units, the tool was run twice for each of the underlying units. Units which lay close to the bottom of the trench were extruded down to the TIN created from the DEM of the bottom of the trench (fig.

4.12 (B)). Once the volumes of each unit for each trench were generated, they were merged to form a multipatch feature class containing all units within each respective trench (fig. 4.13).

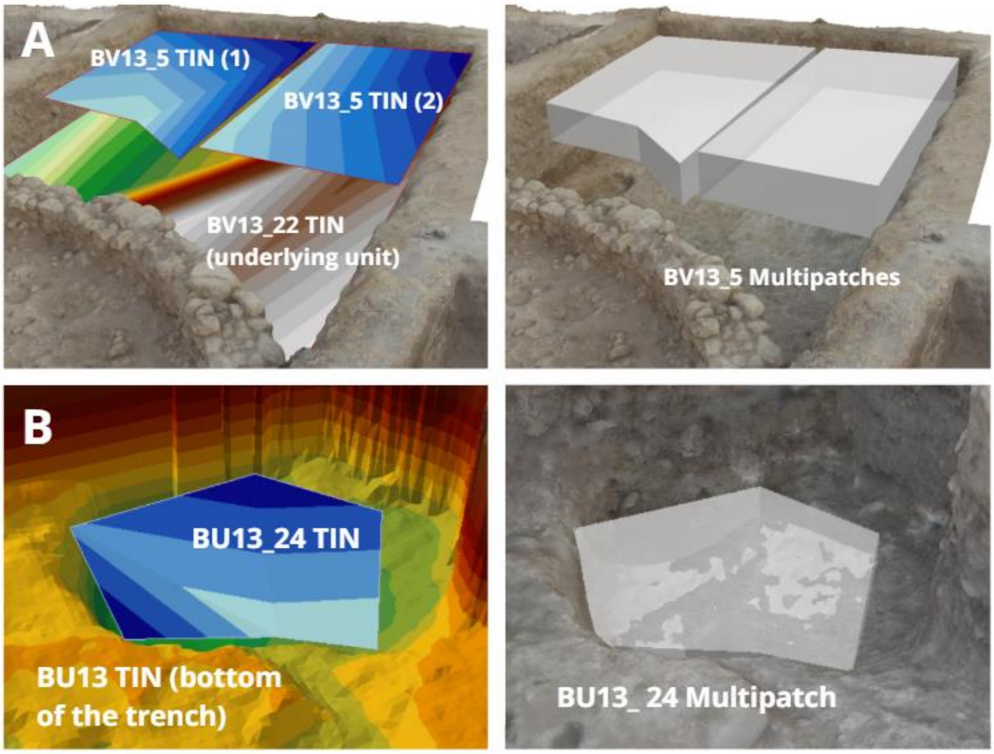

Figure 4.12: Examples of units modeled using Method 1: Extrude Between TINs: (A) Since BV13_5 was recorded using two different polygons, both were extruded down to the underlying layer: BV13_22; (B) BU13_24 is extruded down to the TIN created from the bottom of the excavation trench. The resulting multipatch represents the volumetric space between the two TINs (figure by author).

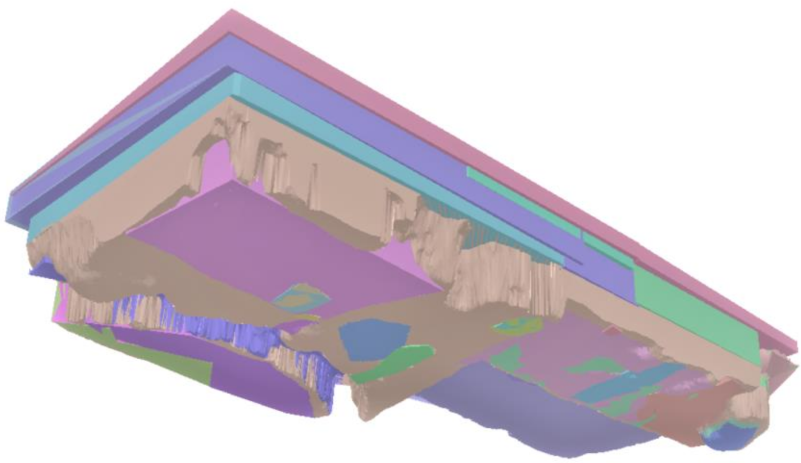

Figure 4.13: All volumetric units in trench BU13 created using the 'Extrude Between TINs' method merged into a single multipatch feature class and symbolized with a unique color for each unit (figure by author).

4.5.2 Method 2: Minimum Bounding Volume

The second method implemented to model the volumes of the units is by using the 'Minimum Bounding Volume' tool in the 3D Analyst toolbar of ArcMap 10.5.1[4] which "creates multipatch features that represent the volume of space occupied by a set of 3D features" (http://pro.arcgis.com). This tool has the option of a few different modeling methods. In this case, I utilized the 'Convex Hull' method which models the outer boundaries of 3D features without including concavities between input features. The input features used in this case are the 3D point shapefiles of the lots and the points recorded by the TS demarcating unit boundaries. Since the bottom of each lot location and the top interface of each unit was measured, this tool may provide a rough approximation of the volume of each unit between these recorded points.

The dataset for lots included 3D point shapefiles for each year. These shapefiles included the lot numbers in the attribute table, however it was necessary to join the database to these shapefiles in order to determine the corresponding trench and unit number for each lot. These three joined 3D shapefiles were then merged and the lots corresponding to trench BX13, BV13, and BU13 were extracted and respectively made into new shapefiles. In order to obtain the points for each unit within each trench, the polygon shapefiles for each trench created during Method 1 were converted to 3D points using the 'Features to Points' tool in XTools Pro. The resulting three 3D point shapefiles for the units were merged with the 3D point shapefiles of lots.

These merged shapefiles were used as inputs in the 'Minimum Bounding Volume' tool, using the 'Convex Hull' modeling method. The points were grouped by unit numbers, thus creating volumes for each unit (fig. 4.14). This tool has the option to include the geometry characteristics to the output, thus easily providing the user with an accurate area and volume for each multipatch feature created. An example of the resulting model can be seen in figure 4.15.

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[4] This tool is not available in versions earlier than version 10.5.1 of ESRI ArcMap and ArcScene.

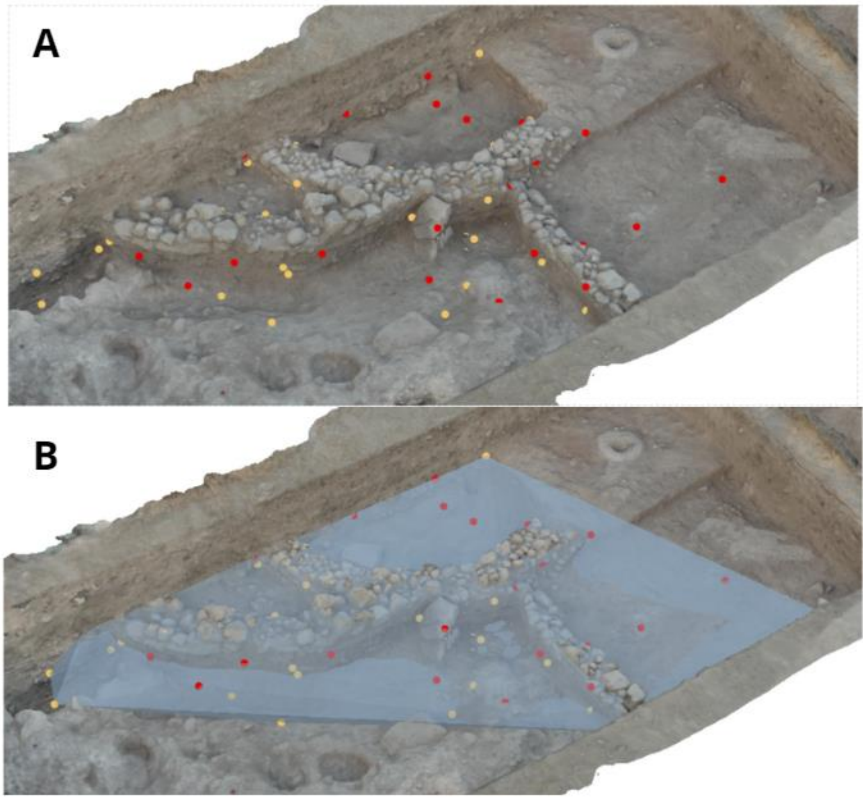

Figure 4.14: Modeling unit BX13_28 using the Minimum Bounding Volume method: (A) Points used for the calculation. Unit points are depicted in red and lot locations in orange; (B) resulting multipatch feature of the unit (figure by author).

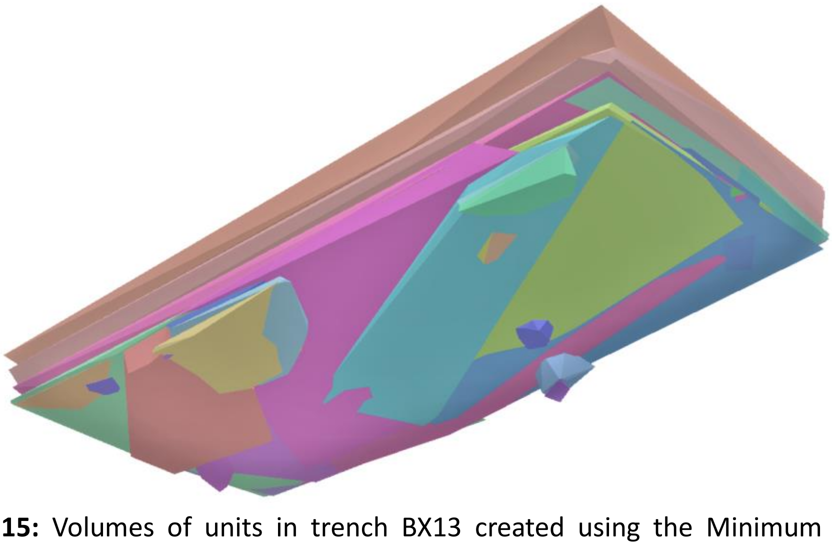

Figure 4.15: Volumes of units in trench BX13 created using the Minimum Bounding Volume method, visualized with a unique color for each units (figure by author).

4.5.3 Method 3: Digitizing Section Stratigraphy

The third method involves digitizing the unit boundaries found in the sections of each trench using the ‘Create Features’ tool within the 3D Editor in ArcScene. As mentioned previously in the discussion of the excavation documentation methodology employed by the researchers at Lund University, ESRI ArcScene allows users to draw 3D features (points, lines, and polygons) directly on multipatch 3D models imported into the software. Using this functionality, I created a new 3D polyline feature class for each trench and digitized the interface boundaries of the units directly on the trench models. As a reference, I used the annotated section drawings from my dataset which were created from orthoimages taken from the 3D trench models (fig. 4.16).

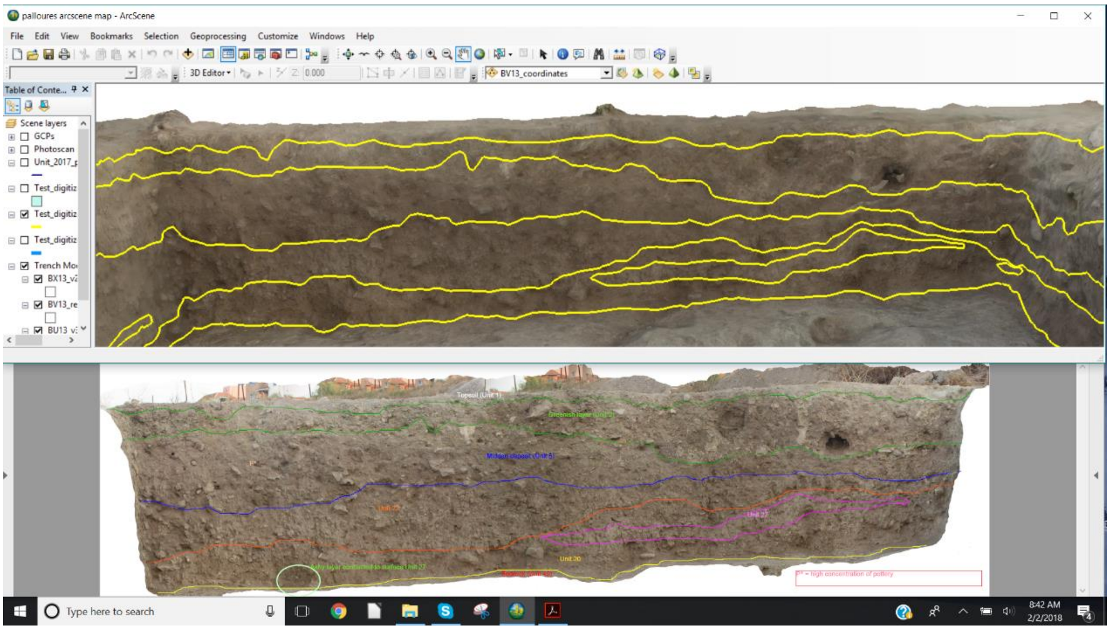

Figure 4.16: Top: Digitizing unit interfaces in ArcScene as 3D polylines; bottom: the annotated section drawing used as a reference (figure by author).

In order to create the volume between each section, I made sure to digitize both the top and bottom interfaced between each layer, one trench wall at a time. For example, I digitized the top interface of unit 1 in each trench by following the contours of the top of the trench wall. Next, I digitized the bottom interface by following the annotated drawings. This bottom interface of unit 1 also served as the top interface of unit 2, and so on. Only the units identified within the annotated drawings were digitized. For instances of pit features in which units were identified only within one wall, I also digitized the entire top interface of the pit on the 3D model to create a complete contour of the feature.

Once the digitization was complete, I transferred the resulting 3D polyline shapefile to ArcMap. There, I used the Xtools Pro add on tool ‘Polygons from Polylines’ to convert the boundaries of each unit to a 3D polygon shapefile. Next, I followed the steps I utilized in method 1 (Extrude TINs) to create TINs of each unit boundaries and used the 'Extrude Between' tool to generate the 3D volumes of each unit identified in the sections (fig. 4.17). The result is a watertight model of all stratigraphic layers identified in the annotated section drawings (fig. 4.18).

