# A New Methodology for Archaeological Analysis:

## Using Visualization and Interaction to Explore Spatial Links in Excavation Data


By

**Eileen Louise Vote**

B.A., Rice University, 1990
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This dissertation by Eileen Louise Vote is accepted in its present form by the following faculty as satisfying the dissertation requirement for the degree of Doctor of Philosophy in Special Studies.

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# Curriculum Vitae

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**BORN:**

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**Brown University / Providence, RI**
*Ph.D.(May 2001) in Special Studies with the Department of Anthropology and the Department of Computer Science,* ***"A New Methodology for Archaeological Analysis: Using Visualization and Interaction to Explore Spatial Links in Excavation Data."***

**Brown University / Providence, RI**
*Master of Arts in Architectural History*, 1997

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**EXPERIENCE:**

**Shape Lab and the Department of Computer Science / Brown University (1998-present)**
**Providence, RI**
***Research Assistant:*** Research and development of the Archave system. The system allows a user to conduct research with three-dimensionally referenced archaeological data in the context of an immersive virtual reality environment, i.e., the Cave. Specific research goals using the system include developing ways to do visual queries, represent data containing multiple variables (specifically different spatial and temporal variables) and interact with data in VR to conduct analysis.

**Shape Lab / Brown University (1999-present)**
***Author, Consultant and Collaborator National Science Foundation Grant and new Research Lab****:* Key role in the writing of a successful proposal for an NSF - KDI grant, which led to the establishment of the SHAPE lab at Brown in late 1999. The Shape Lab is developing new reconstruction (using computer vision) and data visualization and analysis techniques (with Computer Science and Archaeology) for archaeologists through the cooperation of the Department of Anthropology, the Department of Applied Mathematics, the Department of Engineering and the Department of Computer Science.

**The Great Temple, Petra, Jordan – Brown-University-Sponsored Excavations (1998 - 1999)**
**Petra, Jordan**
***Researcher****:* Conducted a survey using photogrammetry to document architecturally significant areas of the Great Temple site. Surveyed, processed and published a paper outlining time/cost/accuracy rates for potential survey strategies in archaeology.

**Graduate School / Brown University (1995-1998)**
*Research Assistant:* Design and implementation of the graduate school on-line fellowships and grants database. Design and maintenance of the Brown University Graduate School web site. Interaction with all

Brown University departments and mediator on projects in conjunction with the Scholarly Technology Group.

**Department of Architectural History / Brown University (1997-1998)**
***Teaching Assistant and Lecturer:*** "Visual Cultures of the Spanish Empire" and "The History of Modern Architecture from 1890."
*Computer Consultant:* Lead on the project to digitize the art slide library.

**Robert Luchetti Associates (1990-1994) Cambridge, MA**
***Architect:*** Design and construction for two residences in Sausalito, California. Research, planning and development for new Steelcase interior architecture line. Competition for future interior architecture installation at Steelcase.

***PUBLICATIONS:***

***Vote, E., Acevedo, D., Joukowsky, M.S. and Laidlaw, D.H. "What's Virtual Reality Good For?*** *The Archave System – Problems and Possibilities "Proceedings of VAST: Virtual Archaeology Between Scientific Research and Territorial Marketing, Conference held in Arezzo (Italy) 24 - 25 November 2000, Archaeopress, publishers of British Archaeological Reports (BAR), 2001. (in press)*

***Acevedo, D., Vote E., Laidlaw, D.H., and Joukowsky, M. S., "ARCHAVE: A Virtual Environment for Archaeological Research,"*** *Work in Progress paper presented at Vis2000, 11th annual IEEE Visualization conference, October10-13, 2000, Salt Lake City, Utah.*

***Vote, E., Acevedo D. "Archave," article in "Immersive Virtual Reality for Scientific Visualization: A Progress Report,"*** *van Dam, A., Forsberg, A., Laviola, J.J. Jr., Laidlaw, D.H. and Simpson,R.M., IEEE Computer Graphics and Applications, Special Issue on Virtual Reality, Vol. 20, No. 6, November/December 2000.*

***Vote, E., Acevedo, D., Joukowsky, M.S. and Laidlaw, D.H. "ARCHAVE: A Virtual Environment for Archaeological Research",*** *Proceedings of Computer Applications in Archaeology, 28th annual international conference. Held in Ljubljana, Slovenia, April 18-21, 2000. To be published by Archaeopress, publishers of British Archaeological Reports (BAR), 2000.*

***Leymarie, F., Cooper, D., Joukowsky, M.S., Kimia, B., Laidlaw, D.H., Mumford, D. and Vote, E. "The SHAPE Lab - and the Development of a Shape Language for 3D Artifacts,"*** *Proceedings of Computer Applications in Archaeology, 28th annual international conference. Held in Ljubljana, Slovenia, April 18-21, 2000. (in press) Archaeopress, publishers of British Archaeological Reports (BAR), 2000.*

***Vote, E., and Joukowsky, M. S., "Using Desktop Photogrammetry to Document Archaeological Remains: The Great Temple at Petra, Jordan",*** *Proceedings of Computer Applications in Archaeology, 27th annual international conference. Held in Dublin Castle, April, 1999 Dublin, Ireland. Published by Archaeopress, publishers of British Archaeological Reports (BAR), 2000.*

## Acknowledgments

I first learned about the Brown-University-sponsored Petra Great Temple excavations in the summer of 1995 when my officemate at Brown's Scholarly Technology Group, Geoffrey Bilder, showed me a three-dimensional reconstruction of the temple he built while working as a technical consultant for Martha Sharp Joukowsky, the lead archaeologist. I finally met Martha in 1996 and since then, she has been a significant resource and inspiration for my graduate work at Brown. I could never have completed this project without her dedication and support.

In the fall of 1999, the SHAPE Lab was created to conduct research on problems related to archaeology. The lab represents an interdisciplinary cooperation among members of the Brown University Departments of Anthropology and Computer Science and the Divisions of Engineering and Applied Mathematics. As a member of this new lab, I was given the opportunity to work in a highly collaborative environment and I believe that this experience played a key role in my research success. For this I thank David B. Cooper and Frederic F. Leymarie who invited me to participate in the collaboration, which resulted in funding for the project through the NSF/KDI Grant. My research efforts would not have been possible without funding provided by the National Science Foundation.[1]

Soon after becoming a member of the SHAPE Lab team and under the auspices of David H. Laidlaw from the Department of Computer Science, I was introduced to Daniel Acevedo,. who became my research partner. Daniel and I have spent the last year and a half working together in the immersive virtual reality environment provided by the Brown University Cave facility. It has been an exciting and satisfying experience for me, and I have Daniel to thank for making it far more interesting and productive than it might otherwise have been. In addition, David H.

Laidlaw gave us both continuous support and guidance and was particularly inspiring throughout the whole process. I would especially like to thank Andy van Dam for his continued enthusiasm for the project.

Finally, I would like to thank my parents, Fred and Charlotte Vote, who have been tireless in their enthusiasm for this research even when I had doubts.

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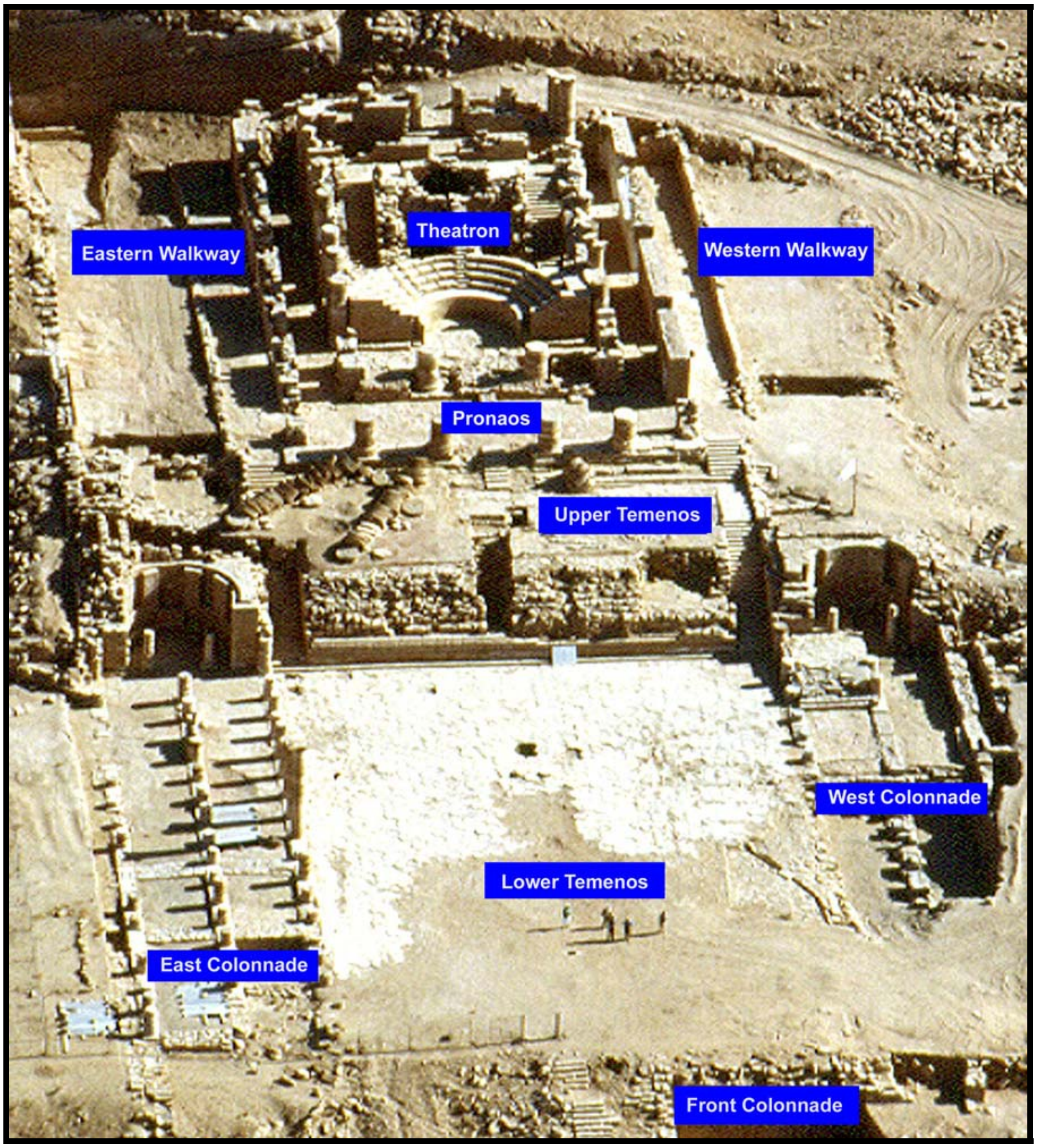



***Figure 1*** *Aerial view of the Petra Great Temple, showing the entire excavation precinct with important areas referenced throughout this document (photograph taken by A. Joukowsky, summer 2000).*

## Aerials, Plans and Elevations

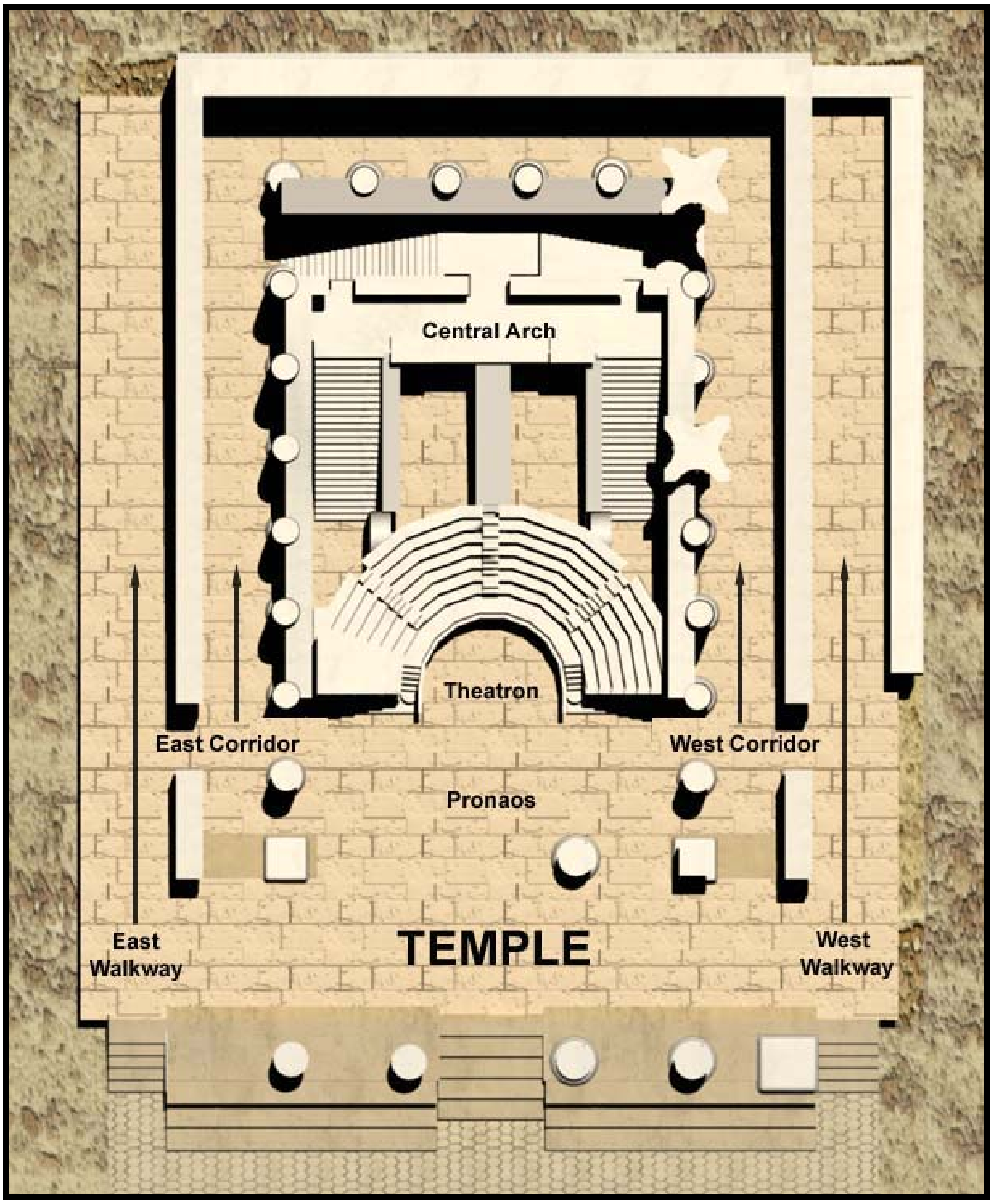



***Figure 2*** *Plan showing a reconstruction of the in situ architectural remains in the 'temple proper' region of the Petra Great Temple. These are areas that will be referenced extensively throughout this document, especially in the evaluation section of Chapter 5.*