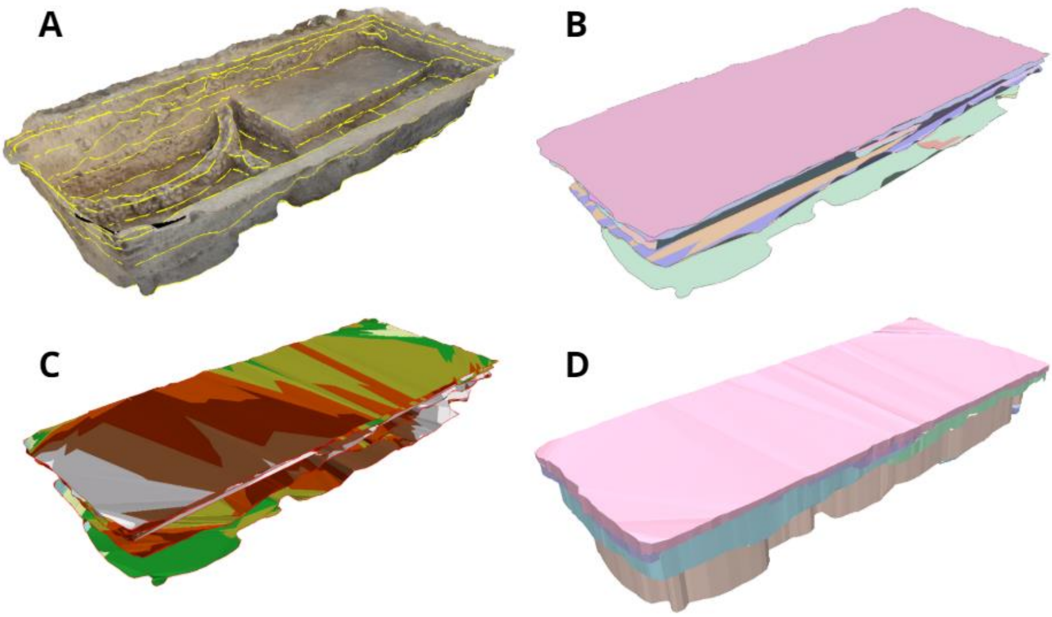

Figure 4.17: Steps to creating a volumetric model of trench BU13 using the Digitizing Sections method: (A) digitized unit interfaces as 3D polylines; (B) 3D polylines converted to 3D polygons; (C) 3D polygons converted to TINs; (D) volumes generated between TINs using the 'Extrude Between' tool (figure by author).

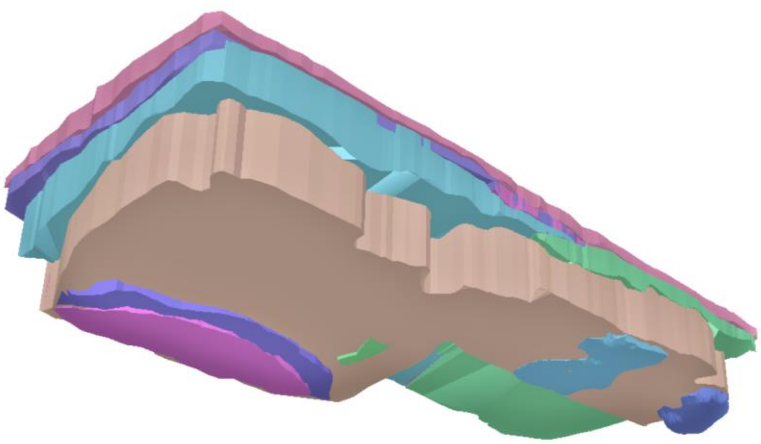

Figure 4.18: Model of trench BU13 created using the Digitizing Section Drawings method (figure by author).

4.6 Calculating Volumes of Units

Although the Minimum Bounding Volume method automatically generated the volumes of the output features, the other two modeling methods did not. Thus, calculating the metric volumes of each unit in the other two methods had to be done manually. The 3D Analyst tool 'Add Z Information' calculates and appends the volume of multipatch features to the attribute table, but only works on multipatches with closed geometry. Unfortunately, due to unspecified issues within the tool algorithm, the 'Extrude Between' tool often generates multipatch features which are not enclosed.

I attempted to enclose the multipatch geometry by applying the 'Enclose Multipatch' tool but unfortunately this process lead to malformed units that bared little resemblance to the original models. Therefore, the only option available to calculate volumes was using the 'Surface Difference' 3D Analyst tool which calculates whether one TIN lies above, below, or at the same elevation as a second TIN and calculates the volume difference between them. Although each unit had to be run one at a time based on the unit relationships identified during the volumetric modeling phase, I was able to manually calculate the volume of all units.

4.7 Joining 3D GIS Models with the Excavation Database

In order order to perform spatial analysis on the patterns evident in the resulting 3D GIS model, each model created using the methods described above was joined with the excavation database. The database used for the *Palloures* excavation was created in Microsoft Access using the .accdb file format. Unfortunately, this database format cannot be directly read by both versions of ArcMap used in this project. As a workaround, I exported the necessary tables from the database to Excel files and then joined the Excel tables to the newly-created multipatch feature class layers based on the trench unit designations. The data joined to the units included the general unit information as well as artifact counts for animal bone, groundstone, and lithics. Additionally, I connected unit relation and lot data to the models using a relate so that this data could be queried as needed.

Ideally, connecting the excavation database to the models would facilitate comparison between stratigraphic layers based on artifact count. Unfortunately, since much of the artifact analysis has not been done, very few artifact counts were available. However, if this data were available, this method would allows the user to change the symbology of the model to illustrate different spatial patterns within the acquired data. One other downside is that since this join is not directly connected to Access, the data will not update dynamically when information is edited or added into the database.

The result of the methods laid out above was three different 3D GIS models within each of the three chosen trenches: BU13, BV13, and BX13. Each model offers a different rendition of the volumes of the stratigraphic units. These models are presented and analyzed in chapter 5.

Chapter 5: Results and Analysis

The results of the workflow outlined in the previous chapter are presented here. First, I illustrate how spatial data collected in the field was integrated into a true 3D GIS system as defined in chapter 2 and provide an overview of the three volumetric modeling methods tested during the course of this project. I comment on the strengths and shortcomings of these methods and present a quantitative comparison of the volume of individual units modeled using each approach. Finally, I present the results of five stratigraphic analyses performed using the created 3D GIS model and discuss what these results reveal about the settlement patterns at *Palloures*.

5.1 A True 3D GIS Workflow

First, the success, or lack thereof, of the workflow described in chapter four can be assessed by comparing the results with the definition of a true 3D GIS system. In chapter 2, I adopted a working definition of 3D GIS as a volumetric model depicting objects and materials in three dimensions and their spatial relationships. This model must be able to function within four different subsystems; these are (1) data entry, (2) spatial database, (3) manipulation and analysis, and (4) reporting and visualization (Klinkenberg 2016, 39; van Leusen and van Gessel 2016, 34; Wheatley and Gillings 2002, 8-9). Overall, the 3D GIS system created for the *Palloures* excavation during the course of this project fulfills these requirements.

Data entry of spatial information is already a staple of GIS systems as TS data is easily imported into a georeferenced environment (Klinkenberg 2016, 41). The workflow used in this project introduces a three-dimensional component to the data entry phase by converting all unit and lot data to a 3D format. Additional context information is consented within the photogrammetry models of excavation trenches which are easily incorporated into the same 3D GIS environment. This process preserves the complex spatial relationships of layers, features, and artifacts. Furthermore, since ArcScene allows joining external tables to spatial data such as the unit and lot features, this workflow allows for the creation of a comprehensive spatial database. This functionality facilitates easy retrieval of excavation data by simply clicking on the associated features within the 3D GIS environment (fig. 5.1). Data can also be queried and filtered as needed.

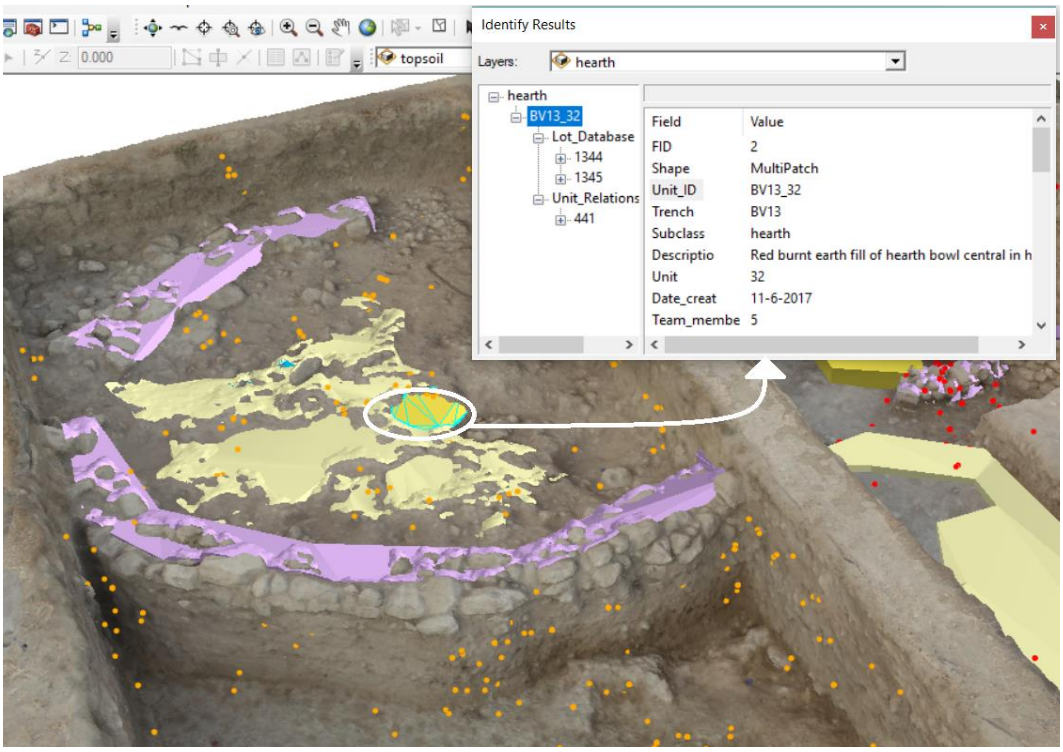

Figure 5.1: Using the 'Identify' tool, you can click on a unit within the model to bring up its attributes, information on lots removed from the context, and unit relations (figure by author).

Reporting and visualization is also one of the strengths of ArcScene as different three-dimensional data formats can be combined within the same workspace in an easy-to-navigate user interface. The workflow presented here leverages these visualization capabilities in order to display the complex spatial relationships between excavated materials. This is possible to a limited extent by displaying 3D polygons of unit boundaries as recorded with a TS, although this data can be disorienting because it is sometimes difficult to distinguish the spatial relations between flat polygons. Modeling the volumes of the units helps with this issue and creates a visually coherent representation of trench stratigraphy, although more work needs to be done in order to enhance the accuracy of these models.

Most of the data presented here is in the form of 2D screenshots of the model within the program. Yet, ArcScene also allows for the creation of videos panning around the 3D model to convey the three-dimensionality of the GIS system (see supplementary materials). Cross-sections of the stratigraphy can also be created at any angle and any direction needed while preserving the information in the database connected to the model (fig. 5.2). Furthermore, models created in ArcScene can be exported as 3D virtual reality modeling language (VRML) models files and imported into other 3D modeling or visualization programs such as MeshLab (http://www.meshlab.net) if desired.

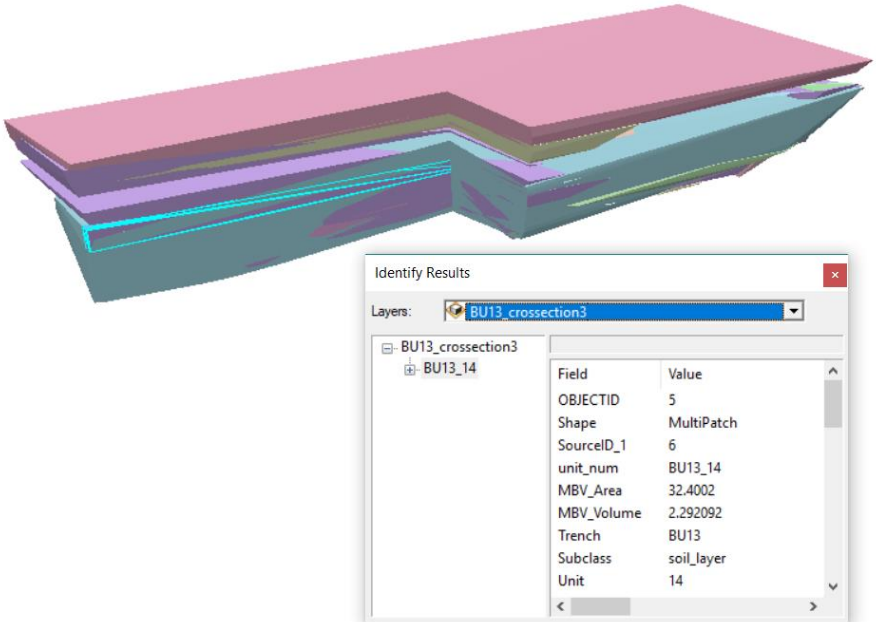

Figure 5.2: Trench BU13 cross-section. Layers inside the model can be queried in the same manner as the complete models (figure by author).

Finally, this workflow specifically focuses on exploring whether the resulting 3D GIS model can be used for intra-site stratigraphic analysis. Indeed, this model greatly aided in understanding the settlement patterns on the site by facilitating three-dimensional spatial analysis including correlating relationships of stratigraphic units between trenches and checking interpretations made in the field. The results of this analysis is discussed further in this chapter.

5.2 Modeling Unit Volumes Methods: Results

In order to test the efficacy of 3D GIS for the analysis and visualization of stratigraphic relationships between excavation units, this project involved modeling the volumes of each unit through three different vector-based modeling approaches using the toolkit available in ArcScene and the add-on XTools Pro. The results of this experiment lead me to infer that each method has unique advantages and drawbacks as neither one proved to be without flaws. Here, I present the generated models to give a visual overview of the outcomes (fig. 5.3). The strengths and weaknesses of each approach are discussed below.

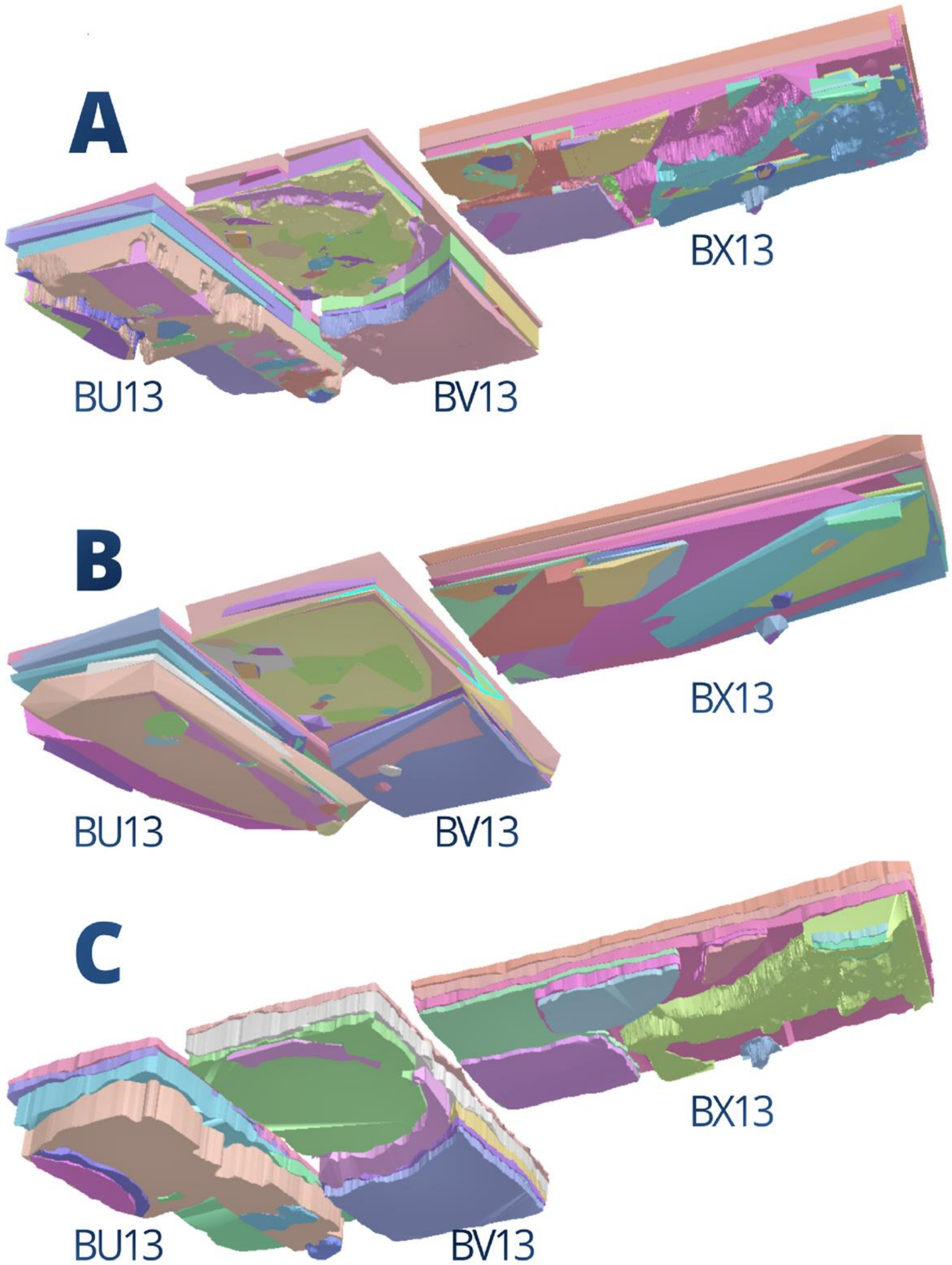

Figure 5.3: The results of all three modeling methods visualized with a unique color for every unit (A) Method 1: Extrude Between TINs; (B) Method 2: Minimum Bounding Volume; (C) Method 3: Digitizing Section Drawings.

5.2.1 Method 1: Extrude Between TINs

Method 1 uses the 'Extrude Between' tool to extrude the volume of each unit down to the next underlying unit based on the stratigraphic relations described in the database. At the beginning of the project, this approach seemed the most promising since it leaned heavily on the theory behind single-context recording. Indeed, this method serves as a means of testing the relations identified in the field based on the spatial information recorded by the total station. ArcScene allows the user to visualize all the units as 3D polygon shapefiles, pan around them, and toggle each unit on and off to focus on specific areas of each trench. Thus, it is possible to visually review the relationships between each stratigraphic unit before extruding.

This is particularly useful in cases when some stratigraphic relationships between units were missing in the database. For example, the only underlying units for BX13_28 specified was BX13_22. However, looking at the relation between the 3D polygons demarcating the unit boundaries, it appeared that BX13_22 was recorded as actually overlapping BX13_28, rather than succeeding it. Therefore, I looked to see which other 3D polygon shapefile lay beneath BX13_28, and extruded the unit down accordingly, in this case to the bottom of the trench (fig. 5.4).

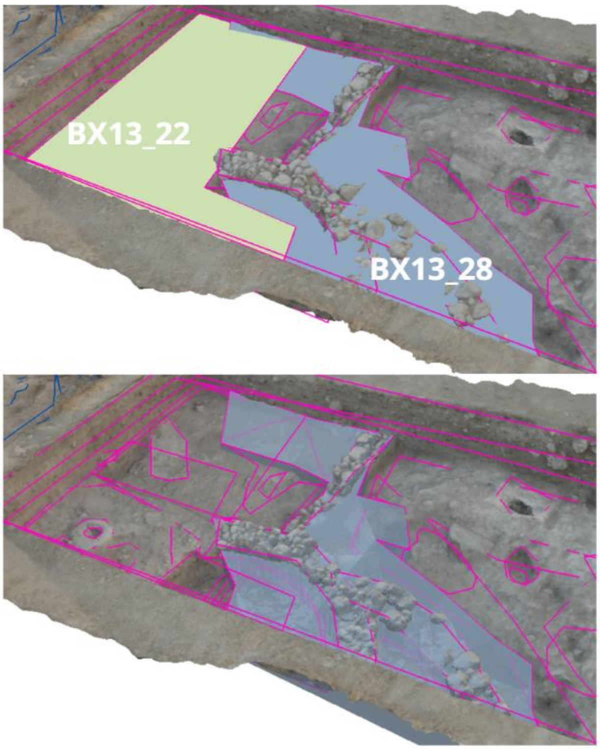

Figure 5.4: Top: BX13_28 spatial relation with BX13_22. BX13_22 was interpreted as lying below, however the 3D GIS model offers a contradicting visualization. Bottom: BX13_28 was extruded down to the bedrock.

Moreover, the final model of each trench contained gaps within the stratigraphy thus highlighting the inaccuracies of the method. This may have resulted from the technical limits of the software since the 'Extrude Between' tool will only extrude the area of the unit which overlaps both TINs used in the calculation. This limitation also meant that some units had to be modeled several times if it lay over multiple other units. This is evident in BV13_1 which had to be modeled using six multipatches since the underlying units BV13_3, BV13_4, and BV13_5 were each recorded as two polygons each with the TS and there were gaps between them (fig. 5.5). This issue leads to duplicate entries in the attribute table and difficulties calculating the volume of each unit as all multipatch unit volumes must be summed up to attain the final volume.

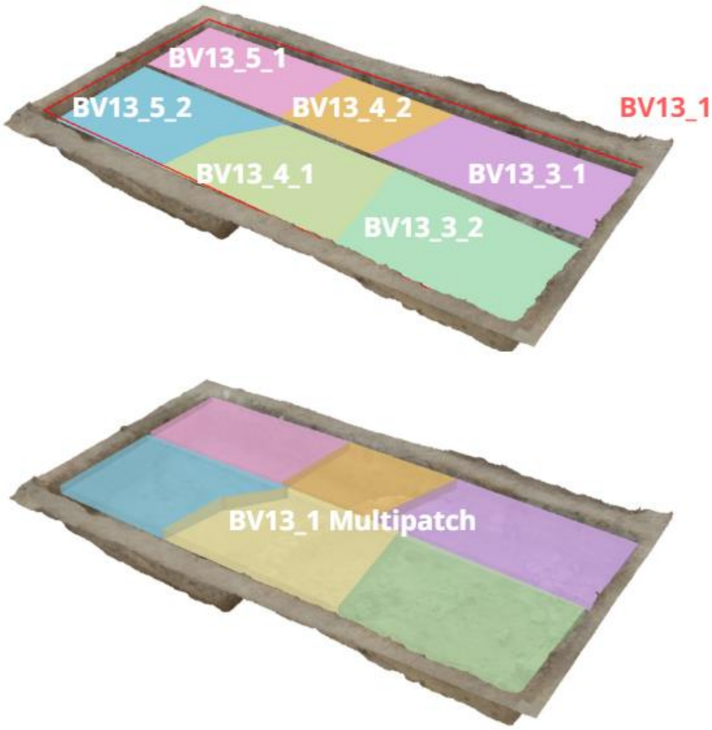

Figure 5.5: Top: There were three units underlying BV13_1, each split into two parts during the recording process. Bottom: This resulted in unit BV13_1 modeled in six parts.

Another downside is that it is not possible to accurately model the volumes of wall features which where not taken out during excavation. Only the top contours of the walls were recorded and there is no underlying unit to extrude the walls down to. On a practical level, this method is also computationally slow because the units must be extruded one at a time after reviewing their unique stratigraphic relationships. Creating volumetric models of all seventeen trenches at *Palloures* with over fifty units within each trench would therefore take a long time.

5.2.2 Method 2: Minimum Bounding Volume

Method 2 utilized the 'Minimum Bounding Volume' tool in the 3D Analyst toolkit of ArcScene to calculate the volumetric space between the boundaries of the units and the lots found within them. Since the tool processes quickly, I was able to process the units and run the tool for all three trenches in this case study within the span of four hours. Because the tool can process all units within a trench at the same time, there is also no need to look up the stratigraphic relationships between each unit beforehand as in method 1. This is added benefit of this approach since it relies solely on the primary spatial data recorded by the TS and therefore operates completely independently from the stratigraphic interpretations made in the field. Overall, this method proved to be the fastest and most efficient method of the three presented in this thesis.

Furthermore, this approach is the only one which automatically generates closed multipatch features and allows the user to automatically add geometry characteristics as attributes to the output. This is a major strength of the method since the volumes of each unit are calculated without requiring additional processing steps. Since cross-sections can only be created for closed multipatch feature classes, this is currently the only method which allows for creating cross-sections of trench stratigraphy directly within ArcScene (see fig. 5.2).

This method works especially well for pit features in which artifacts were found at the bottom. Yet, this also highlights the major downfall of the approach: units in which no lots were recorded cannot be modeled at all. This is especially true for wall features as the resulting model simply includes a flat top boundary of these features which distorts the stratigraphic relationships within the trench. Furthermore, the resulting volumetric models includes a lot of gaps in the stratigraphy due in part by units without associated lots (fig. 5.6). Another contributing factor as well as another major problem with the method is that lots are never evenly distributed at the bottom of each unit. Therefore, the resulting volumetric geometry of the units is inherently inaccurate. All in all, the resulting model may only be utilized as a rough estimation of the stratigraphic sequence and the volumes of the units.

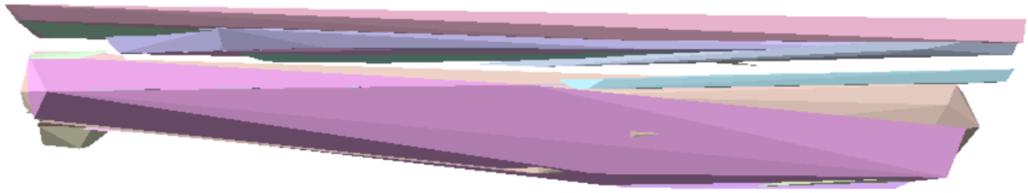

Figure 5.6: Major gaps in the stratigraphy of trench BU13 using the Minimum Bounding Volume method (figure by author).

5.2.3 Method 3: Digitizing Section Stratigraphy

The third method explored during the course of this project was digitizing the section drawings directly on the photogrammetry model within the ArcScene interface and then using the 'Extrude Between' tool to derive the volumes of the units identified in the sections. This was the only method that did not show gaps in the stratigraphy within the final model of each trench which is a major advantage of this approach. Furthermore, this is also the only method which allowed me to model the volumes of the wall features. Therefore, the resulting models provide a very clear three-dimensional visualization of the stratigraphic sequence identified in the section drawings.

Unfortunately, here is a major weakness to this approach since only the units identified and annotated in the section drawing created by the excavators can be modeled and the result is a very simplified rendition of the stratigraphy of each trench. Units found only within a single wall of a trench cannot be modeled either as it is impossible to recreate the complete contour of the unit interface. Another drawback is that the only stratigraphic relationships depicted in the final model are those that have already been identified in the section drawings as it is essentially a direct copy of the annotations, albeit in a 3D format. Thus this modeling method serves as a good visualization tool, but is limited in generating any new interpretations of the spatial dataset.

5.3 Differences in Unit Volumes

Overall, the models created using each of the three methods above lead to vastly different results which are visually evident in the 3D models themselves and in the volumes calculated for each unit. This can be readily observed after calculating the total combined volume of all the units within each trench (fig. 5.7). The differences between these modeling methods are discussed in detail below.

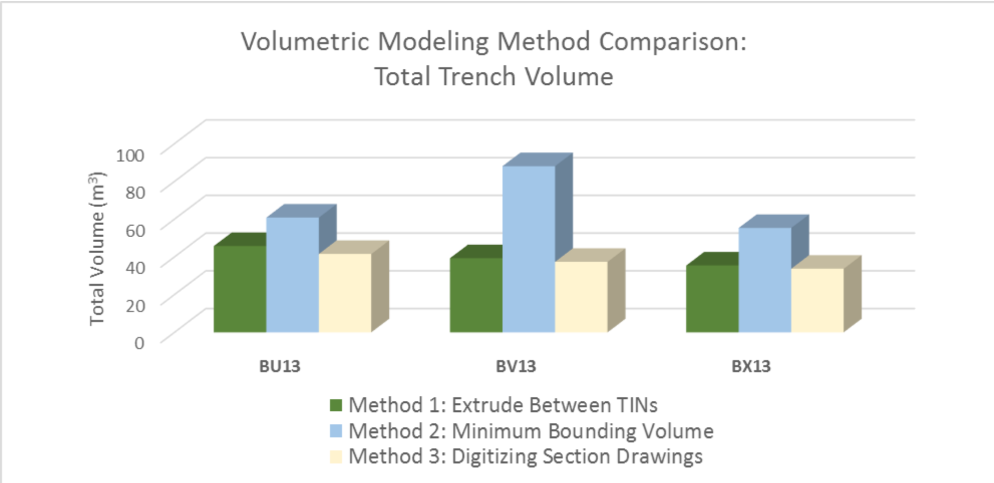

Figure 5.7: Graph showing a comparison of the combined total volume of all units within the trench between the different volumetric modeling methods tested (figure by author).

There are significant differences evident between modeling volumes of different types of deposits, thus illustrating the advantages and disadvantages of all three approaches. For example, it was only possible to approximate the depth of wall features using method 3 (fig. 5.8). Method 1 only modeled the volume between the contours recorded with the TS and the surface of the photogrammetry model, thus leading to shallow volumetric representations of more complex materials. Method 2 captured the volume between the wall contours and all the lots found a short distance away in association with the wall debris, which distorted the model geometry. For burials, all three methods visually appeared to give a similar result although the volume calculations revealed quite divergent volumes (fig. 5.9). This may be due to an issue encountered in the modeling process in which using method 3 for features close to a trench wall with overhanging features sometimes led to distorted geometry and issues in volumetric modeling (see fig. 5.9 C)).

Soil layers that covered a large part of the trench were difficult to model using method 1 since this method required extruding the unit down to underlying deposits. If more than one deposit lay beneath the unit, the modeling process had to be repeated multiple times, thus leading to multiple multipatch features depicting a single unit (fig. 5.10). Finally stone layers or debris layers were modeled well using method 1 (fig. 5.11). Method 2 seemed to encompass more of the volume of the trench as it took into account all the lots associated with the deposit and method 2 only included parts of the deposit which could be seen within the trench wall.