## Aerials, Plans and Elevations

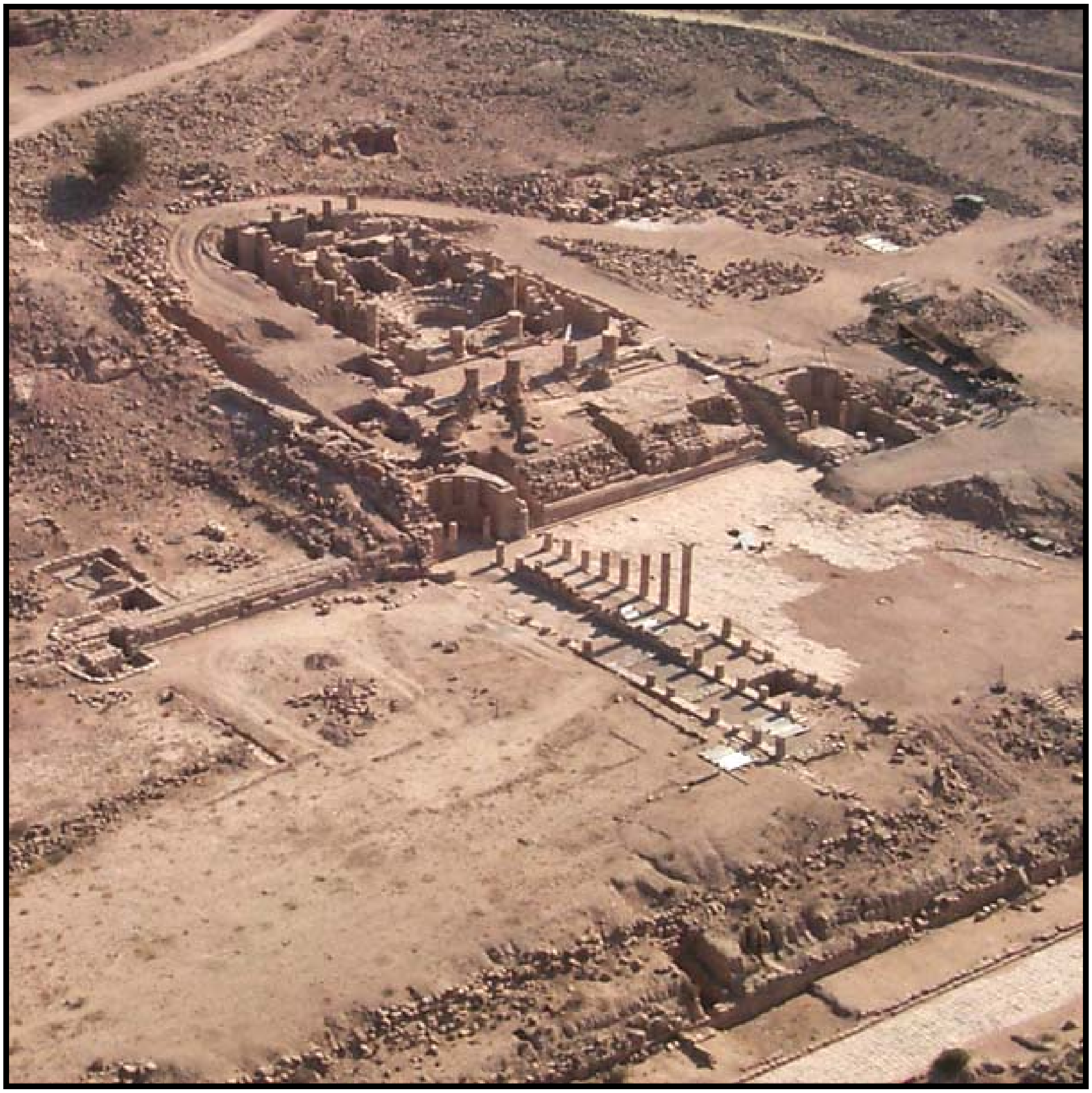


***Figure 3*** *Aerial photograph showing the entire site (post-excavation, 1999). The Roman road and lower temenos are located in the lower right, the upper temenos and Great Temple, top center.*

## Aerials, Plans and Elevations

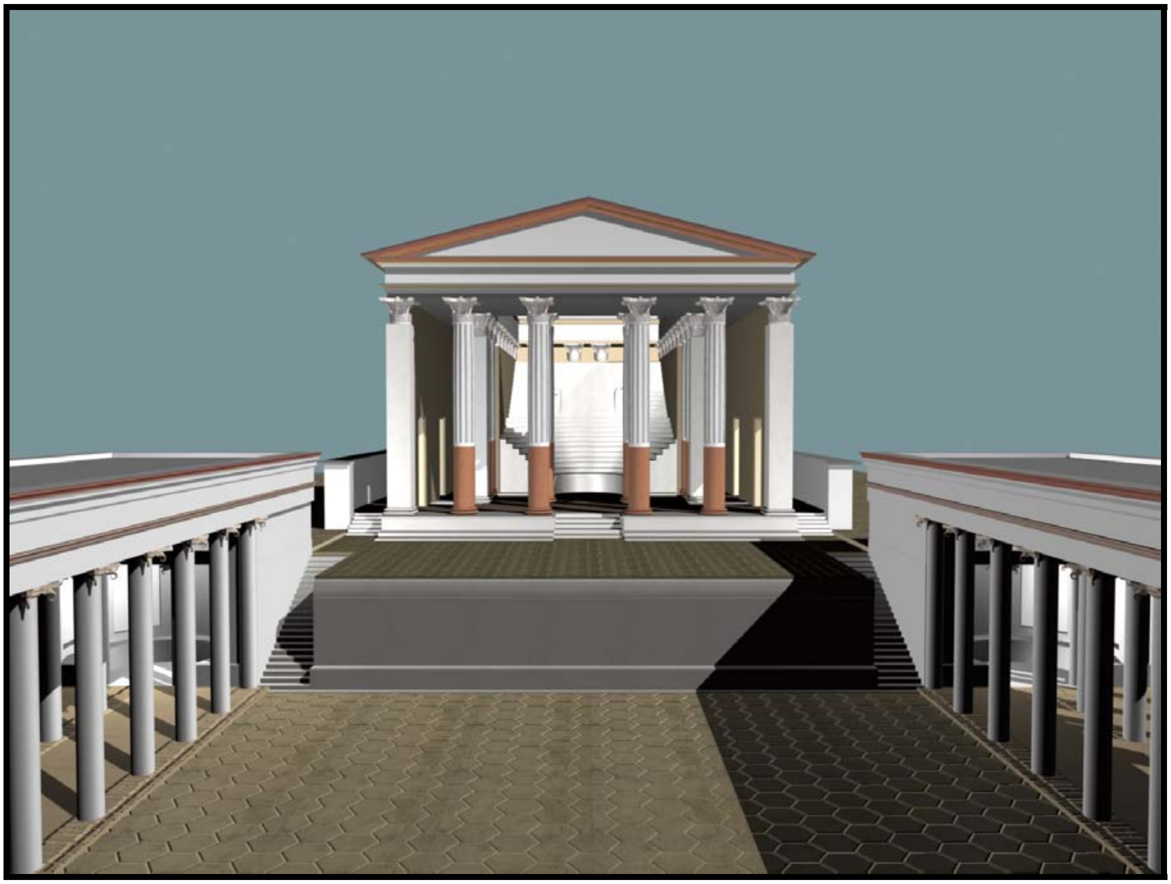


***Figure 4*** *Rendering showing a bird's-eye view of the reconstruction of the entire Petra Great Temple precinct.[2] The reconstruction was constructed using data collected by archaeologists working in the field and team surveyors armed with a total station. In addition, other technical means of field data acquisition were employed such as photogrammetry and ground-penetrating radar, see Appendix B. A similar version of this model was used as a context for investigation for the Third Prototype in Chapter 4.*

# Chapter 1: Introduction

This dissertation presents a new methodology for analyzing archaeological excavation data by providing the archaeologist with a visual schema for analytical tasks. The research assumes the following hypothesis: given a comprehensive, three-dimensional index of the archaeological record, an environment to explore it and tools for visualizing and interacting with it, analytical tasks that are difficult, if not impossible, to generate with standard methods can be performed. Using the methods developed in this body of research, archaeologists were able to pose general questions, formulate new hypotheses, and test existing ones with aspects of the excavation record.

Until recently, post-excavation archaeological analysis was limited to observing site features and excavated objects with two-dimensional, paper-based visualization methods. Statistical analyses using the excavation record databases are generally performed off-site to augment these observations. These formal methods severely constrain the archaeologist's ability to synthesize excavation findings because they do not represent the spatial component of the data set and, therefore, do not depict the complex relationships that exist within it. These relationships and associated attributes in the archaeological record consistently prove to be rich sources of information indicative of the cultural practices, site occupation patterns and histories of ancient civilizations.

The proposed methodology implements graphic visualization and interaction techniques for archaeologists and researchers to navigate, visualize, query, observe and interact with the range of three-dimensionally referenced finds, in context with the site features unearthed during the excavation process. It not only provides a new medium for archaeologists to synthesize on-site findings, but it also allows them to posit new conclusions about their field data by exploring inherent spatial linkages within it. The dissertation will introduce the new methodology and then present findings derived from observing archaeologists who are using it for analysis.

In the remainder of this chapter, we will advance a new hypothesis to facilitate the analysis tasks archaeologists require and review many of the research contributions. In addition, key aspects of the archaeological field and analysis methods employed at the Petra Great Temple site will be presented to provide a context for discussion of the issues surrounding current approaches and the necessity for new ones.

## 1.1 State of the Research and Hypothesis

During the span of an excavation, archaeologists produce a tremendous range of information in the form of maps, plans, elevations, sections, surveyed data, photographs and drawings, in addition to the detailed statistics of smaller objects stored in the site database that they cannot process individually. A marked problem of existing analysis methods is the fundamental inability to synthesize on-site findings and to establish patterns using the spatial components of the data set. For example, empirically-based analysis methods prevent the archaeologist from making a thorough comparison of all the on-site findings, that is, the findings that he/she has not been exposed to personally (see Figure 5). Further, the excavation spans many years, and early familiarity with certain areas of the site will inevitably fade with time. Additionally, by implementing the site databases to generate quantitative comparisons of objects throughout the site, the archaeologist relies on estimations by region (propylaeum, upper temenos, or lower temenos, see Figure 1) and thus most ignore the more explicit information provided by the relationships among individual trenches.

***Figure 5*** *This figure represents five different trenches at the Petra Great Temple excavation site. An independent archaeologist unearths each area and, as a result, becomes quite familiar with the trench strata and associated objects. Consequently, it is often difficult for the other members of the team to become familiar with disparate areas of the site that they have not excavated personally.*

In the process of developing methods to resolve some of these issues, the tasks that archaeologists wish to accomplish which cannot be done using empirical or database solutions were considered first. When questioned about some of their goals, archaeologists responded with the following list of tasks that they would like to achieve:

1. Observe relevant objects and associated finds in their excavated positions and in the context of the site.

2. Trace relationships among trenches, trench loci (layers), stratigraphy and artifact finds.

3. Model stratigraphy and locus relationships throughout the site.

4. Look at different types of artifacts together, e.g. coins and lamps.

5. Study important finds; this would allow specialists, such as numismatists, to derive a context for analysis.

6. Find anomalies in the data set; for example, objects from remote sites found within a sealed locus of Roman-period finds can tell archaeologists about trade.

7. Perform predictive modeling.

In assessing some of these tasks, it is apparent that archaeologists need improved ways to visualize their data and interact with it in order to assess patterns that cannot be captured quantitatively.

**Hypothesis**

An obvious drawback of current methods of field data analysis is the inability to obtain a complete picture of the physical information extracted during the excavation and to visually process its characteristics. Hence, during the course of the research, it was hypothesized that if archaeologists were provided with a physical model of the site and the excavated features, while being given an environment and interaction methods to examine the data and to perform other analytical tasks, they would be able to understand many things that they could not formerly explain (see Figure 6). Given these capabilities, it is believed that archaeologists will be able to perform some of the following essential research tasks:

- Synthesize on-site findings.

- Trace relationships between trenches.

- Look at different types of artifacts together.
- Find anomalies in the data set.
- Formulate hypotheses.
- Confirm on-site hypotheses.

In order to test this hypothesis, it was necessary to implement a system that could provide an environment for archaeologists to interact with aspects of their data to perform these tasks. Consequently, during the course of this research, a series of four prototypes were built and evaluated using an iterative method to provide such an environment. Each "prototype," acted as a type of "strawman" or working model so that archaeologists could assess and respond to it and improvements could be integrated accordingly in the next version (see Figure 6).


***Figure 6*** *View of a user in an immersive virtual reality environment interacting with the fourth prototype to perform the hypothesized research tasks. The prototype provides elements from the Petra Great Temple site such as architectural and site features and artifacts such as lamp, bone and metal finds.*

## 1.1 Contributions

The significance of this research lies in its ability to assess a variety of methods for archaeological field analysis both on- and off-site. Furthermore, it presents a new, more comprehensive alternative for archaeologists to describe and analyze their data and advances several iterations to the method. Finally, this project tests and evaluates the method in comparison to traditional approaches. As a result of this research, archaeologists have been provided with suggestions for changing their data-collection procedures to facilitate the new research scenarios.

**Initial Findings**

In the early phases of this research, the types of data acquired in the excavation process and the complex procedure of establishing associative relationships throughout the physical record were assessed during a visit to the Petra Great Temple site in Petra, Jordan. In addition, archaeologists who have worked at the site for the last seven years were consulted to outline their past and current research, the types of hypotheses they generated with the record and the processes they employed to derive them. Several key finding emerged from an evaluation of these methods. First, in performing off-site analysis, archaeologists rarely used the three-dimensional find locations of artifacts or their relative find locations throughout the site when considering those objects, due to the difficulties imposed by current methods (maps, drawings and the database of finds). In addition, individual artifacts were usually analyzed by themselves or with like objects (e.g., lamps with lamps) but were not compared with minor like objects (broken lamps) or with other artifact types (such as coins, bones and pottery). Finally, it was significant that when the archaeologists were asked about the sorts of questions they would investigate *if* these objects could be related in three dimensions, they had trouble thinking of any. After assessing current methods for data understanding and analysis and developing a more integrated approach with the help of site archaeologists, a series of tasks for evaluating the spatial components of the site record was generated. Significantly, these tasks can be used to evaluate the usefulness of one method of analysis in comparison with another (i.e., the new method described in this research as opposed to the traditional methods).

**A New Methodology**

As it has been determined that archaeologists need more sophisticated ways to visualize and interact with their data in order to assess patterns that cannot otherwise be captured, a new method for analysis was developed to provide a physical model of the site and the excavated features along with data-interaction methods to examine the data and perform other analytical tasks. The method employs principles of visualization to facilitate more comprehensive analysis of the entire record. Its importance lies in its provision of a visual framework possessing the spatial properties of excavation data with elements such as architecture, site features, trenches/loci, artifacts and three-dimensional locations. In addition, a variety of tools have been provided for archaeologists to navigate, interact and conduct analysis tasks with the three-dimensional components.

An iterative process was completed to develop the new methodology. For example, four prototypes were built and evaluated so that archaeologists were not only comfortable with the new methods, but could also derive results that are difficult or impossible to generate with other means. During this process, a list of general characteristics that facilitated visualization and research tasks was defined and some of the issues were isolated. Wherever it was possible, the issues were addressed in the next iteration.

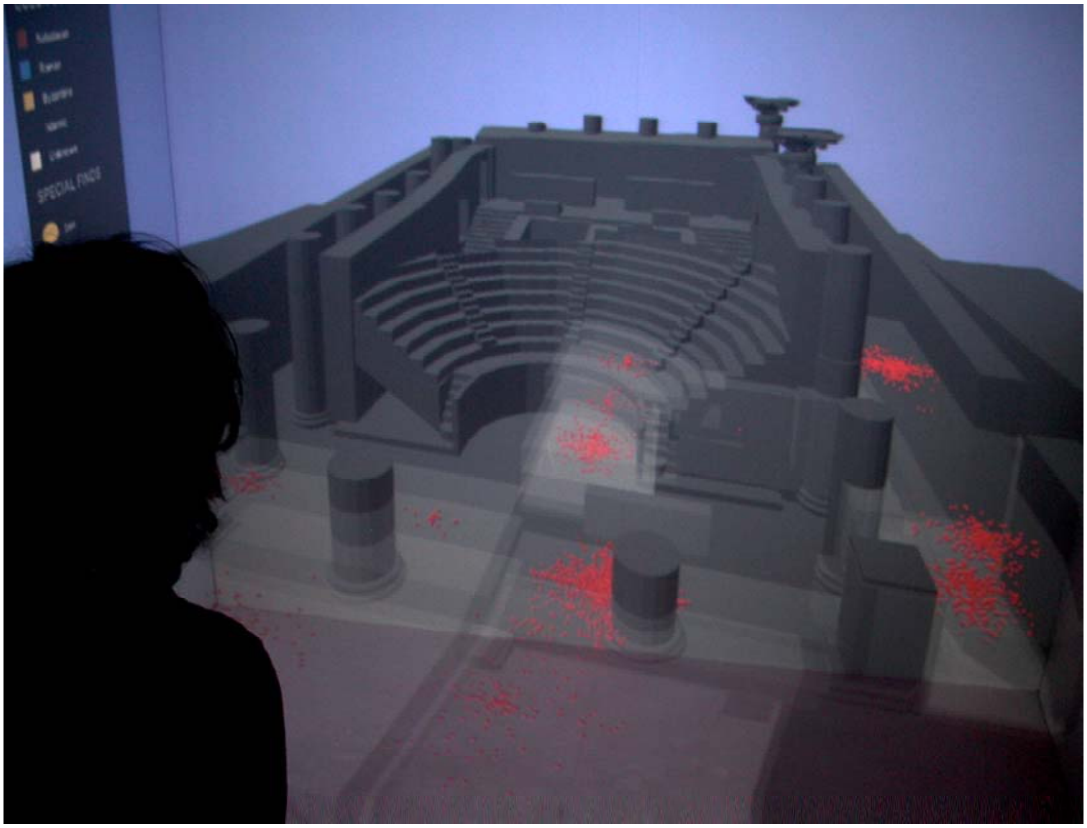



***Figure 7*** *User interacting with the fourth prototype to examine bulk pottery finds in the context of a representative sample of trenches and site features from the Petra Great Temple site.*

## Evaluating the Method

Archaeologists were encouraged to use the research model presented here to observe the record from the Petra Great Temple site and to perform different types of investigations based on their personal research interests, so that the method could be evaluated (see Figure 7). It was observed that archaeologists were not only able to substantiate patterns that they had observed while excavating on site, but were also able to identify new patterns and anomalies in the excavated record that they had not previously noticed and, more significantly, that they would not otherwise be able to find.

**Findings**

These findings suggest that the proposed methods of data visualization and interaction can supply alternatives for analyzing the spatial components and associations inherent in archaeological data and may even provide a new paradigm for data analysis in other disciplines (e.g., forensics). These methods may also offer effective ways for archaeologists to maintain physical records of the destruction caused by the excavation process as well as allowing them to share data from different sites.

Furthermore, by presenting archaeologists with the spatial components of the record and by illustrating a variety of high-level analyses that cannot be currently conducted, the archaeologists were convinced of the value of improving their excavation and recording methods. Appendix A presents some improved strategies for data recording that will directly affect analysis possibilities in the future.

## 1.2 Related Work

The search for new methods to analyze excavation findings began around the same time that archaeologists initiated standardized data collection processes for cataloguing field information. Understandably, they quickly adopted quantitative methods due to the fact that they were now faced with immense amounts of physical data to manage. Yet the majority of these approaches neglected to take advantage of the three-dimensional components of excavation findings.

Recently however, a series of projects began to integrate the physical aspects of archaeological evidence by employing technically based methods. In addition, scientists are testing the virtual interface to facilitate interactions with large three-dimensional data sets.

**Archaeology-Based Analysis Tools**

Several projects in the past ten years have attempted to mediate problems in performing analysis with the spatial aspects of archaeological data. In the early 1990s, Paul Reilly began working on techniques for archaeological data visualization to examine survey data, provide virtual excavations for training and evaluation studies, and reconstruct and exhibit archaeological data using WGS (Winchester Graphics System image processing system and WINSOM (Winchester Solid Modeling system).[3] He found that by reconstructing certain aspects of the recorded data from an excavation he could provide a way for archaeologists not only to synthesize on-site findings, but also to generate new observations. Although it was not yet possible to dynamically interact with the data, the ability to observe topographical features either alone or with reconstructed features of the site stimulated the researcher to see new information.

Reilly also developed “Grafland,” a simulated excavation that consists of a series of layers (called loci in archeological terminology) with various features cut into them. The layers are hypothetical profiles and the locus is defined as the volume between the measured surface and an arbitrary datum plane at some depth below. Using the system, different “exploration scenarios”[4] can be devised to attempt a reconstruction of site features, site activities and post-depositional processes operating there. Grafland was intended to demonstrate that archaeologists can produce realistic records of the data destroyed during the excavation procedure, and that there are improved methods of using that data for analysis. However, due to inaccuracies in how the data was recorded, this system was used primarily as a teaching and simulation tool.

Donald Sanders of Learning Sites, Inc., has also been working on ways to use excavation data for “reliable” archaeological visualization in education and research.[5] He focuses on presenting aspects of the excavation record in the form of multimedia excavation reports that use available plans and three-dimensional models and, access pictures of relevant artifacts and site reports. Via digital excavation reports such as the one provided for Tsoungiza, a Bronze Age settlement in ancient Nemea, Greece, important features from the site can be accessed using a VRML interface on a desktop monitor. An advantage of this presentation technique is that it allows the archaeologist or layman to examine a reconstruction of the site with some objects in context. However, the method is limited in that it provides a realistic post-excavation site reconstruction only in the form of separate text-based records. It cannot provide the physical and visual integration of site features and excavation information.

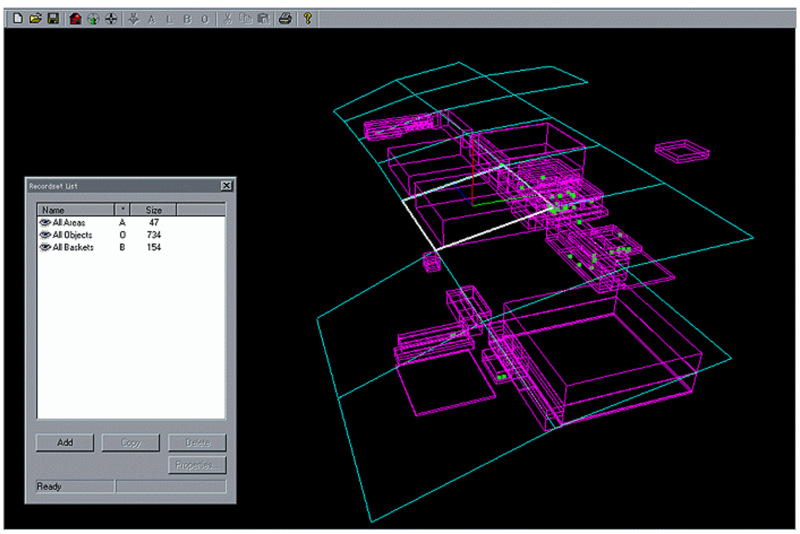



***Figure 8*** *Dig Dug, a physical database developed by the Lahav Research Project of Mississippi State University, 1999.*

A physical database called “Dig Dug” was developed by the Lahav Research Project (Mississippi State University) during the 1999 field season at Tell Halif, Israel to improve data management and to disseminate basic archaeological information[6] It is significant because it allows the introduction of three-dimensional analysis and simulation to a dig while it is still in progress. The database allows each area of the site, including individual loci and baskets, to be represented as a volumetric area. Although the system does not provide enough data about the site to isolate anomalies or perform comprehensive analysis, archaeologists have successfully utilized it as a visual error-checking device for data entry and recording. However, “Dig Dug” does not yet handle site and architectural features, nor has it integrated ways to interact with the available data in a useful way outside of a desktop viewer.

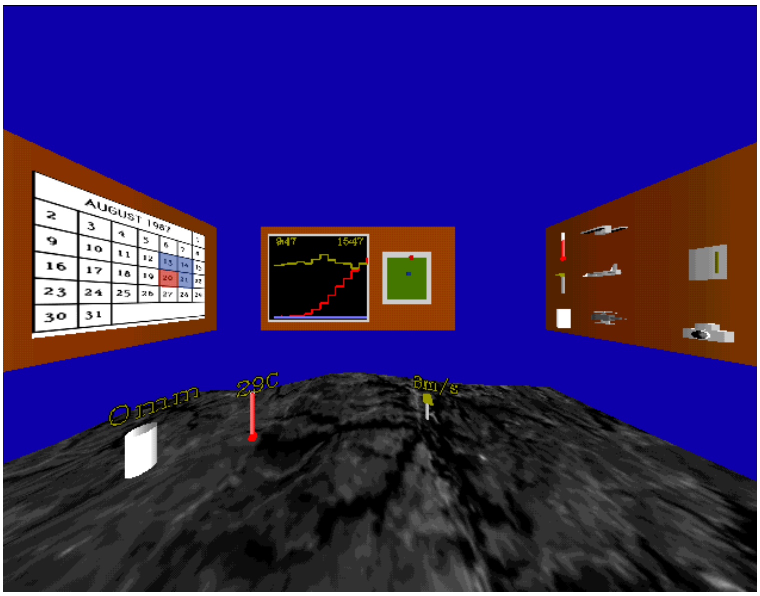



***Figure 9*** *SANDBOX, developed by Andrew Johnson and implemented in a cave virtual reality theatre Electronic Visualization Lab at the University of Illinois at Chicago*

**Visualization Using Immersive Virtual Reality (IVR)**

Also in the last decade, a number of visualization systems employing immersive virtual reality have attempted to deal with large data sets such as those presented by climatological data or the urban environment using GIS (Geographical Information Systems) systems software. “SANDBOX,” for example, was developed as a virtual reality tool, to allow an investigator to visualize the contents of a scientific database while retrieving data.[7] Because the information retrieved from the database was collected from experiments, this interface allows scientists to observe the data by recreating the experiment in three-dimensions. In this system, users have access to visual and auditory clues that enable them to process information visually to determine surface climatology from satellite observations. A prototype of the SANDBOX was implemented using a Cave Virtual Reality Theatre at the Electronic Visualization Lab, University of Illinois at Chicago. This protype is significant because it provides scientists with a means to interact with a variety of data using visual clues; however, the prototype focuses on completing tasks with the aspects of a climatology data set that is two-dimensionally based. Therefore, even though this system gives users a way to explore and interact with a data set, the research problems are markedly different from the ones presented here as they are essentially two-dimensionally based.

Karma VI is a virtual reality interface for ESRI's (Environmental Systems Research Institute) Spatial Database Engine developed at the Delft University of Technology that supports visualization, manipulation and editing of standard GIS data in a VR environment.[8] Users of this interface can walk through three-dimensional environments, see planned buildings and view changes in the landscape; in most cases, however, interaction with the data is impossible. There is some limited navigation and interrogation: for example, the user can walk around in the virtual environment, point to objects in the scene, and ask for information from a GIS database that is shown as text. The ability to experience the data set at close range and to access important statistics provides a powerful visualization tool for three-dimensionally based data. Nonetheless, in employing these methods, the ability to interrogate the GIS database in a more intelligent way and to access more advanced GIS functionality is limited.

**Next Steps:**

Recent projects provide archaeology-based analysis tools to reconstruct and simulate excavation formations for teaching and visualization efforts. However, they have not been wholly successful for conducting analysis tasks since they lack essential navigation and visualization features and do not offer access to a range of components from the archaeological record. Although some of the immersive virtual reality visualization applications demonstrate how complex data sets can be interrogated in a three-dimensional environment using navigation and interaction tools, they have not yet provided a means to deal with archaeological specific problems. Nonetheless, building on recent advances in VR for analytical tasks, this research proposes that significant investigation can be performed by adaptation the system to contain the following features.

1.) Improved access to a comprehensive data set from the Petra Great Temple site.

2.) A visualization interface that enables users to navigate and interact with the three-dimensional data set.

3.) New tools to conduct key research tasks.

In the process of implementing four iterative prototypes we attempted to integrate these features and also evaluated archaeologists' abilities to conduct research using each of them.

***Figure 10*** *Excavations must uncover a tremendous amount of debris and index it to perform analysis with the record. This aerial photograph of the Petra Great Temple site before excavations began in 1992 shows the contrast between the site then and now (see Figures 1-4, above).*

## 1.3 Methods – Field Data and Site Recording

By reviewing related work that provides tools and methods for analysis of the excavation record, we gained an understanding of some recurring problems. Also, in the process of becoming acquainted with standard conditions on site we can outline new solutions. Therefore, this section introduces the Petra Great Temple site conditions and a few of the major issues archaeologists encounter while excavating a site and collecting data, and also in performing material analysis.

### The Nature of Field Data

The temple precinct, where the remains of the Petra Great Temple are located, is set in the heart of Petra to the south of the Colonnaded Street and measures approximately 7560 square meters (see Figures 1-4).[9] Although it is difficult to see from the excavated remains, the temple was once a significant building with dimensions approximately twenty meters high, twenty-six meters wide and thirty-nine meters long (see Figure 4).[10] Indeed, the Great Temple of Petra in Jordan is believed by many to be the most important building unearthed by archaeologists in recent times.