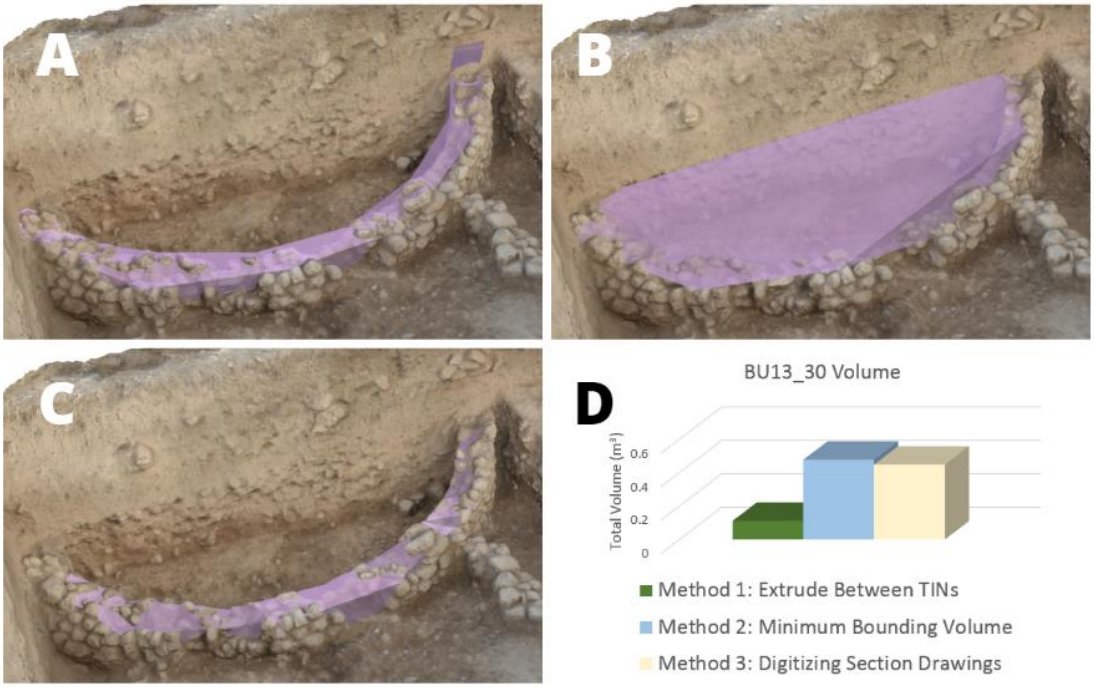

Figure 5.8: Differences in volumetric modeling methods for unit BU13_30, a wall feature. (A) Method 1: Extrude Between TINs; (B) Method 2: Minimum Bounding Volume; (C) Method 3: Digitizing Section Drawings; (D) Graph comparing the volume per modeling method (figure by author).

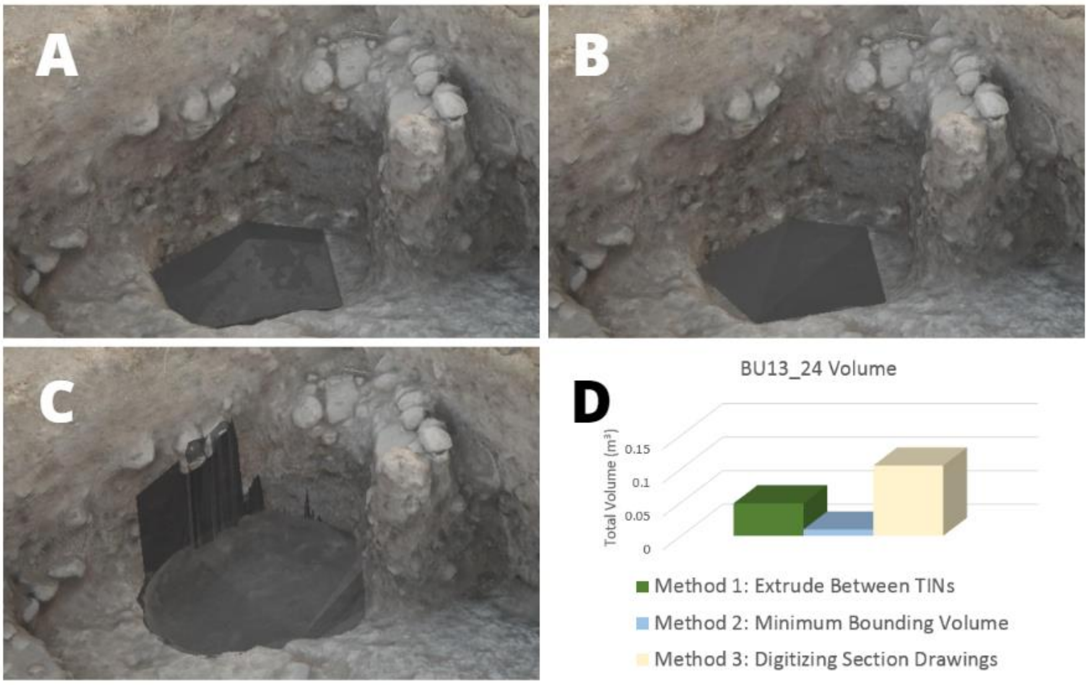

Figure 5.9: Differences in volumetric modeling methods for unit BU13_24, a burial pit. (A) Method 1: Extrude Between TINs; (B) Method 2: Minimum Bounding Volume; (C) Method 3: Digitizing Section Drawings; (D) Graph comparing the volume per each modeling method (figure by author).

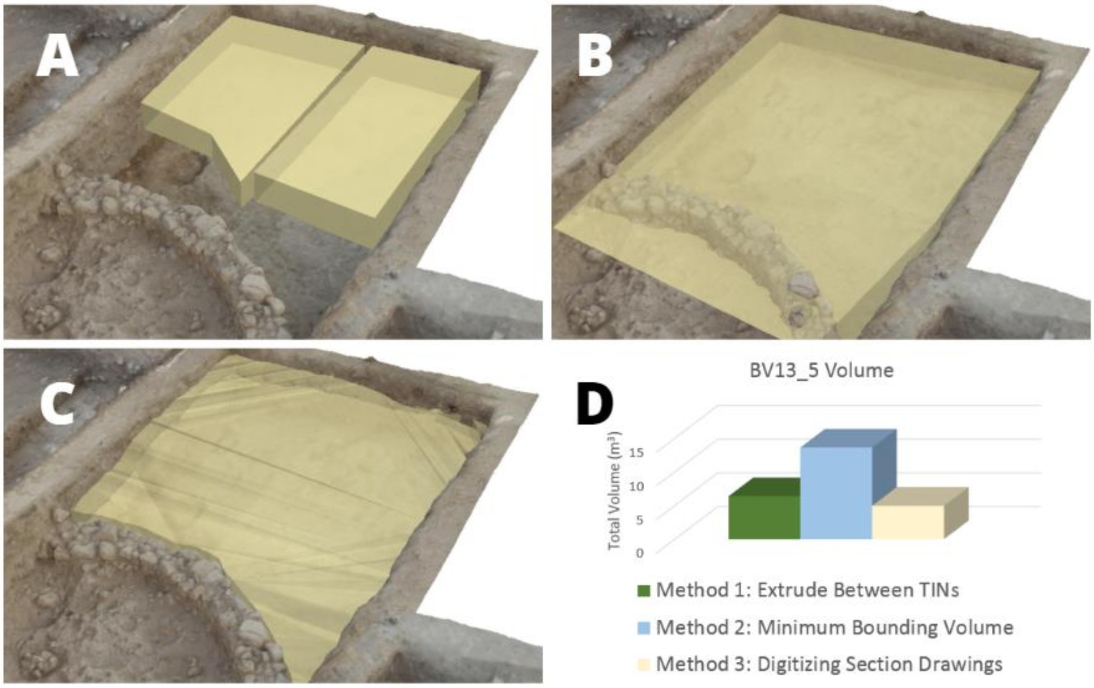

Figure 5.10: Differences in volumetric modeling methods for unit BV13_5, a top soil layer. (A) Method 1: Extrude Between TINs; (B) Method 2: Minimum Bounding Volume; (C) Method 3: Digitizing Section Drawings; (D) Graph comparing the volume per each modeling method (figure by author).

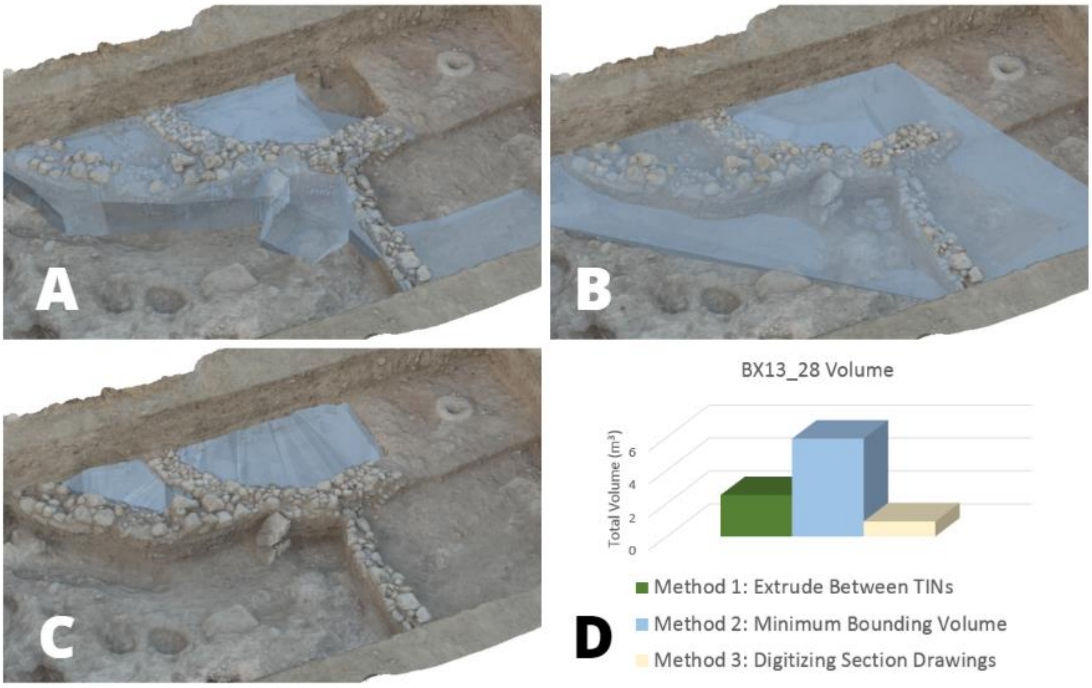

Figure 5.11: Differences in volumetric modeling methods for unit BX13_28, a stone layer. (A) Method 1: Extrude Between TINs; (B) Method 2: Minimum Bounding Volume; (C) Method 3: Digitizing Section Drawings; (D) Graph comparing the volume per each modeling method. (figure by author).

In summary, the volumes for each unit vary considerably between the different volumetric modeling methods used. Perhaps using a combination of all there methods would improve the overall accuracy of the final trench model. The chosen method would then depend on the type of unit modeled: for instance, using the Minimum Bounding Volume for pits with many finds or modeling all wall features by drawing directly on the photogrammetric models. Unfortunately, testing this is currently beyond the scope of this project but this discussion should serve as a starting point for future endeavors into improving vector-based volumetric modeling.

5.4 Stratigraphic Analysis

As mentioned in chapter 4, it would be useful to calculate artifact densities to reveal spatial patterns within the trench layers. However, the discrepancies in unit volumes described above would impact the results of such an analysis. Despite this, the 3D GIS models can still be used to perform other types of stratigraphic analyses. To do this, I created a separate ArcScene document in which I merged all units per modeling method, then split the units by unit Subclass using the 'Split by Attributes' tool (see supplementary material). At *Palloures*, the unit Subclass is a field used in the excavation database to designate the type of unit found, such as whether the unit is a wall, soil layer, hearth, burial, or otherwise(see supplementary material). This approach proved especially useful for comparing unit relations, reviewing interpretations made in the field, and better understanding settlement patterns at the site. The results of five different stratigraphic analyses are briefly discussed below.

5.4.1 Visualizing Bedrock

First, the 3D GIS model made the slope of the underlying bedrock beneath the site immediately apparent. Since each of the trenches were generally excavated until solid rock was reached, the bedrock can be seen within the photogrammetry models of the bottom of the trenches as well as in the volumetric models created from the recorded TS dataset. This is most evident in the Extrude Between TINs modeling method, which presents the bedrock as physically conforming to the topography of the bottom of the trench (fig. 5.12). Toggling the photogrammetry models on and off revealed that the bedrock sloped downwards in a northwest direction, thus providing a better understanding of the settlement arrangement in relation to the natural landscape.

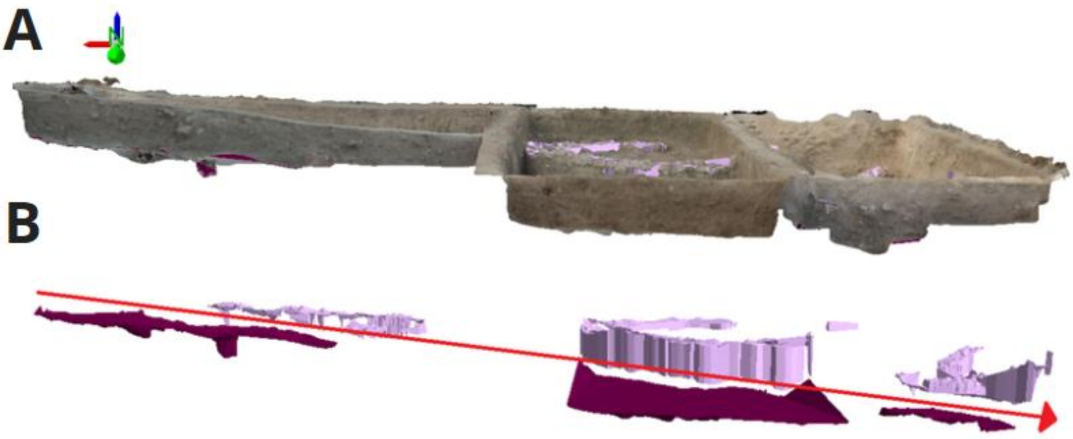

Figure 5.12: The direction and angle of the bedrock in comparison to architectural features found in the project study area: (A) oblique profile view of photogrammetry models facing south; (B) photogrammerty models hidden to show individual units with red arrow representing the slope of the bedrock. Architectural features are shown in light purple and bedrock is depicted in dark purple (figure by author).

5.4.2 Identifying Relationships Between Trenches

Furthermore, the 3D GIS models could be used to check interpretations made in the field concerning the relationships between trenches. In the trench reports, the midden deposit BV13_5 was identified as being part of the same layer as BU13_3 in the adjoining trench. But do correlations between units seem probable based on the spatial and descriptive information recorded in the database and visualized in the 3D GIS model?

To check this, I looked at the volumetric models of these two units within each of the three volumetric modeling methods. By placing all units into a single cohesive spatial context, I could check whether the vertical and horizontal extent is consistent with these interpretations. Both units appear to have a similar elevation and appear to form a continuous surface when disregarding the trench walls. Clicking on each unit to see the unit attributes further allowed me to compare the documented data concerning the color, consistency, and artifacts found within the layers (fig. 5.13). The results proved similar enough to warrant the assumption that these unit are highly likely to be part of the same deposit.

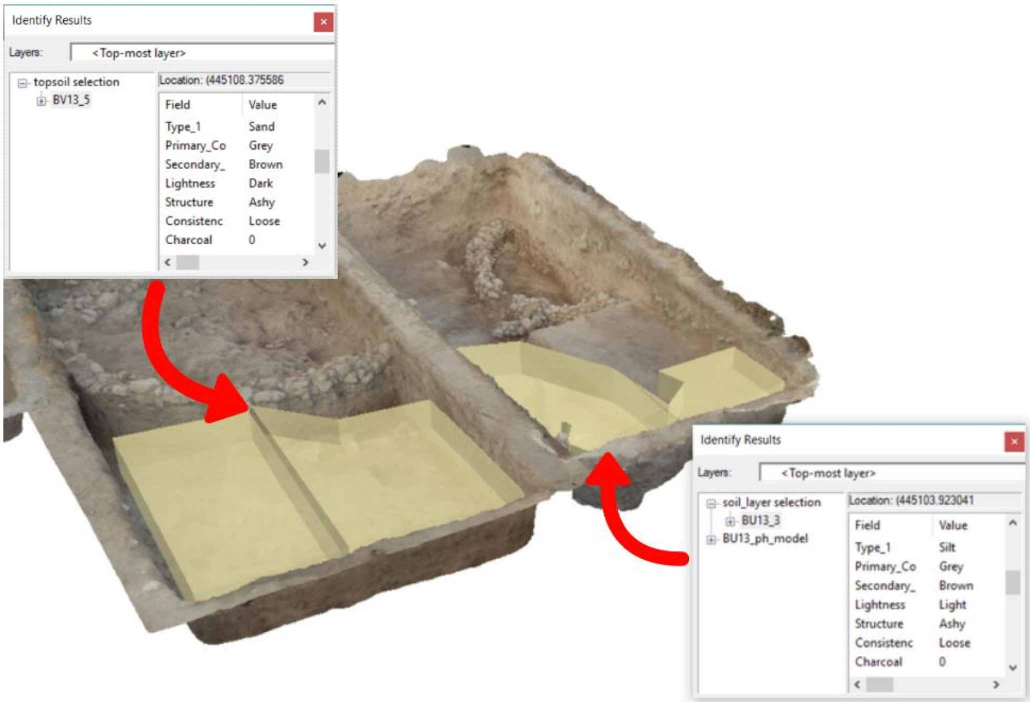

Figure 5.13: Evaluating the spatial relationship between units BV13_5 and BU13_3 using the Extrude Between TINs modeling method. Clicking on each unit shows that the color, structure, and consistency of the layers is identical (figure by author).

5.4.3 Clarifying Settlement Patterns

One of the stratigraphic questions raised through the *Palloures* excavation was the spatial and chronological relationship between the large structure uncovered in the southern half of trench BV13 and the building found one meter lower in trench BU13. This 3D GIS model helps clarify their relationship.

In order to better understand whether these building may have been contemporaneous, I examined the stratigraphic relationships between the units related to each of the structures, such as the floor surfaces and walls (BV13_8 and BU13_30). Additionally, I made the soil layers within trench BU13 visible at 60% transparency to help to understand the stratigraphy within this area of the site. Panning around the structure and querying the descriptions of the layers revealed that there were two major layers found which appear to separate the two structures: soil layer BU13_11 and an ashy midden layer BU13_13 (fig. 5.14). These observations could then be compared to the interpretations listed in the trench reports.

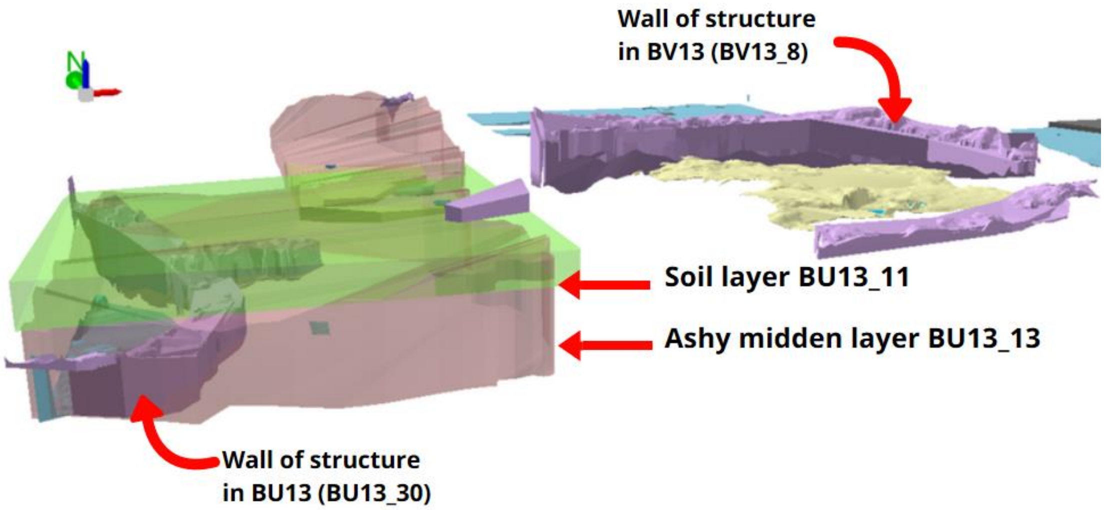

Figure 5.14: Spatial relationship between structures found in trench BU13 and BV13. A soil layer and ashy midden separate the two buildings (figure by author).

Based on the fact that the structure in BU13 was a meter deeper than the one in BV13 with a few soil layers in between, it is highly likely that these buildings were not in use at the same time. This notion runs counter to the dating of the buildings which were identified as both belonging to a single chronological phase: the Late Chalcolithic period. However, as Düring points out, settlements are dynamic. Structures dating to a single time period did not necessarily exist at the same time (Düring 2012, 331). Hence, these findings suggest that there may have been multiple occupation periods at *Palloures* during the Late Chalcolithic.

5.4.4 Identifying Post-Deposition Disturbances

Furthermore, the model provides the opportunity to identify post-depositional disturbances. One of the issues encountered during the *Palloures* excavation and at other sites in the Lemba cluster is that certain architectural features that were predicted to be continuous were not found in the locations there were expected. This 3D GIS system provides insights into the extent of the damage to the archaeological record.

For instance, trench reports identified major disturbances in trench BU13, most notably in the fact that there was no evidence found in this trench of the walls and floor surfaces of the structure uncovered in the southern half of trench BV13. However, by combining the photogrammetry models of the two trenches in a single 3D GIS environment, it becomes evident that there are some rocks in the balk between the trenches that are likely associated with the building (fig. 5.15).

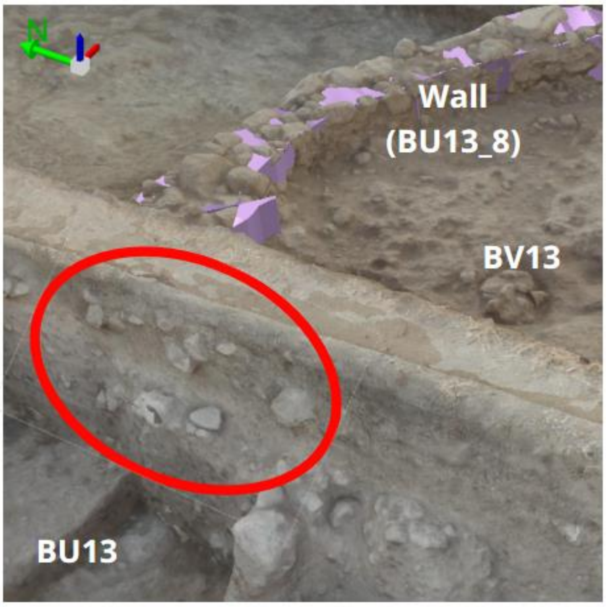

Figure 5.15: Remnants of the wall feature BV13_8 can be seen in the balk between trench BV13 and BU13 (figure by author).

The evidence of damage extends down into trench BU13. The structure in BU13 (wall unit BU13_30) has a wall segment jutting out of the side oriented toward the eastern trench wall (unit BU13_40). This short wall segment was identified as being part of the same structure. Additionally, two distinct features were identified at a comparable elevation adjacent to the structure: unit BU13_36, a potential fireplace, and BU13_22, a stone feature with evidence of burning which was interpreted as a possible kiln. Visualizing these features within the 3D GIS environment in conjunction with the trench photogrammtery models allowed me to form interpretations regarding the relationships between these features.

Although no more wall features were documented during the excavation, there may be a possible correlation between the abutting wall segment of the structure and an alignment of large rocks evident in the eastern profile (fig. 5.16). This may be evidence of an additional structure attached to the building found in BU13 surrounding the hearth and possible kiln. However, much of the architectural remains are missing, possibly due to post-depositional disturbances also evident in the destruction of part of the building in BV13. Perhaps excavating the balk between these two trenches may help support or reject this hypothesis.

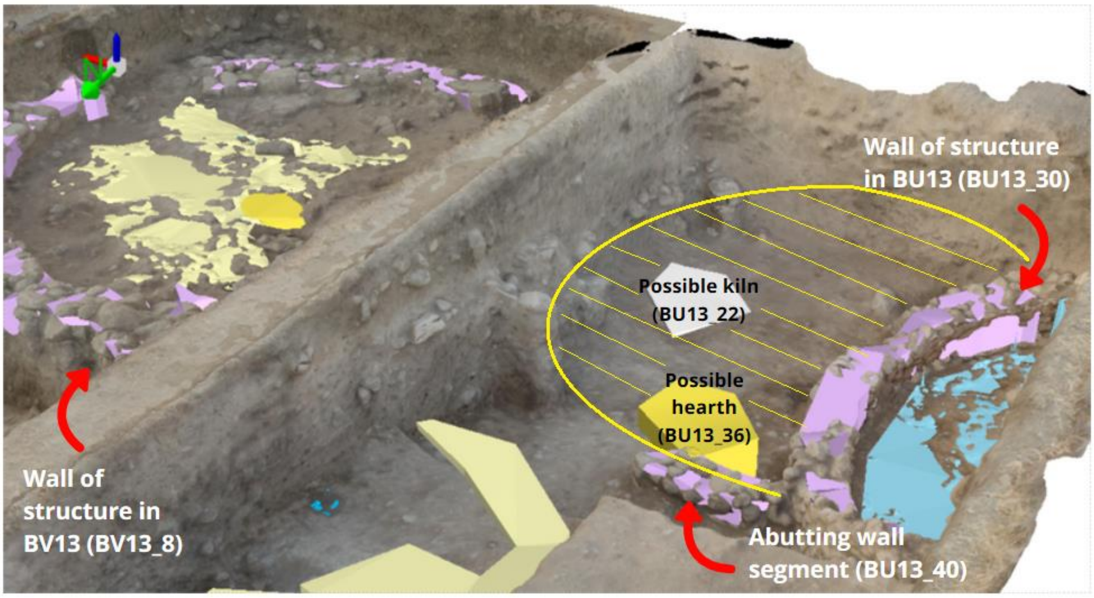

Figure 5.16: Yellow outline demarcating the boundaries of a possible adjoining structure in trench BU13, as identified through a review of the 3D GIS model (figure by author).

5.4.5 Solving Stratigraphic Problems

Finally, this model proved useful for clarifying the stratigraphic sequence of a series of plaster floor surfaces uncovered in the northern half of BV13. Due to the nature of the rescue excavation, this area was excavated quickly and the relationships between the layers was not thoroughly investigated. I closely examined the volumetric models created through the Extrude Between TINs and Minimum Bounding Volume methods in comparison to the unit relations entered into the database. The three-dimensional nature of the model and the user-friendly ArcScene interface allowed me to pan around and zoom in to the units of interest. Based on my observations, there is evidence of at least two different surfaces atop each other, separated by a soil layer (fig. 5.17).

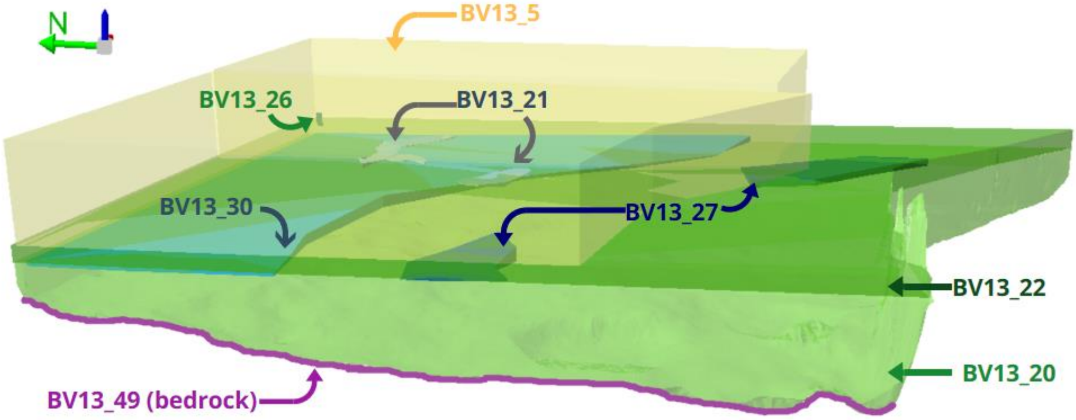

Figure 5.17: The sequence of plaster surfaces excavated in trench BV13, as visualized through the Extrude Between TINs volumetric modeling method (figure by author).

As these three units appear to have been recorded at the same elevation and extended to a similar depth. Based on the model, I hypothesized that the three plaster surface layers (BU13 26, BU13_27, and BU13_30) might be part of the same floor surface. A simple Harris Matrix visualizing these relationships is given in figure 5.18. Overall, this analysis further supports the possibility of multiple occupation or reuse of this site.