As is evident from early aerial pictures of the site (see Figure 1), the only visible signs of the temple were the monolithic column drums that lay in tandem where they had fallen after the site was abandoned. Therefore, from the outset of the excavations, unearthing the edifice has posed a particular challenge due to its condition.[11] In order to excavate the site in the most systematic way, lead archaeologist Martha Sharp Joukowsky used a site grid (Figure 11), which facilitates the excavation of any given quadrant when necessary, while maintaining a clear pre-surveyed set

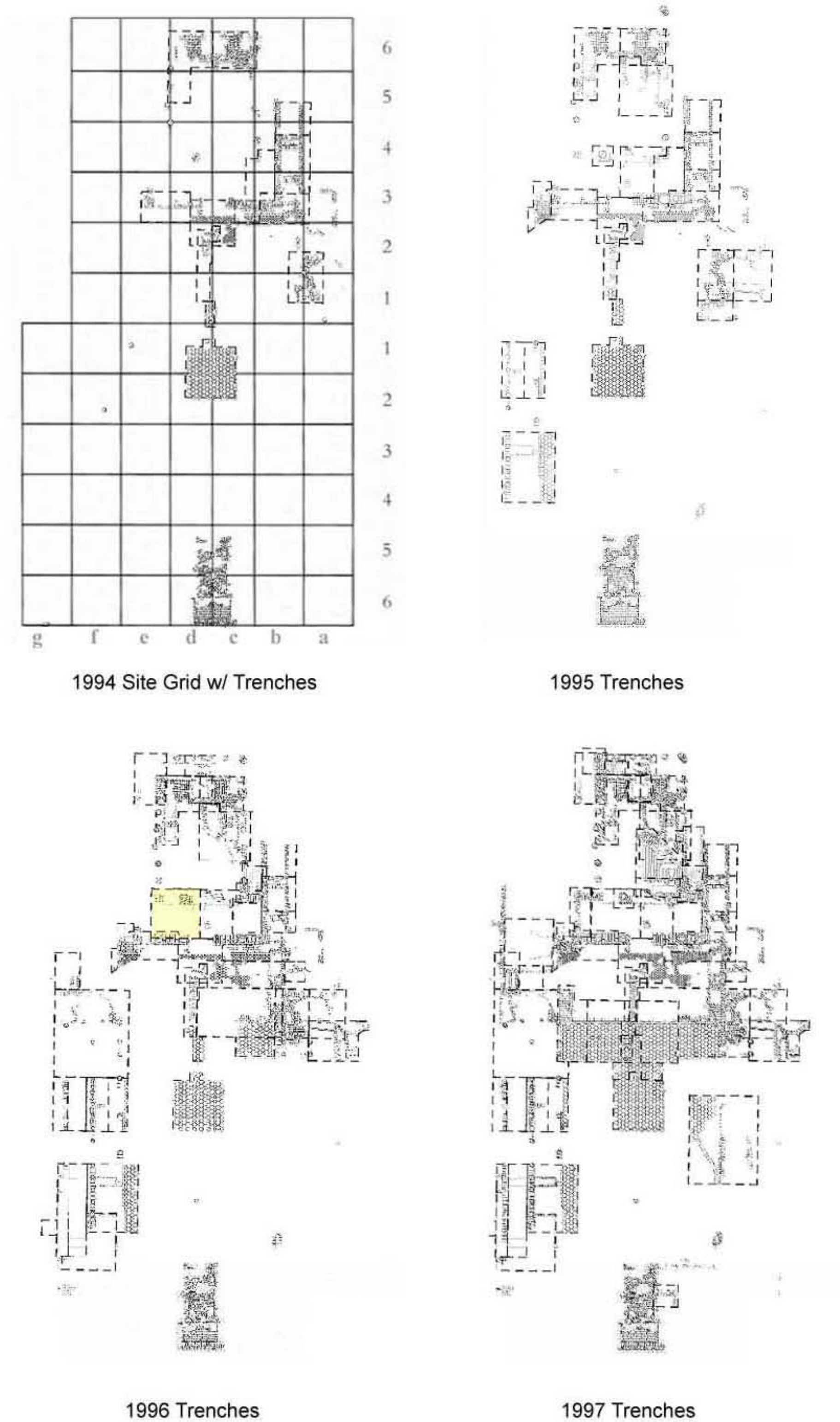



***Figure 11*** *A standard way of organizing the removal of debris on site is to establish a site grid with trenches. (top left) Plan showing site grid and trenches from 1994. (top right) Plan of additional trenches added in 1995. (bottom left) Plan with trenches from 1996 (highlighted region represents trench 24 shown in Figure 12). (bottom right) Plan of site with trenches from all years up until 1997.*

of quadrants. The quadrants are then divided into trenches or series of trenches. In addition, using the grid allows the team to reference architectural features and trench information easily while providing a careful reference for the archaeological record.

### Trenches

Most excavations develop a strategy to sample the site by using a series of test trenches to determine where large-scale excavations should occur (Figure 11). A trench is a small (approximately 10′ x 10′) section of the surface area that covers the site under investigation. The archaeologist systematically excavates a trench by analyzing sediment as it is uncovered. In addition, any artifacts that are unearthed are carefully catalogued in order to reference them when analyzing of the site. A trench is generally divided into a series of layers or loci (see Figure 12), that represent simple layers of stratigraphic sediment, walls, columns and floors, or denote significant artifacts. Usually, when an architectural element or important find is uncovered, a new locus is defined. This system works because, by referencing independent features as new loci, a trench is organized into separate elements that can be indexed in the record.

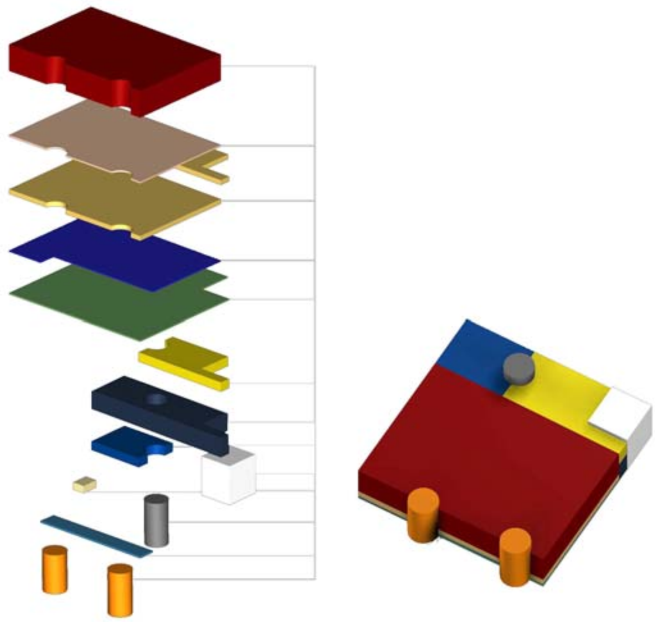


*Figure 12  Figure showing a model of trench 24 as it looks in the fourth prototype. The colored regions on the left are individual loci that represent the debris removed in a specific region of the site.. Each locus represents a layer of sediment, an architectural feature (column, wall, rock, etc.) or a special artifact.*

**Artifacts**

The individual artifacts uncovered during the excavation process are divided into two categories: bulk finds and special finds. Special finds are those rare objects that are in fairly good condition such as amphorae, coins or sculpture (see Figure 13). As these objects are still complete, they often often yield enough physical information about their origins to allow archaeologists to analyze them rigorously, compare them with like objects either on site or at other sites, and also use them to date objects found nearby. By contrast, bulk finds are those objects such as pottery sherds, lamp fragments, and other fragmentary or deteriorated objects that are found in great quantity during the excavation process. These small fragmentary objects are often difficult to identify with the same accuracy as special finds, but they are nonetheless useful in on-site analysis. For example, if there are a great many pottery sherds in one trench representing different pot typologies, archaeologists might believe that that area was used for dumping or a similar purpose. However, sometimes pottery sherds can be assigned dates on the basis of their surface characteristics. Therefore, both of these two types of artifacts are useful to the archaeologist, and both classes of artifacts need to be carefully excavated, catalogued and analyzed as important evidence about the site.

***Figure 13*** *The figure above shows the two types of finds that have been discovered at the Petra Great Temple site. (top) Special finds are those objects that are in fairly good condition such as the amphora, oil lamp, sculpture, coins and architectural fragments. (bottom) Bulk finds are those objects, such as pottery sherds, lamp fragments and other fragmentary or deteriorated objects that archaeologists find in great quantity during the excavation process.*

### Site Recording Methods

In order to minimize confusion and error, a standard method for recording information from the field has been implemented for every excavation. Due to long-standing conventions inherited from paper and paper-like interfaces, including textual descriptions of finds, associated drawings, illustrations and photographs, the two-dimensional paper interface is still the accepted and practiced norm (see Figure 14).[12] Therefore, a team organized to excavate a specific trench is armed with a two-dimensional trench notebook to record all three-dimensional findings.

Traditional methods use plan and section drawings to document all balks (triangular, wedge-shaped strip of earth used for stratographic analysis), layers (loci), and artifacts.[13] All features unearthed are measured while *in situ*, recorded on the plans, labeled and then bagged. Important finds or assemblages (special finds) are usually photographed in their *in situ* positions. Also, excavators are required to document trenches in plans and section drawings at a scale of 1:20. The results form a composite trench notebook that acts as a primary record of the excavation and is kept as a reference during the analyses of associated artifacts.[14]

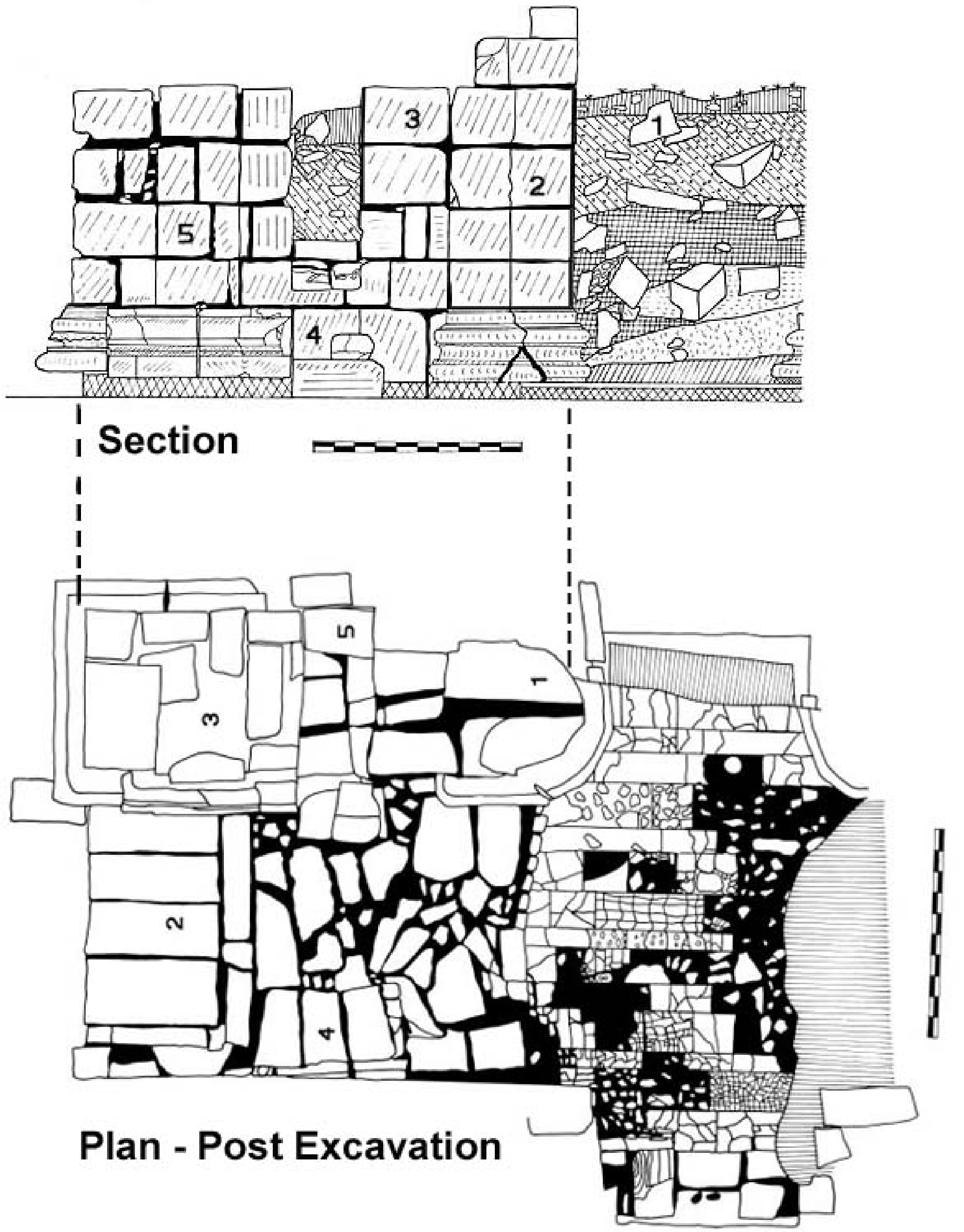



***Figure 14*** *Section and plan of trench 29 showing an anta and column architectural feature located in the western corridor. The section looking east shows the balk with the stratigraphic sequence of debris.*

## 1.4 Methods for Analysis

*Figure 15* *These images represent the variety of on-site observations that occur in the span of an excavation. (left) A fragment of an elephant-headed column capital. (middle) Workers excavating the western walkway. (right) Reconstructing part of an inscription.*

Because traditional analysis methods present a significant way of dealing with excavation data, they should be carefully considered if methodological improvements are to be made. In the following two sections we will outline methods for empirical analysis conducted on site and quantitative analysis conducted off site.

**Empirical Analysis – On Site**

Archaeologists work carefully to unearth and catalogue objects. However, in most cases, finding relationships among a diverse set of artifacts found on site is done empirically; that is, the archaeologist relies on his/her ability to observe, assimilate and recall significant characteristics of the physical data that establish patterns within the site. This is primarily achieved by excavating a trench or area. For example, by slowly and systematically removing layers of debris in a trench and witnessing the exposure of artifacts and their relationship to the architecture or site, the archeologist gathers important clues about the entire context. Yet since the excavation usually progresses as a series of trenches, the archaeologist can be exposed only to those trenches he/she excavates personally. One of the ways archaeologists gain exposure to the trenches that have not been personally excavated is through the site tour, which helps the archaeologist synthesize on-site findings. Site tours are conducted once a week by allowing each archaeologist to present the trench he/she has been working on, they introduce the team to the areas they have not personally excavated.

In addition to the observations made through surveying the site, excavating specific regions and gaining exposure to the trenches being excavated by other team archaeologists, the team attempts to solidify some of its findings in a phasing meeting held at the end of each season. During this meeting, team archaeologists meet to exchange their observations about the site findings and to attempt to formulate theories about the chronology of the building phases of the Petra Great Temple.

**GROSSO MODO:**
Excavated 8/8/96 by LDB.

Excavation Information

**Trench(es) 29** **Loci 4**

**Area:** T (NE) **Phase:** VI

DIAGNOSTIC Information

**Seq#** 24081
**Bag#** P24018

**Comments**

| Quanty | Material | Part | Function | Shape | Liq Color | Pnt Color | Motif | Plastic Dec | Culture |
|---|---|---|---|---|---|---|---|---|---|
| 3 | P | AF | RT | F | W | | | | IND |
| 1 | P | R | B | E | W | | | | IND |
| 1 | P | H | JJ | RD | BK | | | | IND |
| 1 | P | H | JJ | F | W | | | | IND |
| 1 | P | H | JJ | F | W | | | | IND |
| 1 | P | CHR | SF | PV | BK | | | | IND |
| 1 | P | B | B | RG | | | | | IND |
| 2 | P | R | PLT | ID | | W | | | IND |
| 1 | P | R | IND | PV | W | | | | IND |
| 1 | P | BS | PLR | F | | R | IND | | N |

Click on a line above to view the details of a Record

***Figure 16*** *At the Petra Great Temple site, data archiving includes recording almost all the salient features of the objects unearthed, such as: object type, location (by trench/locus), material, part, function, shape, liquid color, motif, plastic decoration, culture, phase, area of site, excavator and year.*[15] *Above, a report generated from Grosso Modo (the bulk find database) in a relational database format.*

There are several difficulties in attempting to process large amounts of information empirically. Although the methods of observation provide archaeologists with a tangible and very personal representation of the record, they are exposed to a tremendous amount of information over the course the excavation. In addition, as they cannot personally excavate every trench (and in fact excavate many trenches over the years), it becomes extremely difficult for them to recall and process all the salient features of the objects they uncover in order to come to conclusions.