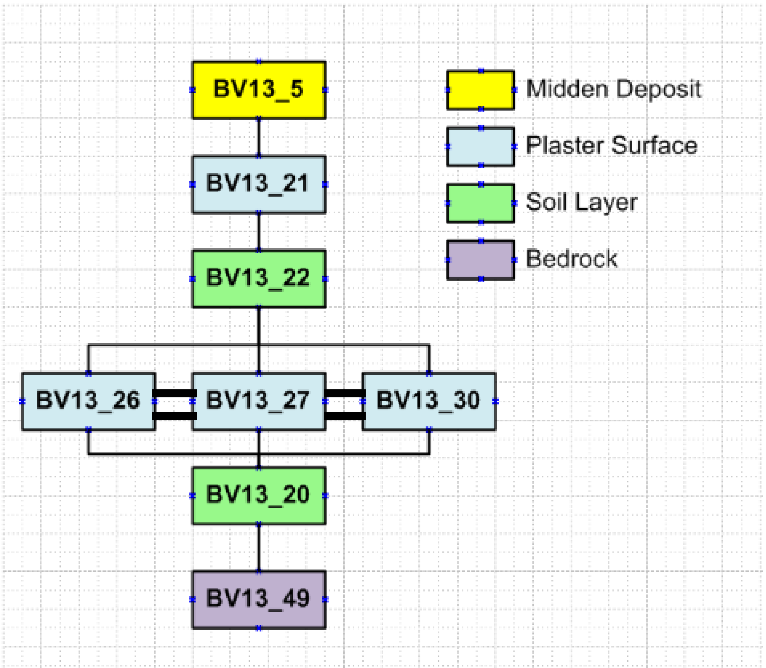

Figure 5.18: Harris Matrix depicting the stratigraphic sequence of plaster floor layers found in the northern half of trench BV13.

5.5 Settlement Patterns at Chlorakas-*Palloures*

The results presented above show that this 3D GIS system is capable of enhancing stratigraphic interpretations. But what can we learn about the occupational patterns at *Palloures* based on the trench stratigraphy? But how does it compare to other sites? Analyzing the spatial arrangement of excavated units and comparing the relationships of the structures found in trenches BV13 and BU13 shows there were likely at least two phases of occupation within the Late Chalcolithic period. This supports the notion that although structures may date to the same chronological period, they may not have been in use at the same time. This site likely experienced multiple periods of building, abandonment, and resettlement thus showing the dynamic nature of the settlements during the Chalcolithic period in Cyprus.

Furthermore, analyzing the spatial unit recorded with a TS in the context of the 3D photogrammtery model of the trench aided in identifying a potential architectural feature in trench BU13 that was heavily damaged by post-depositional disturbances. This structure is connected to a larger circular building and encompasses possible hearth and kiln features. If this is indeed the case, this building arrangement is similar to the structures found at the Late Chalcolithic phase settlement of Kissonerga-*Mosphilia* (see fig. 3.3). This observation illustrates the cultural continuity between these two settlements.

All in all, this chapter establishes that the workflow undertaken through this investigation results in a true 3D GIS model of the excavation. Although the volumetric modeling methods can be improved through further research and testing, this approach is nevertheless capable of not only visualizing the materials found on site, but also facilitating insightful stratigraphic analysis. The next chapter compares the workflow used in this project with the methodologies employed by other researchers and reviews the efficacy of 3D GIS in regards to traditional 2D recording.

Chapter 6: Discussion

The results presented in chapter 5 offer an ideal starting point for discussing the possibilities and limitations of the 3D GIS workflow outlined in this research project. In this chapter, I present the issues faced and comment on how the data acquisition methods employed on site impacted post-processing and 3D modeling. I also compare my workflow with the methodologies employed by other scholars and suggest a possible excavation documentation method that would facilitate 3D GIS model building. Next, I discuss the difference between digital 3D GIS and traditional 2D plan and section drawing methods in respect to documenting, analyzing, and interpreting the stratigraphic sequence of a site. Finally, I comment on the potential of this approach for aiding in the interpretation of spatial data and discuss issues of data accessibility.

6.1 Workflow Overview

The workflow used to build a 3D GIS system for the *Palloures* excavation is presented in detail in chapter 4. Here, I discuss the challenges faced during the process in order to elaborate on the work involved in processing excavation data into a usable format. It is likely that many of these issues resulted from mistakes within the initial documentation process, thus highlighting the crucial role that data acquisition methods play on the quality of the resulting 3D GIS model.

One of the major difficulties using the given dataset was that organizing and cleaning the TS data was an extensive and labor-intensive process which slowed down the workflow considerably. First, there were excavation units recorded with an incorrect sequence of coordinates, thus resulting in 'bow-tie' units (fig. 6.1). To accurately represent the geometric properties of a stratigraphic deposit, each unit in the GIS environment must be a closed polygon without intersections. As the TS measures individual coordinates which form the boundaries of a unit, the sequence of points must be sequential otherwise the resulting polygon would "bow-tie", or intersect itself. In order to rectify this, the sequences of coordinates in the raw TS dataset had to be re-evaluated and re-numbered, then converted to polygon format before being merged with the remaining dataset.

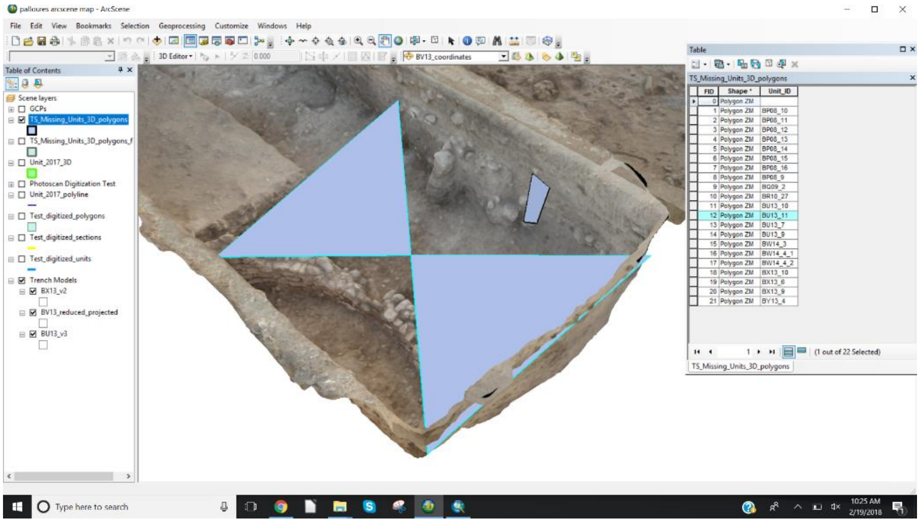

Figure 6.1: BU13_11: An example of a bow-tie unit (BU13_11) (figure by author).

Next, there were instances in which the geometry of units was recorded incorrectly, although this was far more difficult to identify. For example, unit BU13_13 was recorded incorrectly during excavation (fig. 6.2). In single-context recording, the entire horizontal extent of the unit should have been documented. However, this was not the case. This sounding unit, which in reality represented the excavated area of most of trench BU13, was recorded as a rectangular polygon covering the north-east corner of the trench. Unfortunately, this error was not discovered until late in the 3D GIS workflow while I was creating volumetric representations of each unit using the Extrude Between TINs method. This method required me to reference multiple lines of evidence including the excavation database, section drawings, trench reports, and more. The records for BU13_13 exhibited conflicting information: the database described the units as the northern half of the sounding. However, the lots associated with this unit were dispersed throughout most of the trench and the section drawings included this unit as a large stratigraphic layer running along the majority of the east and west walls. It was therefore necessary to consult Klinkenberg, the field direct on site, to determine the exact nature of the unit geometry.

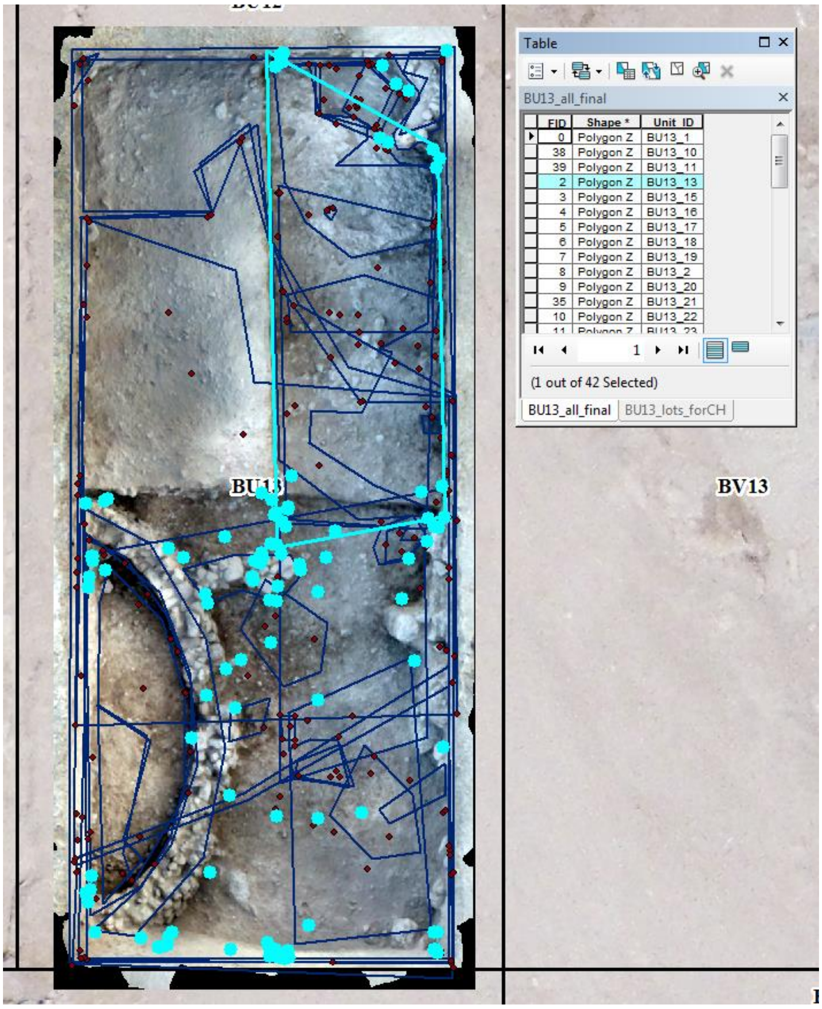

Figure 6.2: The boundary of unit BU13_13 as recorded during excavation and associated lots. The lots cover a wider spatial extent than the unit boundary (figure by author).

There were a few stratigraphic deposits inaccurately documented with similar circumstances, however it proved difficult to both identify these mistakes and to determine their actual extent. This problem carries over to the sixty-five units which were missing from the TS documentation altogether. As mentioned in chapter 4, I consulted alternative forms of documentation, such as the daily drawings of each trench, the trench reports, and the annotated plan and section orthophotos, in order to reconstruct the extent of missing archaeological deposits. This method is far from ideal because the outlines of units are not always apparent in photographs and occasionally the various sources conflict, such as in the case of unit BU13_13 mentioned above. Only units located close to the bottom of the trench were annotated in the final orthophotos and not all unit could be located in the daily field drawings. Having not participated in the excavation itself, the geometry of the units I digitized reflect my own interpretations of secondary data.

This inaccuracy in the digitized dataset is exacerbated by the fact that I did not have elevation data for any of these units. Granted, height information for some units could be reconstructed from associated photogrammetry models. However, for others this was not possible. One method that I could have employed to recreate the missing height data could have been to average out the elevations of the overlying and underlying units. However, this does not present an effective or even recommended strategy because ultimately, the result would be a subjective and misleading representation of the truth. Therefore, I left the missing data out of the final models. Overall, cleaning the spatial dataset and recreating missing units took up a significant portion of the time within the overall workflow. Specifically, digitizing the sixty-five missing units slowed down the process since recreating each unit required an extensive investigation of multiple data sources.

The problems mentioned above highlight the importance of keeping adequate secondary records (daily logs, drawings, etc) alongside digital recording strategies, especially within an excavation such as *Palloures*. I hypothesize that due to the nature of the excavation being a rescue operation, the chosen documentation strategy allowed excavators to record quickly to allow amply time for digging. The nature of TS recording could have had an impact as well: excavators would need to export all TS data at the end of each field day and review this data for accuracy in order to spot these mistakes. Missing data on an excavation is not a new problem; Harris mentions this issue as well by stating that "working with one site of several thousand deposits, it was determined that the loss of stratigraphic data amounted to about 40%"(Harris 1989, 109). Yet, stricter checks and reviews by field supervisors could help insure the completeness of the archaeological documentation since the destructive nature of the excavation process would otherwise obliterate the ability to go back and record the necessary measurements after digging recommences.

In either case, it is evident that the accuracy and analytical potential of the final 3D GIS model is predicated on the methods used to document the excavation and the degree of reliability of data recorded in the field. For instance, if the geometry of the units is not recorded properly, then any efforts made to recreate the volume of the unit will be inherently inaccurate. For instance, documenting round stakeholes at *Palloures* by recording only three TS points demarcating the unit boundary consequently resulted in a triangular polygon shape in the final dataset. The misshapen morphology of these features then leads to misleading results in subsequent analysis and negatively affects the possibility of calculating artifact densities. This is important to consider since scholars have recently hailed digital methods, such as photogrammetry models, as allowing for more empirically accurate measurements than traditional methods (De Reu *et al.* 2013, 1110-1112).

It is important to note that although the discrepancies in the recording of the units at *Palloures* impacted the quality and accuracy of the resulting 3D GIS model, it does not indicate that this data acquisition method does not work, nor does it imply that recording units using digital methods is inferior to recording using traditional pen and paper. Rather, this research demonstrates that much like traditional 2D drawings, 3D recording is susceptible to the subjective biases and technical expertise of the wielder. As Morgan and Wright cheekily point out, "robust datasets rely on good practice—as is commonly stated in the field of computer science: garbage in, garbage out" (Morgan and Wright 2018, 150).

6.2 Comparison with Other 3D GIS Workflows

In order to better evaluate the efficacy of the workflow utilized within this case study, is important to consider this methodology in respect to those proposed by other scholars as summarized in chapter 2. It is not my intention to argue that one workflow is better or more effective than another. Rather, I wish to offer a critical analysis of the different ways in which digital technology is used in real-world archaeological case studies in order to open up a discussion on best practices for intra-site digital data acquisition and 3D GIS model building.

First, my workflow is influenced by the digital data recording approach used at Çatalhöyük in Turkey. Both integrate various spatial datasets within ArcScene, though the Çatalhöyük method is more focused on a viewer's experience within a virtual reality platform. Although the *Palloures* documentation methods contain 3D models that could be virtually 'walked through,' there is limited use for it since, for the most part, there are no separate 3D models for each excavation layer. Both workflows allow for combining spatial data from multiple field seasons for a holistic representation of work done at each site.

Next, the KAP recording system presents a volumetric modeling method which relies on the creation of photogrammteric 3D models of each context. My modeling approaches are far less comprehensive in capturing unit volume and topography. Since the bottom of each unit was not recorded at *Palloures*, the volumetric calculations are not nearly as reliable. Furthermore, the KAP models display a suitably water-tight stratigraphic sequence while some of my models contain gaps. On the other hand, my volumetric modeling methods are far faster and require less processing time than the KAP approach.

Furthermore, the multipatch features of each stratigraphic unit do not take a significantly large amount of computer storage space and multiple units and multiple trenches can be combined within the same 3D GIS environment.