**Quantitative Analysis – Off Site**

Quantitative analyses are generated using the Petra Great Temple site databases: Grosso Modo (bulk finds), the architectural fragment database and the special finds database. Quantitative reports are derived by looking at reports from the databases of the materials grouped and sorted in various ways, such as: pottery by phase, pottery by trench, materials by phase, materials by area, frequency of occurrence of the pottery by phase. In using these databases to generate reports on the objects uncovered on site, archaeologists can:

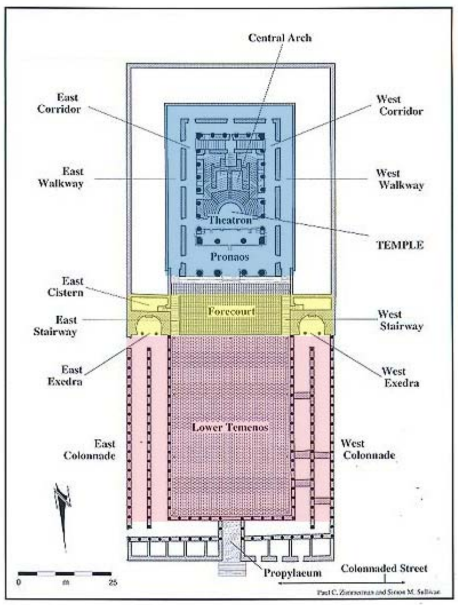
1. See basic statistics about the site as it is being excavated.
2. Derive breakdowns of various features such as pottery concentrations in general areas, upper temenos, lower temenos, etc. (Figure 17).
3. Derive percentages of different object types in relation to the whole artifact record.
4. Look at areas with specific phase definitions to see if objects from a specific time period are stratified in relation to architectural areas.
5. Use quantities and quantitative breakdowns to perform statistical analysis for predictive modeling purposes.[16]

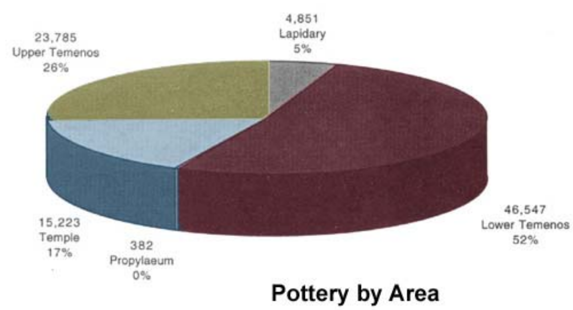
We observed a number of difficulties while assessing some of the results achieved when using the site databases for analysis. First, it is immediately obvious that, in attempting to understand the find locations of objects or object concentrations throughout the site, the spatial component of the data is inadequately represented. For example, in Figure 17, the pie chart shows how the database produced statistics for bulk pottery finds in several areas of the temple precinct. However, since the precinct is the size of a football field, the areas represented are still quite large (the lower temenos is about half of the size of the whole precinct). While it is possible to derive statistics about individual trenches, without a precise map of all the trenches in relation to one another and a way to plot the find concentrations for the individual trenches, it is difficult to get a comprehensive idea of the configurations of objects.

In addition, current strategies for looking at concentrations of artifacts in the various areas are limited to a two-dimensional reading; that is, they can be understood from a plan perspective but it is almost impossible to understand where they are located in the Z or depth dimension within the trench. The archaeologist wishing to understand the configuration of bone finds in two different trenches, can do so only with a top plan. In order to investigate the location of the bones among the layers (loci) of the trench, he/she will have to refer to the trench notebook to determine how each locus looked in relation to the rest of the trench. Therefore, in using the database to attempt to synthesize on-site findings, it is difficult not only to correlate objects spatially but also to difficult to form hypotheses regarding on-site findings.

**Needs**

The last two sections discussed some of the issues archaeologists face in attempting to carefully survey and analyze field findings. Throughout this discourse, an obvious and marked problem with existing methods is the basic inability to get a complete picture of the physical information extracted during the excavation and to visually process important characteristics. Each year archaeologists unearth a variety of new areas within a site and need the ability to access a comprehensive record to integrate newer evidence with older findings. Outside archaeologists also need this, since they often attempt to do inter-site comparisons. To do this, the archaeologist must attempt to understand how the site was excavated and its important characteristics by studying textual references like site reports, with accompanying maps and drawings; a complex task.




| Area | Total | Percent |
|---|---|---|
| Lapidary | 4,851 | 5.30% |
| Lower Temenos | 46,547 | 51.30% |
| Propylaeum | 382 | 0.40% |
| Temple | 15,223 | 16.80% |
| Upper Temenos | 23,785 | 26.20% |
| | 90,788 | 100.00% |

***Figure 17*** *Reports are generated from the Grosso Modo database to allow the site archaeologists to isolate percentages of objects by area within the site. (left) A plan of the Petra Great Temple precinct showing levels of concentration of pottery by area. (right) A report generated from Grosso Modo with the percentage of pottery found on site, concentration by area.* [17]

## 1.5 Road map

In the process of implementing four prototypes, this research advances a new methodology to test a hypothesis about new ways to perform analysis with excavation data. There was also an effort made to determine whether archaeologists could perform the hypothesized research tasks.

Each chapter (2 through 5) presents a prototype developed to conduct research tasks with field data and an assessment of its usefulness. In successive prototypes many of the issues encountered in the previous assessment process are addressed. After implementing the fourth prototype, presented in Chapter 5, tests were conducted to evaluate the archaeologists' performance of the hypothesized research tasks. Chapter 6 summarizes some of the research findings and presents final conclusions.

# Chapter 2: The First Prototype:
A Conceptual Model

The original conceptual model or ‘prototype’ (as it will be called to it in its many iterations throughout Chapters 2-6), was developed in the fall of 1997, prior to visiting the Petra Great Temple site (summer 1998). This prototype is essentially conceptual in the sense that it was never implemented to use the information from the site databases. However, by establishing a loose structure for solving some key analysis problems encountered on site, it provided the basic model and impetus for later system development. This chapter outlines how the prototype was designed and how the investigations completed on site during the summer of 1998 altered many of the original perceptions about the quality of physical evidence. These investigations resulted in the creation of the second prototype outlined in chapter 3.

## 2.1 The System – The First Prototype

This prototype was created to index many of the architectural fragments unearthed on site in Petra and to facilitate establishing a chronology of the building phases of the temple and its precinct (see Figures 1-4). The conceptual plan was designed to consider a set of variables present in the site databases, along with three-dimensional models of the objects, drawings and photographs that would allow new comparisons to be made and unprecedented links between objects to be established.

*Figure 18 Photographs showing some of the column drums found at the Petra Great Temple site. Architectural Fragments, specifically column drums often have a signature marking of the stonecutter. See image of the base of a drum above, top right.*

For example, Figure 13 describes a group of artifacts found on site, specifically architectural fragments and coins. Each artifact has been labeled with a series of variables that: establish its exact *in situ* position in the site, define its size, the material it is composed of, residues found (e.g., paint or plaster) and, where applicable, the date it has been assigned. This preliminary diagram of a small data set shows how the object variables can be linked by each artifact's labeling structure.

**Stonecutter Markings:** The focus in Figure 19 is on the relationship among architectural fragments possessing similar stonecutter markings (see Figure 18). Items one, two and three in Figure 19 illustrate a proposed relative dating method that can be used to assign dates to architectural fragments. Specifically, stonecutter markings can be identified on some of the architectural fragments. As outlined in Judith McKenzie's book, *The Architecture of Petra*, it has been argued that stonecutters left signature-type markings on the various segments they carved. Since it has been established that there were various schools of stonecutters in Petra and other Nabataean regions such as Medain Saleh, it is possible, by a comparison of markings, to identify segments belonging to a specific school of stonecutters. Fragments belonging to different stonecutter schools can be identified by comparing the carving marks with a datable monument within Petra, or with one in another area such as Medain Saleh.

Item one in Figure 19 (Architectural Fragment – Column Base), for instance, represents a hypothetical column base with type (A) stonecutter marks. Assuming that type (A) marks were found not only on several undatable tombs within Petra but also on tombs in Medain Saleh, if the Medain Saleh tombs were inscribed with the stonecutter's identity and the date, then the date of the fragment can be placed within that stonecutter's life. According to Judith McKenzie's analysis, a stonecutter worked roughly 25 years.[18] Thus, using stonecutter markings to assign a relative date for an architectural fragment (a column drum) can give us a date range for that object of 25 years. Items two and three also show markings from stonecutter (A), and if it can be established that this stonecutter worked between 31 and 50 A.D., those objects can also be assigned dates within that time range.[19]

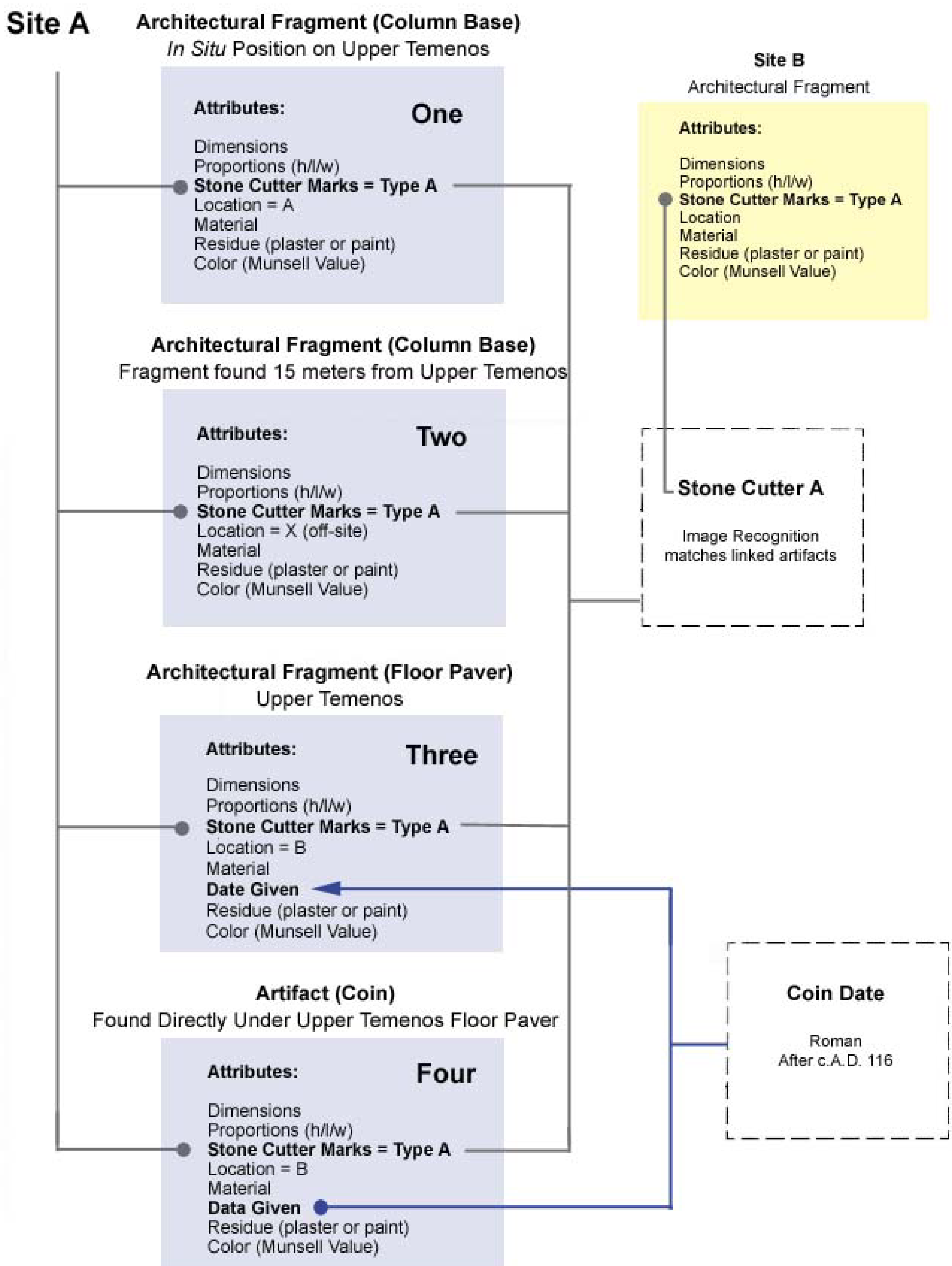



***Figure 19*** *Original system model, 1997. The diagram above shows the relationship among a set of text-based entities that are physically related by architectural elements in the upper temenos of The Petra Great Temple.*

***Figure 20*** *Coins found at the Petra Great Temple. Many of the coins found on site can be identified and and dated based on minting marks. Notice the two bottom examples. Even though the one on the bottom right is fairly eroded, one can still identify it as the same type as the one on the bottom left.*

**Relative Dating:** Assigning dates to specific artifacts is essential in reconstructing the chronology of the temple. As each architectural section is given an exact or relative date, it is possible to evaluate when each section (series of columns or walls) was being worked on. However, presently, the archaeologist only provides an annotation (in the field notes) describing the markings found on the object along with a photo of the marking. Due to the nature of the recordings made in the site trench notebooks, accessing these markings or indexing them in the site database is not currently possible. Therefore, dynamic links among the architectural fragments are not established in the process of assigning chronologies to different areas. Instead, most of the site chronology is derived collectively in the phasing meeting, (see Chapter 1, Methods for Analysis).

The alternative method of establishing chronology provided in this conceptual prototype allows archaeologists to access and index the objects with these distinguishable markings (provided they record an image of the marking, along with other artifact attributes) in addition to other objects that can be dynamically linked, e.g., coins (see Figure 17). In order to implement such a system it was originally suggested that the objects might be indexed within a multidimensional database designed specifically to handle different media such as 3D models, drawings and photographs. Within a database format, the data set shown in the diagram would become a complex web of linked variables as new artifacts were added. However, since many of the objects contained in the database would have physical information and an *in situ* find spot, analysis could be performed either automatically or by observing a specific set of objects in three dimensions.

## 2.2 Evaluation

After six weeks on site at the Petra Great Temple in the summer of 1998, several observations were made that necessitated changes to the conceptual prototype outlined above. First, as a result of the advanced erosion of some of the architectural components (columns, column capitals, walls, floors, etc.), many key areas of the site had not yielded adequate datable evidence for identification. Second, the earthquakes that had ravaged the site over the years had moved or misplaced many of the architectural fragments so that their original placement among the built remains was untraceable. Last, many of the architecturally significant areas of the site, e.g., the upper temenos, pronaos, theatron, etc., had been excavated to floor level but not below, making difficult the establishment of dates for floors and walls (since the floor must be assigned a date from the objects just below it).

Based on these findings, it was observed that attempting to automate assigning chronology by using architectural finds and other datable objects would not be possible to the extent that had originally been planned. However, from experiencing the site and the excavation process, and by examining many of the artifacts from the site record, several key observations were made that helped to refine the prototype to make it more useful for archaeological analysis.

## 2.3 Findings

**Relative Dating:** As the site had been excavated carefully, with records kept of all the physical remains, including the material or debris that had been removed (see Chapter 1, Trenches,), it was still possible to arrive at relative dates for specific areas (e.g., the trenches themselves and the related areas). In addition, an exceptional range of artifact finds (15 different types of bulk finds along with a variety of special finds) had been unearthed in the context of the site, with over 60 trenches from all the years of the excavation up to that point (in the year 2000, there were over 80 trenches).

**Spatial Components:** When the site archaeologists were questioned about their analysis strategies and the possibility of using the spatial components of the data, e.g., *in situ* location or object dimensions, they explained that most of the analysis performed using site data did not consider exact find location, and the many other attributes stored in the databases of objects (see Chapter 1, Methods for Analysis). Therefore, it seemed plausible that the original ideas outlined for indexing architectural components could still be applied to individual objects such as bulk finds and special finds. As Clarke suggests:

> "The spatial relationships between the artifacts, other artifacts, site features, other sites, landscape elements and environmental aspects present a formidable matrix of alternative individual categorizations and cross combinations to be searched for information." [20]

**Integration of All Artifacts:** Finally, rather than focusing on ways to link merely the architectural components, one could not only use those components that could be deemed reliable, but also integrate other objects throughout the site. By integrating these new objects, additional attributes could be added that would help to establish clues regarding the architectural phases. Furthermore, by providing a model that could synthesize some of the spatial properties of these objects and their relative positions throughout the site, other important tasks could be accomplished. For example, given a way to look at pottery concentrations in the context of the trenches, archaeologists could gain insight into some of the activities in different regions at the Petra Great Temple. They might also be able to make associations with other objects in that context, that could confirm or reject the findings, e.g., a Byzantine oil lamp in the context of Nabataean pottery fragments betrays a mixed sediment in the find region.

## 2.4 Conclusions

Even though it was not possible to achieve all of the original objectives that this prototype was designed to address, the initial conceptual plan helped to define a loose structure for solving some of the key analysis problems encountered on site. Specifically, providing a method that could link a variety of objects via their spatial components, automatically assign relative dates to artifacts and architectural components and accommodate different types of objects (artifacts, site features and architectural fragments) would help archaeologists perform a variety of analytical tasks not currently possible using existing site databases and two-dimensional records.

# Chapter 3: The Second Prototype:
A Three-Dimensional Database Experiment

The original prototype outlined above is primarily schematic in nature but begins to outline some of the connections necessary to perform new types of analysis with the archaeological record. The implementation of the prototype in a multidimensional database was considered, in order to start using the artifact information from the site databases, as well as to match objects and trace important relationships that would make possible reconstruction of the salient features of the data set either through visual means or by the automatic relationships generated. However, in assessing some of the tasks archaeologists needed to perform to initiate use of the spatial components of the data set, it became clear that they would benefit from access to a physical model of the site. For example, in addition to the automatic and annotated links among objects scattered throughout the data set, the archaeologists wished to visualize those relationships that would help synthesize their own on-site findings. Therefore, it was posited that if additional three-dimensional visualization software were employed along with a database, a variety of analyses with the site findings could be performed. This chapter will review how the site data was implemented using ArcView's 3D Analyst extension, and what sorts of results were achieved.

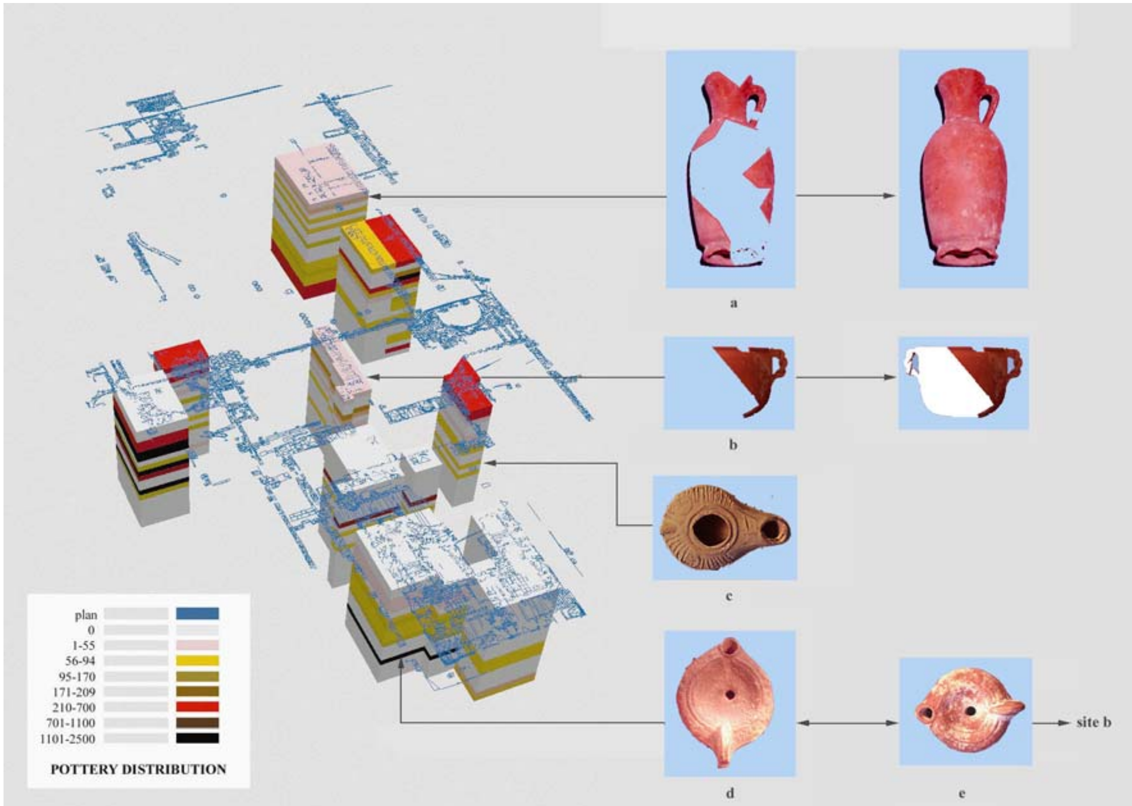



*Figure 21 (left) Results of an implementation using GIS software. Images on the right represent relative locations of find spots within the set of trenches represented.*

## 3.1 The System – The Second Prototype

Although it was not clear what sort of visualization software would be most appropriate to work with a multidimensional database of finds, Geographical Information System (GIS) software was the easiest to implement and could accept some of the preexisting plans, maps and survey data from the site. Therefore, during the fall of 1998, a second prototype was implemented using GIS software called ArcView built by the Environmental Systems Research Institute (ESRI).

### What is a GIS?

The Geographical Information System is visualization and analysis software designed to manage the different kinds of physical information extracted from the excavation record: namely, map-based and data-based records. The main premise behind a GIS is to create a record comprised of different types of spatial data and spatial primitives that will coexist so that correlations between the various layers of information can be drawn. Data types include objects represented by single-point coordinates (or single artifacts), lines or vectors (roads, rivers or other linear features), polygons (trench, pond, wall or post hole) and finally raster or pixel data (from satellite or aerial images). The most obvious application of these data types can be seen in geography where remotely sensed image (pixel-based) data can be used in conjunction with landscape contour information in the form of vectorized drawing and individual property parcels as polygonal entities. Along with the comprehensive mapping component, the commercial GIS system works in conjunction with a relational database of attribute data.

### The New Prototype

In order to investigate whether a GIS would offer the requisite visualization and database options archaeologists need, a new prototype was built using ArcView with a 3D Analyst extension to link the excavation bulk find database ("Grosso Modo," which contains fifteen different artifact types from the site) to a three-dimensional-viewer program (see Figures 21 and 22).[21] Using the viewer, digitally surveyed architecture and trenches (represented as extruded 2D entities) and information about artifact concentrations can be visualized. In order to integrate the many layers/loci within a trench, a series of trench outlines are added. Each two-dimensional layer representing a different locus in the trench is physically joined (through user interaction with the system) with associated records in the database with bulk finds. The 3D Analyst plug in allows the user to manually define height or the Z value in each trench layer. This makes the trench look like a series of extruded layers. For example, in Figure 22, trench loci are represented as a series of colored polygons and a blue plan of the *in situ* architecture overlays the group. The colored trench loci represent pottery concentrations derived from the Grosso Modo database; darker colors represent high concentrations of pottery, lighter colors lower concentrations.

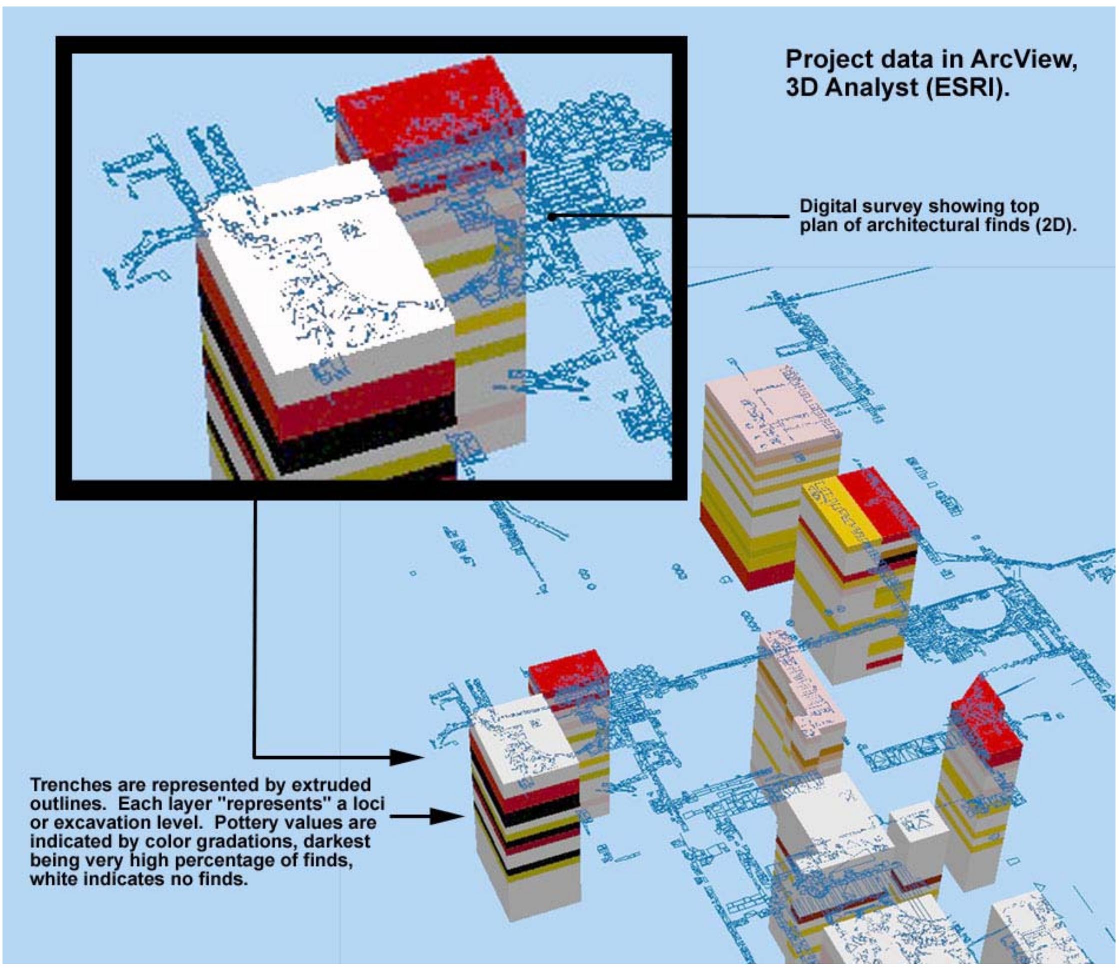



***Figure 22*** *Initial system mocked up using three-dimensional GIS software.*

## 3.2 Evaluation

This prototype was evaluated in the process of implementation by site archaeologists. The integrated prototype shows a relative spatial distribution of pottery in the various trenches that looks a lot like a three-dimensional bar chart (see Figure 22). The way the site and trenches are depicted here is somewhat misleading because it gives the impression that each layer is equal in size to the others within a trench. In reality, each layer is not equal and the complexity of the individual locus shapes and their relationships to the entire trench cannot be convincingly portrayed without the ability to model each layer independently as an irregular shape. When observing the prototype, archaeologist tended to view the configuration of trenches literally even though the depiction was not realistic. They were understandably confused by the too regular nature of loci in the various trenches.

Another concern in using this method was that it was not possible to view multiple artifact types together, such as bone and pottery. Once the archaeologist views concentrations of pottery, a whole new query has to be performed to look at bone concentrations. This was problematic because, unless a picture was generated of each object query, it was impossible to remember where the specific concentrations of the last pottery type were. Also, after loading the trenches from all the years of the excavation, (see Figure 23), it was impossible to see some trenches in the central regions because of crowding. Finally, because the architecture could be visualized only as a two-dimensional layer along with the trench outlines, it didn't provide a realistic context for the trench information.

## 3.3 Findings

**Context:** Several important findings came from evaluating this prototype. First, in building and observing the prototype, the importance of providing an accurate context for the architectural components, trenches, loci and artifacts was realized. However, since GIS systems are developed primarily for mapping applications, they do not address close-range conditions that require subtle height or Z-value exploration. Pfund explains:

> "Geographic Information Systems enable a numeric and abstract description of spatial objects and phenomena of the real world. Although our world and the objects situated in it are three-dimensional, commercial GIS systems usually reduce spatial data by its third dimension and project it onto two dimensions. One of the main reasons for this is the complexity of implementation of a complete three-dimensional GIS."22

This meant that many of the three-dimensional entities and spatial associations among parts of the site would be impossible to represent.

**Interaction, Navigation and Visualization Needs:** In addition, there are marked differences among archaeological interaction, navigation and visualization needs and geographical map-based explorations.[23] GIS software focuses on extracting and analyzing features (generally topographical), at a consistently larger scale. For example, in archaeological problem solving, researchers are required to analyze features that are map- and topographically-based (site location in relation to the surrounding areas, site features, etc.), but they also must consider objects that differ tremendously in scale, sometimes measured in cm (even mm), in the case of pottery, coins, glass, etc. Archaeologists need ways to interact with the physical findings in a variety of scales and resolutions. In addition, archaeologists must also perform comparative-analysis tasks such as tracing artifact typologies to other parts of the site and to remote sites. All of these tasks require a degree of visualization and interaction not presently accommodated in commercial GIS packages.[24]

## 3.4 Conclusions

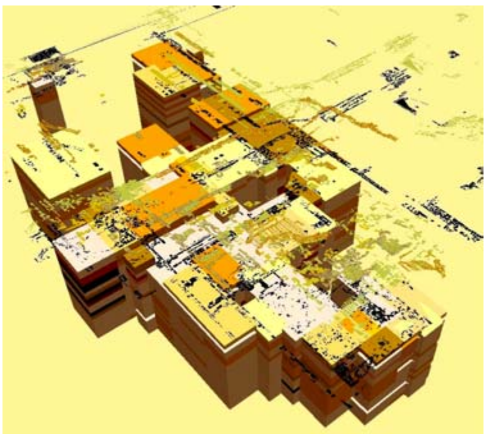


***Figure 23*** *The 3D GIS showing a more complete representation of the trenches excavated since 1993. At this scale it is practically impossible to see some of the concentrations in central regions.*

In conclusion, although GIS systems offer novel solutions in which a variety of two-dimensional data types can be correlated, they are clearly not sophisticated enough to provide a thorough description of Z-dimension (height) relationships among spatial entities. Therefore, even though most of map-based information can be combined in a GIS, there is still a significant gap between it and more descriptive physical information about the site features, architectural components and artifacts that cannot yet be adequately visualized. However, in building and evaluating this prototype, a basic physical model of the site was generated that helped outline some of the additional requirements necessary to perform analysis.