Another comparable 3D GIS methodology is the Uppåkra workflow presented by the Lund University research team. The most critical difference between this approach and the one presented here is that it is done entirely in the field, or, “at the trowel’s edge”(Dell’Unto *et al.* 2017, 638). In other words, there is virtually no post-processing necessary after the excavation is completed since all the excavation data (spatial and otherwise) is generated and processed on-site. All stratigraphic units are drawn within the ArcScene interface and thus there is no need to convert or clean TS datasets. Furthermore, there is no need to join an external database as all the excavation data is recorded directly within the 3D GIS database. The major advantage of this method is that spatial data is immediately accessible to excavation participants. As previously discussed in chapter 2, this allows for a reflexive field practice as it provides the opportunity to review data before excavating further. Thus, excavators can make sure all units have been recorded, and recorded correctly. This is a stark difference from the *Palloures* methodology since many errors were not identified until after the excavation during the post-processing phase. Furthermore, the Uppåkra approach to recording results in more geometrically accurate contours of stratigraphic units (fig. 6.3). A similar result may perhaps be achieved by using an RTS. However, in many excavations such as *Palloures*, excavators may not have access to this equipment.

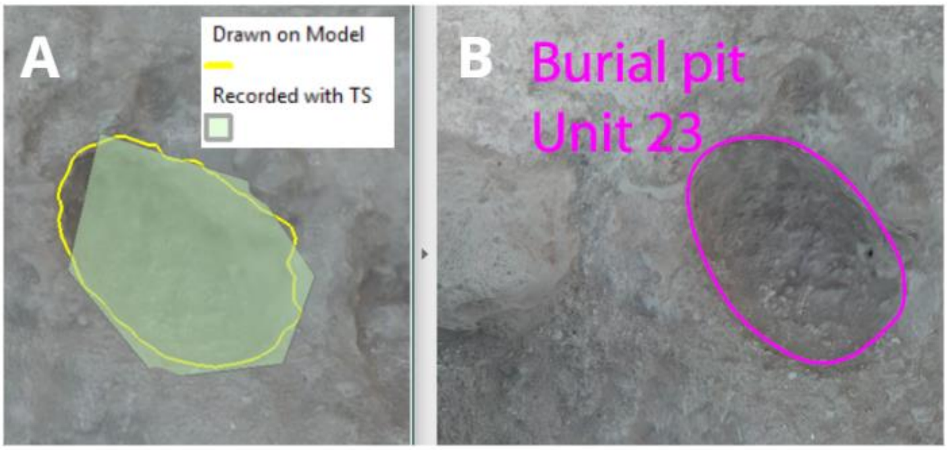

Figure 6.3: Difference in geometric accuracy between recording pit unit BX13_24 using a total station and by drawing the contour directly atop the photogrammetry model within ArcScene. (A) Comparison of different recording strategies; (B) annotated plan drawing (figure by author).

The Uppåkra approach is not without its drawbacks and there are aspects of the workflow that could be improved. For instance, the methodology involves creating a photogrammetry model of every layer of the excavation thus requiring excavators to halt digging and clean the trench at regular intervals. As mentioned in the articles, the researchers kept the number of photographs taken of each trench to a minimum. Even so, acquiring photographs and generating models using Photoscan does take extra time which may not be feasible in a fast-paced context of a rescue excavation.

Furthermore, the photogrammetry models were created to record excavation levels “when a major surface had been found” rather than to document the starting and ending elevations of each discrete phase or individual context (van Riel 2016, 61). Thus, the resulting 3D GIS model of the boundaries of each unit represent the elevations of the photogrammetry models rather than the interfaces or vertical extents of individual contexts (fig. 6.4). Thus, this methodology removes the possibility of accurately recreating the volume of each archaeological deposit. Van Riel mentions this as one of the major limitations to the ArcScene 3D workflow by citing the difficulties of representing posthole depth (van Riel 2016, 61-2). It may be possible to solve van Reil’s posthole volume problem using the Extrude Between TINs method to create a multipatch features depicting the depth of the feature. Indeed, documentation methods at *Palloures* focused on recorded the upper extent of stratigraphic units as they were uncovered and therefore facilitated volumetric modeling. However, since the bottom surfaces of each unit were not recorded, it was also difficult to ascertain the volumetric extent for certain soil layers without a defined boundary.

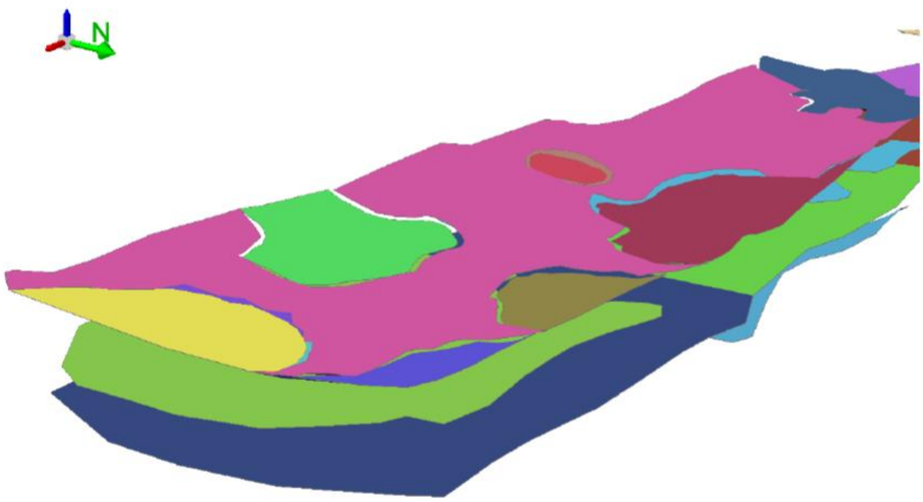

Figure 6.4: ArcScene visualization of horizontal interfaces of archaeological units within a trench at Uppåkra, recorded using the Uppåkra workflow (van Riel 2016, 54, figure 24).

A comparison with voxel-based modeling approaches further illustrates the benefits and challenges of using vector-based 3D GIS workflows. Both the workflow presented in this thesis and Lieberwirth's voxel-based workflow aim to visualize stratigraphic units as solid three-dimensional objects as a basis for stratigraphic analysis (Lieberwirth 2008a, 1). Yet, there are technical differences between them that are important to note.

First, there are key methodological similarities between these two approaches. Indeed, the third volumetric modeling method presented in this thesis (digitizing and extruding section drawings) is both inspired by and borrows methodological elements from Lieberwirth's work. Although my method is vector-based, not voxel-based, it functions in a very similar fashion: existing section drawings are digitized and then connected to form the interfaces between stratigraphic deposits. Then an algorithm is used to fill in the space between each unit. The result is not a solid voxel form as in Lieberwirth's case study, but a hollow multipatch feature. However, I would argue that my vector-based method is both more spatially accurate and much faster to execute.

Lieberwirth's workflow involves digitizing opposite sides of an excavation trench and joining these two sides to form stratigraphic boundaries between units. The approach used for *Palloures*, however, takes into consideration the stratigraphic sequence within all four walls of a trench. In fact, this method can be applied to irregularly-shaped trenches with any number of walls as the algorithm used to connect the digitized lines (Polygons from Polylines tool) can quickly compute complex forms from multiple line segments. Furthermore, this method can also incorporate some features within the interior of the trench, such as pits and walls, which can be traced in ArcScene by following the geometry of the photogrammetric 3D trench model (fig. 6.5).

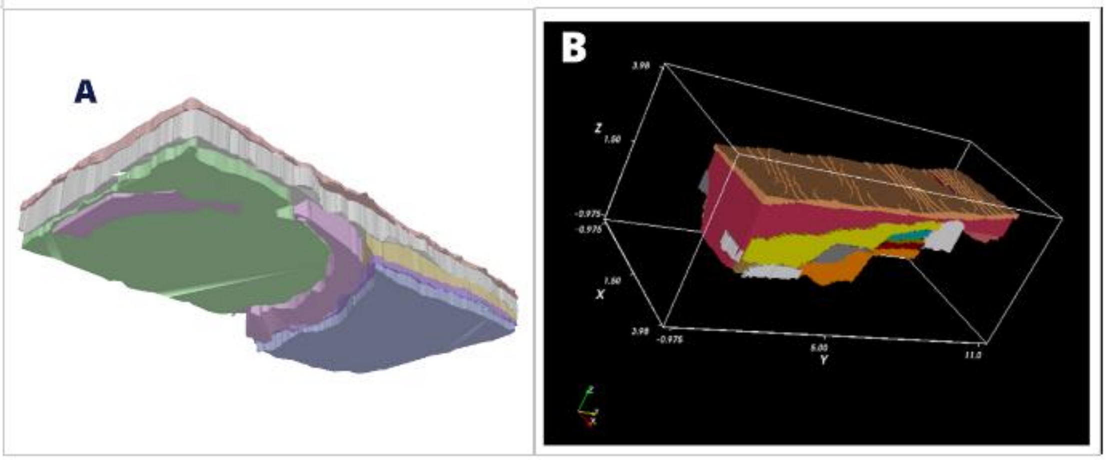

Figure 6.5: Comparison of volumetric modeling workflows: (A) Volumetric model of the straigraphy of trench BV13 using the digitized sections method as presented in this project (figure by author); (B) voxel-based 3D GIS model of trench stratigraphy as per Lieberwirth (Lieberwirth 2008a 6, figure 7). Model A is capable of representing units within the interior of the trench including irregular walls while model B only visualizes the unit found within trench walls.

Another added benefit to the method presented in this thesis is that it is completely contained within a single software package: ESRI ArcScene. Lieberwirth transfers data between a few different software programs for each step of her workflow, a process which is both time-consuming and inefficient. Keeping the entire workflow within a single GIS environment also eliminates the need for georeferencing the unit interfaces and allows for joining the resulting volumetric model to the excavation database. This facilitates a more dynamic interaction with the data as units can be identified and queried directly from the 3D model. Furthermore, the entire modeling process is very fast since the tools used to both create the unit interfaces and extrude the volumes between them process very quickly and the output file sizes are relatively low. This circumvents one of the major problems of voxel-based modeling which is that a high-resolution voxel model requires high processing power and often results in a large file size.

On the other hand, there are a few aspects of Lieberwirth's method that would greatly improve the method laid out here. First, she utilizes free and open source software which are far more accessible than ESRI software packages. There should be a greater investment into developing more robust 3D GIS capabilities in open-source GIS programs to make 3D GIS volumetric modeling more feasible for projects without access to commercial software. Furthermore, Lieberwirth visualizes the final model in ParaView which she states allows the user to make cross-sections of the voxel model "at any location and in any direction" thus providing the opportunity to study the interior stratigraphy (Lieberwirth 2008a, 7). ArcScene has this capability, but the tools to do this require that the features being cross-sectioned must be closed multipatches. Currently, modeling volumes using the 3D sections method does not result in closed features and until this issue is resolved, it is not possible to create cross-sections. Perhaps it would be helpful to develop a tool for ArcScene similar to the 'Swipe' tool in the ArcMap 'Effects' toolkit which would allow users to swipe a multipatch feature class layer up and down in a chosen direction to see a cross-section. All in all, the section drawing method presented in this thesis offers an opportunity for volumetric modeling of stratigraphic units that is in many ways more effective than the voxel-based methodology presented by Lieberwirth ten years ago.

6.3 Suggested Excavation Documentation Methods

Comparing various workflows for site documentation with the workflow presented here helps distinguishing what methods work and which methods need to be improved. Here I offer suggestions for documenting an excavation such as *Palloures* for the purpose of 3D GIS model building.

First, a 3D GIS-based documentation method must follow the single-context method. An RTS should be used to record the top interface of each unit. Unlike a regular TS, an RTS would facilitate efficient 3D conversion and would greatly improve geometric accuracy in unit recording. To increase the accuracy of volumetric modeling, it is important to also record the elevation of several points within the boundaries of the units to capture the variable topography of the archaeological deposit. Creating photogrammtery models of each unit would be inefficient, but it may be useful to create 3D models of special features such as burials, complex floor surfaces. Therefore, areas with complex stratigraphy or special features such as skeletons could be traced as 3D polylines directly on the photogrammetry model. Unlike tracing orthoimages, any features digitized in this manner would be automatically georeferenced and compatible with the remaining spatial dataset.

Borrowing from the Uppåkra approach, all RTS data and photogrammtery models should be processed and imported to ArcScene at the end of every field day. This step is crucial for reviewing that all data has been entered accurately and completely and may allow corrections to be made before the excavation proceeds. Additionally, the recorded dataset can be reviewed in an intuitive 3D interface thus allowing for a more reflexive understanding of the excavation process. Furthermore, I advocate using an external database program such as Microsoft Access, given that the chosen software is compatible with ArcScene. Unlike entering all information directly into the ArcScene database tables, an external program allows for better control over database structure and easier data sharing with other researchers. At any rate, this data can connected to the GIS model seamlessly at any time.

Accurately modeling the volumes of each unit is nevertheless difficult due to limitations in the software discussed in chapter 5. Moreover, it would be ideal to record both the top and the bottom of each unit as per the KAP recording system and extrude between them using the Extrude Between TINs method, yet this is not always possible. Unlike pit features, many archaeological units are widespread and determining the extent of these units after they have already been excavated is challenging. Therefore, I suggest using a variation of modeling methods to recreate the volume of each deposit based on the unique circumstances of each unit. For instance, modeling walls would be easiest by tracing a 3D model of the feature in ArcScene and pits could be created through the Minimum Bounding Volume method. Finally, section drawings for publication can additionally be created by drawing directly on the trench walls of the photogrammetry models while referencing the spatial extent of units as visualized in the 3D GIS model.

The documentation system described above would allows for the complete documentation of excavation units within a 3D GIS model. Yet, supplementary documentation methods, such as annotating daily aerial photographs of each trench, are advised to provide a complete record of the excavation process.

The remainder of this chapter discusses the use of 3D GIS systems in comparison with traditional analog documentation methods and comments on the potential benefits of 3D GIS for the interpretation of spatial data.

6.4 3D GIS v. Traditional Plan and Section Drawings

It is clear that the quality of a 3D GIS model of an excavation largely depends on the methods used to acquire the data in the field. But given the current limitations in our methodology, are there aspects of 3D GIS that are advantageous to stratigraphic studies? Aside from speed of recording and increased accuracy in measurements (Olsen *et al.* 2013, 254), are there tangible benefits to switching documentation methods from a traditional approach using 2D plan and section drawings to a digital approach such as the workflow presented here? Based on the findings of this research, 3D GIS offers some important contributions to for the study of site stratigraphy that are not found in 2D drawing methods. These are discussed below.

First and foremost, 3D GIS has the potential to illuminate complex spatial patterns in excavation datasets that may become lost within 2D drawings of site stratigraphy. As Harris points out, traditional section drawings "give a simplistic, rather than representative, view of the stratification and the stratigraphic sequence" since they are limited to depicting a small isolated portion of a site (Harris 1989, 71). Indeed, recording sections observed in balks or trench walls is inherently arbitrary and is not representative of the site or even a single trench as a whole (Tschauner and Siveroni Salinas 2007, 274). However, 3D GIS volumetric representations of stratigraphic units provides a more complete representation of trench stratigraphy both from all sides and in the interior of the excavated area. ArcScene provides the tools to cut such a volumetric model both horizontally and vertically at any angle and in any direction, given that that it is saved in the proper format as a closed multipatch feature (http://desktop.arcgis.com). Furthermore, models of all trenches could be included in the same GIS environment, thus allowing the user to compare the stratigraphy evident in each trench with those located nearby. In this sense, 3D GIS provides the opportunity to visually depict the complex stratigraphic sequence throughout the entire site.