Finally, besides obvious conclusions that can be made when objects are correlated spatially via two-dimensional means, it is believed that the additional depth dimension can allow us to visualize objects (combinations of architectural components and artifacts) in their original spatial configurations and will provide a crucial layer of information not presently available. In addition, by using this prototype to examine trench and site features, some of the standard interaction and navigation methods were brought into question.

# Chapter 4: The Third Prototype:
## Visualization Using An Immersive Virtual Reality Interface

In looking at Paul Reilly's initial efforts to provide archaeologists with new analysis methods, we learned some important lessons that we integrated during the implementation of a third prototype. Reilly developed Grafland in order to investigate a model of a simulated archaeological formation, which contains all the elements that archaeologists want to observe in the artifact and material record such as loci, pits, post holes, cuts, recuts and so forth.[25] In the context of analyzing the simulation, Reilly outlined an important next step for the observation and analysis of the archaeological record. Specifically, he believes that archaeologists need to be able to integrate samples from the artifact record such as key objects and text-based resources through implementation of a user interface for data interrogation and navigation. Indeed, in the context of implementing a third prototype, we incorporated a novel user interface to perform some of these tasks. We also integrated improvements derived from evaluating the first and second prototypes, as well as a conceptual process: "a methodology" for dealing with the archaeological record in a new way.

## 4.1 Improvements, Goals and Ideal Process

Based on some of the issues that arose in attempting to implement the first and second prototypes, a list of proposed improvements was formulated. At this point, it was generally believed that, in order to conduct analysis with field data in the manner that was specified above, archaeologists need to be able to:

1. Have access to reliable architectural components as well as other key artifacts.
2. Establish linkages among objects for relative dating and chronology (this might entail automatic matching of some objects and human interaction for other connections).
3. Observe realistically-based spatial properties (physical dimensions and find spots) of architectural components, artifacts and site features (i.e., accurate three-dimensional information about the trenches, loci and stratigraphy).
4. Become acquainted with field data from all years of the excavation.
5. Observe different data types together, i.e., pottery and bone, and also, the ability to identify areas of concentration throughout the site).
6. Integrate two-dimensional, paper-based records (maps, drawings, photographs) with artifact variables presented in site databases.
7. Examine the data set flexibly (i.e., with the ability to change scale and resolution if necessary).

In reviewing this list, the objectives specified in the first prototype (before visiting the site), have become part of a scheme to perform a larger variety of analysis tasks. Significantly, this scheme is based not only on observations from more tangible, on-site evidence but also on the results from testing the second prototype. Specifically, there were some aspects about the Geographical Information System (GIS) software that seem appropriate for the physical components of the field data, particularly the ability to visualize site features.

Therefore, the following goals are specified in the process of conceptualizing a better system:

1. Develop a simple method that can accommodate site data from any site.
2. Should be intuitive, so that archaeologists can immediately understand how it works.
3. Can be used by anyone.
4. Mimics reality.
5. Gives the archaeologist access to all objects in their *in situ* find locations along with site and architectural finds.
6. Currently used quantitative methods can be integrated with the method (current databases, statistical analyses, survey data, etc.).

## 4.2 New Conceptual Process

Figure 24 represents what an ideal system can look like. It illustrates how a method of visualization and interaction with the site data will provide archaeologists with the tools they need to conduct a variety of analysis tasks. Using a convention from CAD systems, objects are referred to in this diagram as 'layers.'

If archaeologists are given the ability to interact with many of the elements removed from the site during the excavation process, including a representation of the sediment, they can complete analysis tasks much like they would on site. Layer 3 in the diagram represents the trench and its associated layers and architectural components. Layer 1 indicates the artifacts themselves and their attributes. Using Layer 4 the archaeologists can pick up objects of interest, examine them, see a list of object attributes and even move them to other locations to compare them with like objects. When prompted, the system will show objects that have similar attributes, their find locations or will indicate links with relatively dated objects. The archaeologist can also make annotations to different objects (or relationships) in the system so that other researchers have reference to them. Finally, in the lower right hand corner of Figure 24, the boxes represent how bulk finds will be represented in their associated loci (an empty box signifies an absence of finds, the slightly solid box represents pottery, and the speckled box represents bone finds).

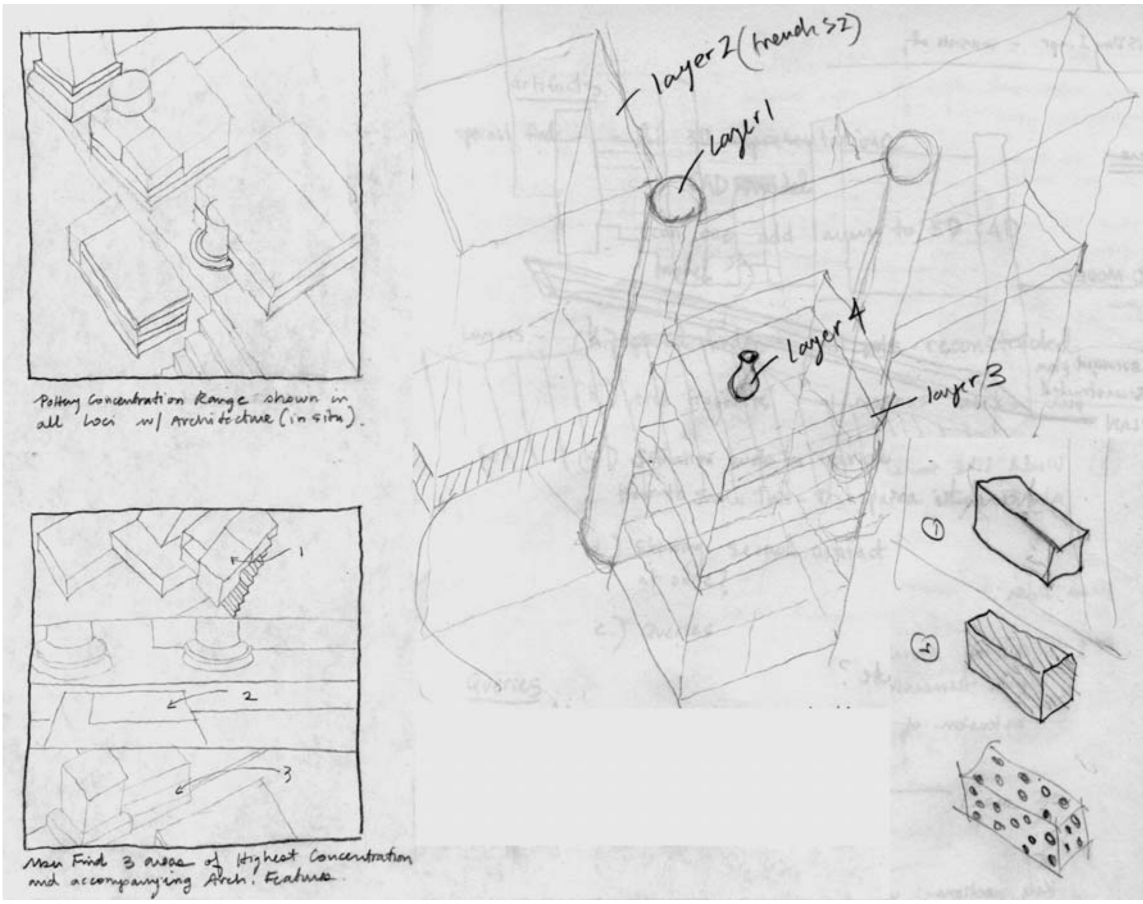



*Figure 24 Concept sketch of visualization and interaction features necessary to conduct analysis tasks with excavation data, Winter 1999.*

## 4.3 Hypothesis Based On Conceptual Process

Even though the concept sketch in Figure 24, developed in winter 1999, is primarily schematic in nature, when implemented; it would provide a means for archaeologists to perform a variety of analysis tasks. Therefore, it was hypothesized that given a comprehensive, three-dimensional representation of the excavation site record and an environment for examination and interaction with it (much like the ideal system described above), archaeologists will be able conduct research and analytical tasks that are difficult to accomplish with current methods. Using these methods archaeologists will be able to perform some of the following research tasks:

- Synthesize on-site findings.
- Trace relationships between trenches.
- Look at different types of artifacts together.
- Find anomalies in the data set.
- Formulate hypotheses.
- Confirm on-site findings and hypotheses.

## 4.4 Implementation

Two important things happened to facilitate the implementation of a system to test this hypothesis. First, implementing a new prototype to test this hypothesis was proposed in early 1999, as part of an NSF/KDI grant for interdisciplinary research.[26] It was a successful grant and funding started in the fall of 1999. Second, since building the new prototype was a challenging task, a meeting of minds occurred between Archaeology and Computer Science. As a result, Daniel Acevedo, a graduate student in Computer Science began working on the project in the fall of 1999.

At that time, we decided to implement and test the conceptual model as the third prototype in a new format. We hypothesized that an IVR (immersive virtual reality) interface like the Brown University Cave research facility would provide the archaeologist with a better environment to visualize and interact with the data model. [27] This prototype came to be called ARCHAVE (Archaeology in a Cave Environment).

**Immersive Virtual Reality**

Caves and head-mounted displays (HMDs) provide what is referred to as immersive virtual reality or IVR. Immersion is commonly defined as the feeling or state of being involved or "being there" in an environment or task. It is a somewhat elusive term because it is difficult to quantify. Generally, most people believe that immersion is achieved in systems, which provide a wider field of view than what is available in desktop displays. In effect, they fill the entire field of view, including the periphery. It is believed that the visual range provided by immersive systems: "help(s) provide situational awareness and context, aid(s) spatial judgments and enhances navigation and locomotion." [28]

Base features of standard immersive virtual reality systems allow users to navigate or move about freely in a model environment with a sense of immersion (see Figure 25). This is achieved by stereoscopic projections that are continuously rendered for the user's perspective; in other words, the system tracks head motion and updates the users' viewpoint up to thirty times a second (In film, motion is captured at about 24 frames per second). [29] This method works because we have "…stereoscopic, or binocular, vision – it is a natural consequence of having two coordinated eyes." [30] Basically, in virtual reality environments we are given a series of still images of a three-dimensional environment that continuously change as we change our physical location in reference to it.


***Figure 25*** *(top) Figure showing a Cave Immersive Virtual Reality environment where a three-dimensional model can be presented in a manner that simulates reality. This is achieved by stereoscopic projections of the scene on the three walls and floor of the cave. The user wears tracked shutter glasses and the model is continuously rendered for his/her perspective. In order to navigate and interact with the scene a wand and pinch gloves are provided that allow users to address commands to the system by finger movements.*

**Immersive vs. Non-Immersive Systems**

In non-immersive systems such as those that implement desktop monitors, users interpret a three-dimensional scene differently than if they were seeing the same scene in a HMD or cave. They see it as if looking through a "window."[31] Ware, Arthur and Booth describe the experience of viewing a stereographic three-dimensional scene tracked to a user's head position on a desktop monitor as "Fish Tank Virtual Reality."[32]

Dealing with a complex three-dimensional scene where the user needs to navigate and perform different tasks is based entirely on graphical information and it is necessary to have a platform where one can access all the elements that are needed to make decisions. Jaron Lanier describes the difficulties that exist in performing complex tasks on a small desktop monitor:

> "The human minds loves concreteness and visual/spatial representation, but that requires a bit of screen space for each thing or concept to be represented. Screen space becomes cluttered and then runs out almost instantly. You can cheat by having scrolling windows and so forth, but even then the boundaries of a usable visual space are almost never large enough to contain all the images the mind would like to see." [33]

There have been several attempts to quantify results that can be achieved in immersive vs. non-immersive systems to provide formal proof that the more "expensive" immersive systems are in fact useful. Pausch showed that VR users performed search tasks better than those using stationary monitors.[34] However, Robertson, found that those results did not apply to Desktop VR where the users' head movements are tracked and the scene is corrected for his/her perspective.[35] Also, Pierce demonstrated that a user responds to a HMD much like looking at a real world scene whereas users responded to desktop display scenes as if looking at pictures. Even these studies admit that we still do not have an adequate measure of immersion in VR. However, at this point, it is generally felt that there are certain specific tasks (i.e., navigation and object manipulation) that can be completed well and comfortably in an IVR environment and other tasks that are appropriate for desktop and desktop VR systems.

## 4.5 The Third Prototype

Developing the third prototype for users to investigate and analyze site data in the context of a cave environment proved challenging for several reasons. First, the original plan to present the context (via architectural and site details) in the IVR environment proved to be a computationally intensive task. Second, since users were performing analysis by visually processing the data types, we had to develop ways for them to observe and to navigate using these features.

**Context, Cave and Performance:**

We attempted to provide a reconstruction of the temple proper and the surrounding region as the basic context for establishing trench locations and artifact discovery. However, the model (see Figure 26) emphasized the computational power limits of the cave hardware. The resulting frame rates were hovering around one to two frames per second (the ideal is 28 frames/second). Because we foresaw adding more physical information in the form of trenches and artifacts, we realized that we needed to be frugal in representing architectural information. Therefore, we stripped the model of all unnecessary detail to reduce the polygon count so that additional evidence such as trenches and artifacts could be added.