Furthermore, 3D GIS greatly improves the single-context recording method on a practical level. Harris states that through single-context recording, units can be placed in the stratigraphic order in which they were uncovered and comparing units recorded in this way could also solve stratigraphic problems (Harris 1989, 95). Unlike comparing and consolidating hand-drawn single-context plans (a process which may introduce human error), the born-digital field recording strategy used at the *Palloures* excavation allows for an objective method of comparing stratigraphic relationships (Morgan and Wright 2018, 142). Digitally recording units and unit elevations and importing them to ArcScene as 3D polygons places them in spatial relation with each other automatically, thus allowing for fast and easy spatial comparison. Furthermore, the inclusion of photogrammtery models provides additional spatial context to single-context recording methods which aids in understanding each deposit's position within the trench and within the stratigraphic sequence.

Moreover, the importance of being able to connect an excavation database to the 3D GIS models cannot be overstated. Joining excavation data means that the user can bring up unit and artifact information simply by clicking on the associated unit. Data can be queried and filtered as needed. Furthermore, models can be visualized using different colors to depict different attributes. For instance, units can be color-coordinated to represent feature types. As shown in chapter 5, this simple visualization approach allows for a very quick method for discerning types of deposits, such as walls, burials, or hearths. This capability facilitated stratigraphic analysis throughout the project study area.

Finally, 3D GIS allows archaeologists to better conceptualize spatial data in a format that leverages the nature of human vision. Human beings are inherently wired to view and interact with the world in three dimensions. On the other hand, two dimensional plan and section drawings inherently simplify complex spatial relationships, therefore detracting from our understanding of how materials interact in three dimensional space. Hence, 3D GIS modeling is especially helpful for visualizing the spatial relationships between different sets of data which are not always explicitly combined in section and plan drawings, such as artifacts find locations.

6.5 3D GIS Modeling for Interpretation of Spatial Data

It is important to mention that one common critique of using of digital technologies for field recording is that it widens the gap between excavators documenting a site and their interactions with the archaeological materials. This may negatively impact the interpretive process at the trowel's edge since the moment of excavation is commonly considered the only chance archaeologists have explore and test interpretations of stratigraphic relationships (Berggren and Hodder 2003, 425-427). Morgan and Wright further argue that there are interpretive benefits to traditional hand-drawing in the field because 2D illustration offers the possibility of a reflexive interpretive method "that is not easily replicated by digital tools" (Morgan and Wright 2018, 148). Specifically, using a TS to record the boundaries of an archaeological deposit or even tracing the deposit in a rectified orthoimage may allow for quantifiable accurate recording but detracts from our ability to interact with the materiality of the archaeological record (Morgan and Wright 2018, 149). That being said, to what extent can 3D GIS aid in the interpretation of spatial data?

First, digitally recording data does not necessarily detract from the interpretive process. Rather, accurate and efficient spatial data recording may facilitate interpretation by giving excavators more time to interact with the materials at hand. Moreover, rather than focusing on flattening spatial relationships into a 2D format, archaeologists could potentially record them as they are: 3D objects with complex vertical and horizontal dimensions. For instance, the KAP recording system described in chapter 2 is fully digital and forces archaeologists to think volumetrically about the stratigraphic layers excavated on site (Roosevelt *et al.* 2015, 326).

Based on the results presented in the Stratigraphic Analysis section of chapter 5, 3D GIS may also provide the opportunity to support and review stratigraphic interpretations recorded in the field or form new observations not readily obvious during the excavation process. Harris mentions that it is possible to use single-layer plans to analyse stratigraphic problems (Harris 1989, 101). Recording units using this single-layer method and placing them into a volumetric 3D GIS environment affords archaeologists the opportunity to visually inspect which units lie above, under, or adjacent to other deposits. This is doubly effective after also importing the photogrammetry models of excavation trenches to provided a detailed topographic context and joining the data on units relations observed in the field from the excavation database to the digitized units themselves. This approach allowed me to make interpretations on the location of a possible secondary architectural feature in trench BU13. Hence, placing all spatial data into a single model allows archaeologists to extend the interpretive process and "search for evidence which escaped attention during the dig" (Reilly 1990, 135).

6.6 4D GIS

A few scholars argue that 3D GIS may additionally offer the possibility of what they call '4D GIS,' a term they use for a "time-based" visualization of stratigraphic units "in relative and absolute chronological order" (Dell'Unto *et al.* 2017, 639; Lieberwirth 2008b, 85). In other words, 3D GIS models allow researchers to digitally re-excavate a trench or "explore the taphonomic and site formation processes" of the stratigraphy (Lieberwirth 2008a, 7). On the other hand, as Harris clearly states, this is the function of archaeological plan and section drawings, as plans record the horizontal (x,y) extent of each unit and sections record the depth (z-value). The combination of these three dimensions create a stratigraphic sequence "which represents the fourth dimension, time, on archaeological sites" (Harris 1989, 83). Thus, I would argue that traditional section drawings and 3D drawings of stratigraphy also include a 4D component in that they similarly conveys the temporal sequence of stratigraphic units, albeit in a 2D format. 3D GIS presents the same information in a different manner.

However, it may be possible to move beyond static representations of site stratigraphy by leveraging the capabilities of 3D GIS software. For instance, ArcScene has a temporal toolkit which allows the user to view components of a model based on a time field within the layer's attributes and create a time lapse of layers building up as time increases. Using this toolkit, 3D GIS volumetric model of site stratigraphy can potential serve as a basis for creating a timelapse which simulates taphonomic processes based on the archaeologist's interpretation of the phases of deposition. By basing this simulation of the date each unit was excavated, it is also possible to recreate the entire excavation processes day by day. This functionality has not been extensively explored through this project due to time constraints, however it would be an interesting concept for future research.

6.7 3D GIS Data Sustainability and Accessibility

It is important to mention that a major issue impeding archaeologists from adopting 3D GIS workflow is the question of data accessibility and sustainability. As previously stated, the 3D GIS models created through this research are most commonly illustrated in this thesis as screenshots. Unfortunately, screenshots are not as effective at illustrating 3D relationships as zooming in on and panning around the actual 3D model. Although supplementary materials have been provided in the form of videos, access to the model itself is predicated on the viewer having a license to ESRI ArcScene. Although many universities have an institutional license for this software and thus costs associated with using this program can be mitigated, access to this program is not universally guaranteed. Furthermore, free and open source programs are lagging behind in 3D functionality and need to developed for more robust handling and manipulation of 3D GIS models. Access to free or low-cost software comparable with the analytical and processing power of ArcScene would certainly spur more interest in and research into 3D GIS methodologies.

Moreover, the file formats used in this project, such as multipatch and COLLADA files, are not necessarily sustainable. As technology changes and develops, digital file formats rapidly become obsolete. For instance, ArcScene is not capable of opening models created in newer versions of the software package without the file first being converted and newer versions of Microsoft Access are not directly compatible with the version of ArcScene used in this project. Although developing solutions to data sustainability is beyond the scope of this thesis, it is important to keep in mind the rapid turnover rate in digital technologies when thinking about the future of 3D GIS in archaeology.

Overall, this project reflects on the use of 3D GIS systems for recording and analyzing excavations and discusses the advantages of this methodology in comparison to traditional documentation methods. It is my intention that this project helps improve digital recording practices by discussing some of the issues that were encountered during the process of creating a 3D GIS system for the *Palloures* excavation and suggesting improvement for future field seasons. The final chapter summarizes the results of this investigation and suggests possible directions for future research.

Chapter 7: Conclusion

Developments in digital data recording technology have opened up new possibilities for documenting excavations and revolutionizing how archaeologists interact with spatial data. Notably, the recent development of more robust 3D capabilities in ESRI ArcScene have allowed more flexibility and functionality beyond the 2.5 capabilities of traditional GIS software. The aim of this thesis was to develop a feasible post-excavation workflow in ArcScene for building a 3D GIS model of three trenches at the Chalcolithic site of Chlorakas-*Palloures* using photogrammetry models and a TS spatial dataset. Additionally, I explored the analytical capabilities of 3D GIS for intra-site stratigraphic visualization and analysis in comparison to the traditional 2D recording strategies of plan and section drawings, and utilized this approach to derive interpretations regrading the settlement dynamics at the site. Based upon the results, it appears that the old adage of 3D models being nothing more than pretty pictures is becoming both tiresome and irrelevant.

The workflow presented in chapter 4 makes it possible to create a 3D GIS model capable of functioning in all four subsystems of GIS as defined in chapter 2: data entry, data management, analysis, and visualization. Unlike traditional section drawings which only contain stratigraphic information observed within a single balk or trench wall, the resulting 3D GIS models provide a complete representation of all units and their spatial relationships, including pits, walls, and soil layers found in the interior if the trench. Models created through this workflow consisting of closed multipatch features could be cut in any angle or in any direction to view a horizontal plan or cross-section of the trench stratigraphy. Furthermore, volumetric models can be connected to the excavation database thus facilitating instantaneous query of excavation data by clicking on the individual features. Archaeologists can pan around the model and visually compare the stratigraphy between trenches, check stratigraphic interpretations made in the field, and identify new stratigraphic relationships that may have been overlooked during excavation, all within a user-friendly 3D interface. Ultimately, stratigraphic analysis using the generated 3D GIS model revealed the possibility of multiple occupation layers at *Palloures*, thus contributing to a more nuanced understanding of the dynamic settlement patterns in Late Chalcolithic Cyprus.

This project additionally tested three different modeling methods for recreating the volume of archaeological deposits using the available dataset: Extrude Between TINs, Minimum Bounding Volume, and Digitizing Section Drawings methods. These approaches allowed for a general representation of trench stratigraphy and different methods worked well to depict different deposit types, such as walls and pit features. However, more research need to be done to improve their volumetric accuracy, such as experimenting with combining these approaches or figuring out better methods for recording unit depth during excavation.

Indeed, the possibility of creating a true volumetric 3D GIS model depends largely on the quality and type of documentation methods used on site. This investigation showed that there are limitations to what can be accomplished using the given spatial dataset as the accuracy of the final 3D GIS model was impacted by discrepancies in the data recorded at Palloures. In chapter 6, I suggested an improved documentation system geared toward the collection of 3D data necessary for creating a more accurate 3D GIS model. Different strategies must be applied to create true 3D objects, bearing in mind the limitations and the possibilities of available technology. But this is no simple task and requires an entirely different mindset geared toward recording volume, rather than just horizontal extent.

Bearing this in mind, future excavation documentation methods will likely increasingly focus on more complex ways of collecting and manipulating 3D data. The several 3D GIS workflows discussed in this thesis are just a precursor for what is to come; I expect that 3D modeling and virtual reality technologies will completely revolutionize excavation practice within the next few decades. For instance, advances in laser scanning could very well become cheaper and more efficient in the next few years. Ideally, it would be helpful to have a 3D scanner that could fit into the palm of your hand and record a surface in seconds, rather than minutes. Software developers are constantly pushing the boundaries of what is possible and this technology might not be far off.

Just as an example, the recently released Microsoft HoloLens device offers a 'mixed reality' experience by projecting holograms into fixed spatial locations, thus bringing together the virtual and the real world. Using an intuitive headset, users can draw and manipulate digital holograms with a wave of their hand. The development of this device has far-reaching ramifications for archaeology. Imagine being able to draw in the boundaries of an excavation unit in seconds by tracing it with one finger. Every archaeologist on an excavation could digitally create their own interpretations of the dig for comparison, thus fully democratizing the documentation process. Furthermore, this functionality could solve the problem of recording unit volumes: being able to see a floating hologram of the top interface of a unit after the unit has been excavated would allow excavators to accurately draw in the extent of where it ends. Ultimately, the completed 3D GIS model of the excavation could be shared with anyone and users could potentially ‘walk through’ the excavation and examine the different taphonomic layers by swiping them away with a wave of a hand.

Using 3D GIS for intra-site stratigraphic analysis is indeed promising. However, we as archaeologists need to start thinking volumetrically in order to make use of newly available 3D recording technologies. On a practical level, the 3D Analyst toolkit in ArcScene should be expanded to allow for greater analytical capabilities, such as querying features based on spatial proximity (adjacent, intersecting, or nearby features) or being able to build 3D models within the 3D GIS interface directly rather than importing them from other modeling programs. Software problems within the existing tools must also be corrected. For instance, generated multipatch features should have closed geometry. Possible avenues for further testing the analytical potential of 3D GIS is leveraging the temporal toolkit in ArcScene to create a dynamic time-lapse of taphonomic processes or recreating the day by day excavation progress. Finally, more investment should be put into developing open-source or low-cost GIS software packages with greater 3D GIS functionality that goes beyond simple visualization. Tackling these issues will undoubtedly encourage more archaeologists to explore 3D GIS approaches and will help propel archaeological research into a new dimension.

Abstract

Advances in digital recording technology make it possible to document three-dimensional data during excavation. Yet this opens up the question: what do we do with this data? Is there an added value to recording 3D data that exceeds traditional 2D drawing approaches? Various 3D GIS workflows have been introduced over the years, yet little research has been done exploring the analytical possibilities of this approach. This thesis presents an effective workflow for creating a vector-based 3D GIS model that is capable of operating in the four subsystems of GIS: data entry, data storage, analysis, and visualization. Three excavation trenches from the Chalcolithic site of Chlorakas-Palloures, Cyprus are modeled using TS spatial data and 3D photogrammetry models. Moreover, three methods are introduced for modeling the volume of stratigraphic units using the capabilities of Esri ArcScene.

This approach presents a significant advantage over 2D plan and section drawings in regards to stratigraphic analysis. The excavation database can be joined within the 3D GIS environment and easily queried, thus creating a complete 3D spatial database of all excavated materials. Using this method, it is possible to find spatial correlations between units in trenches that may have been excavated at different times. Furthermore, unit relations identified in the field can be visualized and verified in an intuitive, user-friendly interface. Along with being able to depict features and materials found within the interior of the trench, models can be cross-sectioned at any angle and in any direction to show the stratigraphic sequence. This is particularly helpful in aiding in the stratigraphic studies of Chalcolithic sites in Cyprus which have characteristically shallow occupation layers and are subject to extensive post-depositional processes. Stratigraphic analysis of the modeled trenches provides evidence of multiple occupation phases at the site, thus supporting the idea of dynamic settlement patterns during the Late Chalcolithic period in Cyprus.

However, the ability to create a 3D GIS model is predicated on the quality and type of data recorded in the field. Volumetric modeling methods showed promise for depicting certain types of features, yet these must be improved in order to accurately represent the volume of all excavated units. An ideal documentation method is introduced that addresses these deficiencies and presents a means of capturing the volumetric data needed for creating a true 3D GIS model for stratigraphic analysis.

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Figures

Tables