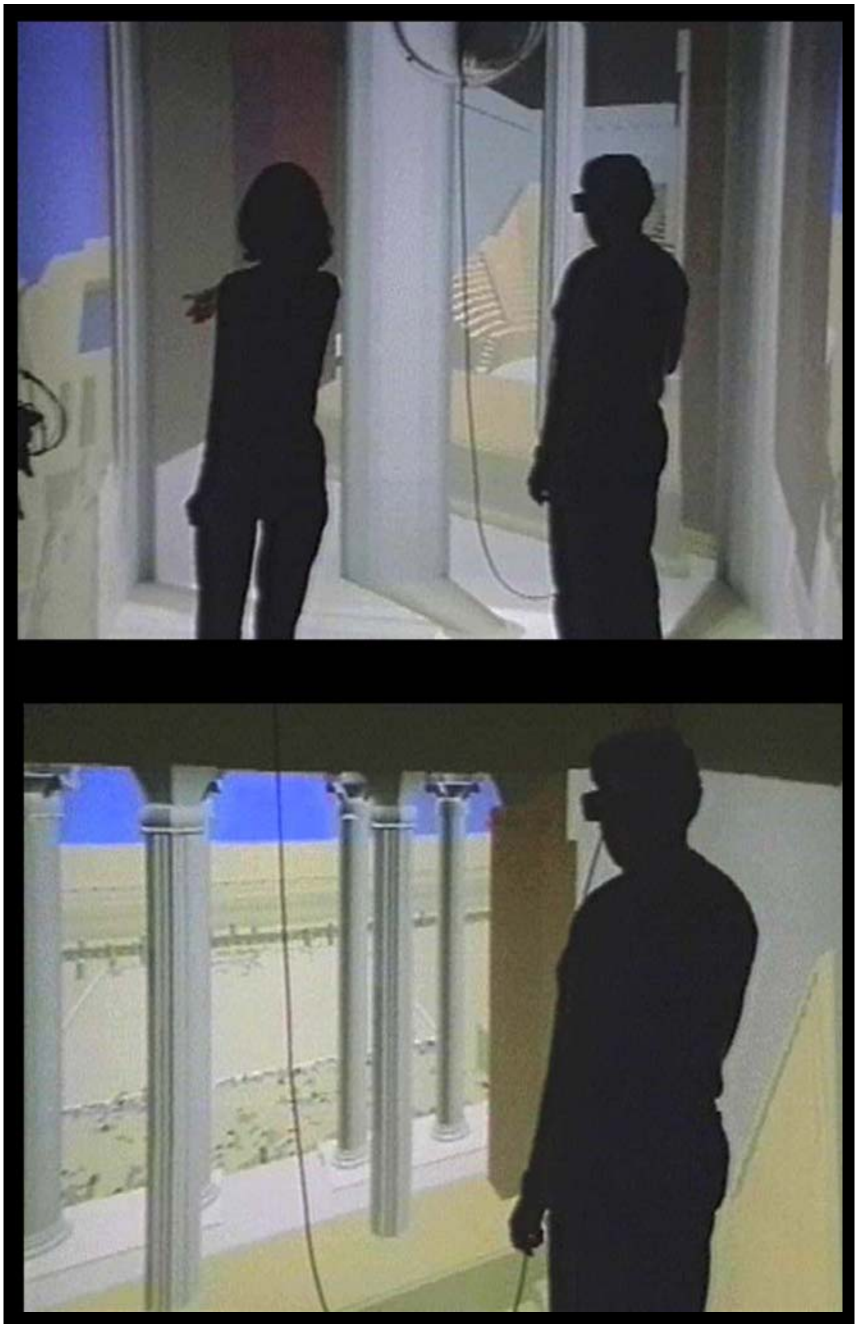


***Figure 26*** *Images of users navigating inside the Architectural Reconstruction of the Petra Great Temple that provides a context for simulating the trench and artifacts from the site database and trench reports.*

**Navigation and Interaction:**

Exploring a three-dimensional world requires a sophisticated interface design so that the user has the ability to move around and interact freely with relevant features. However, because it is not currently possible to achieve these interactions in ways that closely mimic reality (with unlimited freedom or with the sensations that accompany real interactions) most systems incorporate interaction processes that are symbolically linked to real life navigation and interaction. In desktop systems, the user is given a control panel where a variety of tools enable one to zoom towards, fly over, rotate and pick up objects and scenes. IVR systems generally allow users to "walk" or "fly," to move about or "shrink a scene" so that it is possible to get an overview of the environment before being transported automatically to the next destination.

For the prototype, a few fairly standard interaction and navigation techniques were used to provide enough control for the archaeologists to accomplish the tasks necessary for analysis with complex three-dimensional entities and scenes. General transportation is achieved using a tracked mouse equipped with a track ball used to "walk" or move freely on the ground plane, or to "fly" or move freely unconnected to the ground plane (see Figure 27). The base condition provides general site features and elements like trenches, and special finds can be added to the scene with button interactions on the mouse. Queries can be accomplished using the tracked pinch glove to allow users to visualize six of the bulk find artifact types including bone, stone, metal, shell and pottery. Various hand gestures using the pinch gloves allow users to choose artifact types by rotating the wheel and picking associated colors.

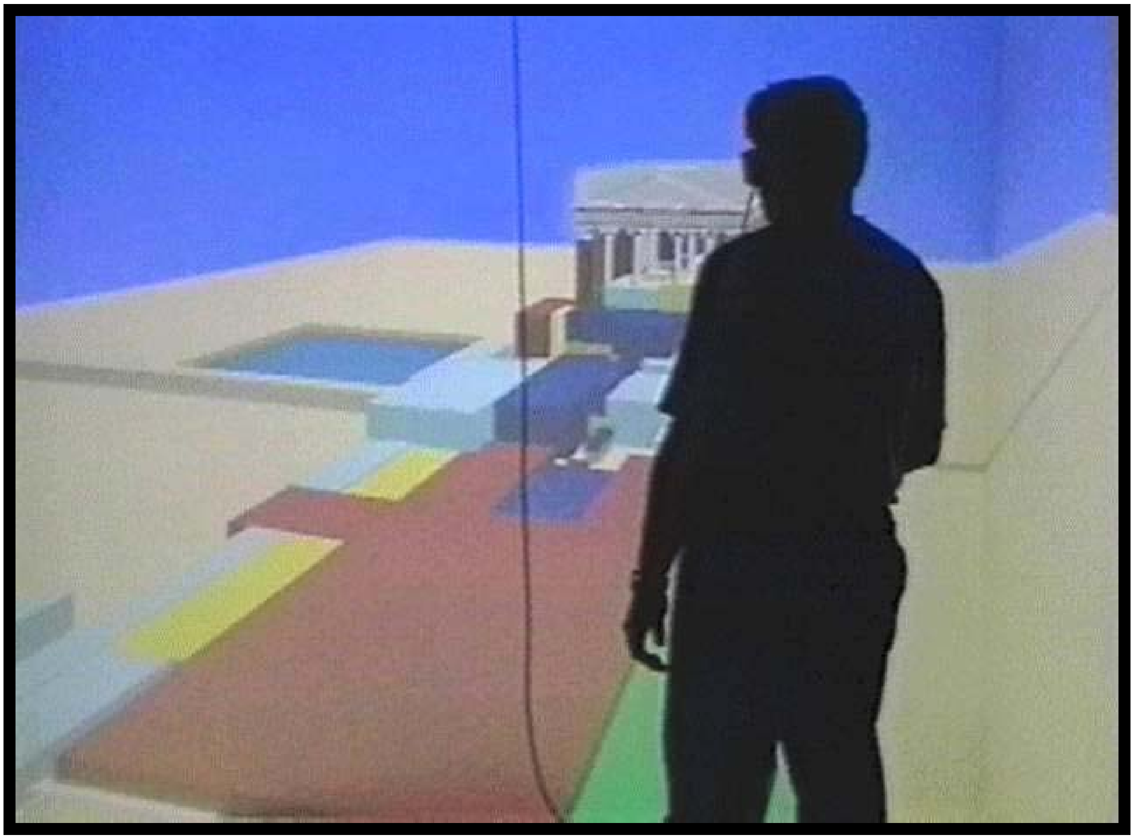


***Figure 27*** *Figure showing the user flying over the site. Multi-colored trenches are in the foreground and temple is in the background.*

**Color Blocking:**

In order to observe some of the artifact data in the context of the trenches we performed a simple join between the trench loci and site database. Each locus is given a colored value based on the amount of artifacts found in it from the database. For example, pottery concentration is presented as a range from white to dark red (see Figure 28), the highest value being the dark red.

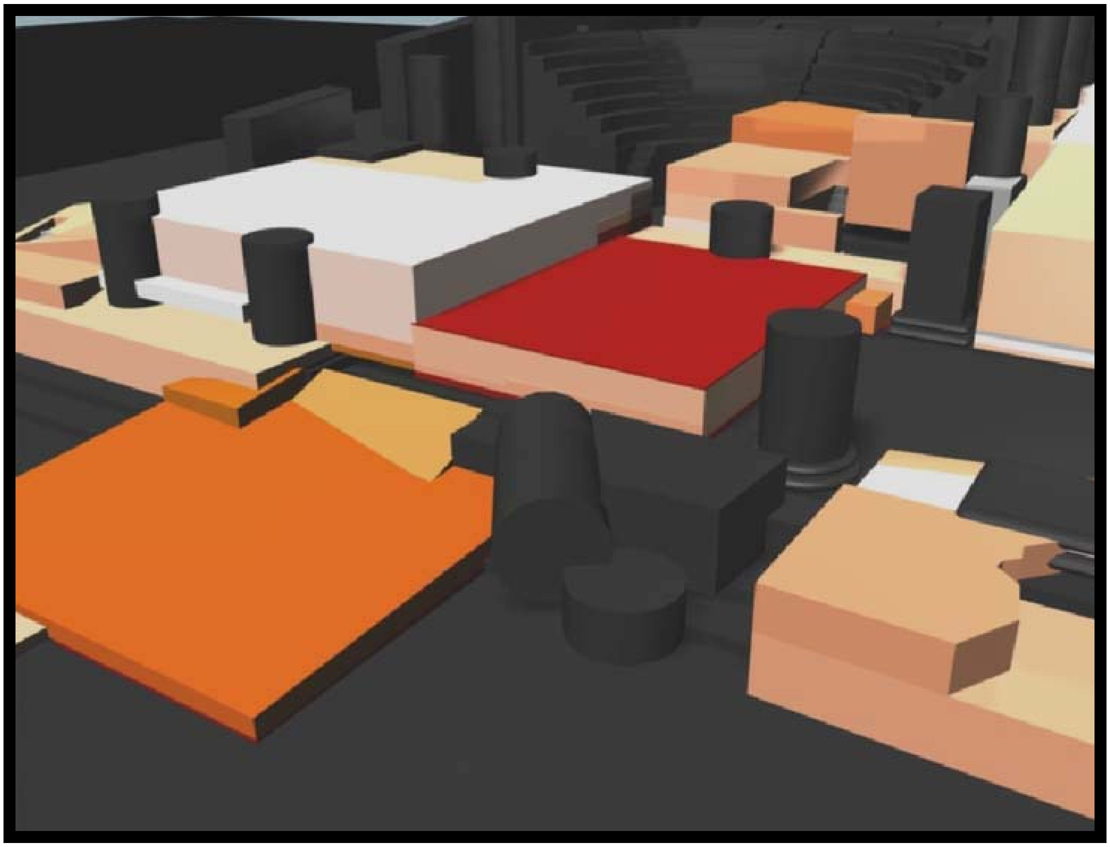


*Figure 28* *View showing trenches with pottery concentrations plotted as a color range from white to dark red. Dark red indicates the highest saturation of objects found.*

**Multiple Entity Representation:**

This prototype was intended to allow archaeologists to view and interact with a variety of object types or entities at once, a task which is not accommodated in any commercial software package now available. Therefore we developed a way to represent additional entity types such as bone, stone, metal or shell graphically along with pottery finds (color range). We accomplished this by using texture mapping to represent quantities of bone finds in each locus. The higher the quantity of bone found in the locus, the denser and darker the image-mapped texture. For example, Figure 29 shows a user viewing a trench with four loci. The light region with a very dense texture indicates low pottery finds and high bone concentration; the darker region with a cloudy texture indicates a medium range of pottery find but a fairly low bone concentration.

***Figure 29*** *Close-up of a user interacting with trenches. Each locus is expressed as a block to enable the user to understand the site stratigraphy. Pottery concentrations are shown via color ranges from clear to dark brown. Bone concentrations are shown as texture on top of the pottery colors.*

**Special Finds:**

Significant or special finds, such as Nabataean, Roman and Byzantine coins and pottery, were modeled in the prototype as realistic representations of objects located throughout the site in their *in situ* find locations (see Figures 30 and 31). The most straightforward way to exhibit special finds graphically along with previous query information (presented on the exterior part of the locus and trench outline) is to make the information transparent so that the user can see relevant objects inside the trenches. Using this method of visualization, the user can observe special finds, interact with them and even call up additional textual information from the database to learn more about the object (see Figure 32).

***Figure 30*** *User interacting with special find data. The previous query for pottery and bone is represented at 10% transparency so that the user can see relevant objects in their in situ find locations.*

***Figure 31*** *User interacting with a special find represented as a sculptural mask.*

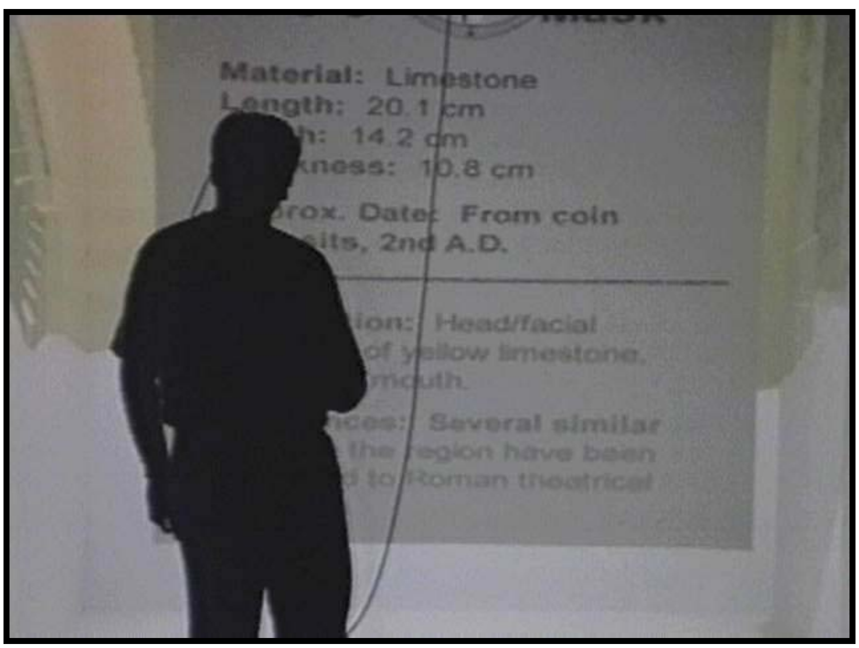



***Figure 32*** *Users can call up additional textural information regarding a specific find.*

## 4.6 Analysis and Evaluation

This prototype was evaluated by observing archaeologists use it over a seven or eight month period. During an introductory process they started to understand how the site was organized for excavation purposes. After the archaeologists entered the cave, they were given a site tour with the architectural reconstruction of the upper temenos and temple to provide a context. In the course of touring the site, they were asked to observe the excavation trenches from a vantage point above the site (see Figure 27).

Next, archaeologists were introduced to a few of the trenches at close range. For example, they were shown how the trenches in the pronaos region (see Figure 2, plan of temple proper) are divided into a series of layers or loci during the excavation process. After they understood how these trenches looked and how they related with the surrounding architecture, we began performing queries for them to observe the pottery and bone finds. Pottery bulk finds were added as color ranges in the various loci and then bone finds as texture mapping ranges (see Figure 29). Finally, the query information was made transparent and special finds were plotted in the various loci. Throughout the whole process, archaeologists were encouraged to navigate around and inside the trenches to acclimate themselves and to discover some of the bulk and special finds.

### Introduction to Issues

Archaeologists were enthusiastic about being provided with the opportunity to experience the Petra Great Temple site at life-size scale. They also felt particularly hopeful about the potential to interact with an accurate visualization of the data from the excavation. However, in evaluating the responses from a variety of archaeologists some specific, recurring issues regarding context, navigation and visualization arose.

### Context Issues

Many of the team archaeologists used this prototype to gain an understanding of the Petra Great Temple site prior to visiting it for the first time. The reconstruction of the temple remains was especially useful. Unfortunately, the reconstruction tended to influence the way archaeologists observed the site data, i.e., the trenches and artifacts. This was due to the fact that, in the process of positing a reconstruction, we made judgments about Nabataean architecture and therefore added unsubstantiated components to the site record. It was generally concluded that a more realistic *in situ* architectural context would provide archaeologists with more accurate evidence to make conclusions about the excavation data set.

### Navigation and Scale Issues

Users navigate in the system at life-size scale using the mouse to “walk” or “fly” through the site and to investigate the trenches and finds. However, when exploring the trenches at this scale, the users were easily disoriented because they could not always maintain a visual reference to the architectural remains. This happened particularly at times when they were entirely immersed in the trenches and navigating on the ground plane.

### Visibility Issues

Navigating in the context of the trenches at ground plane was very difficult because they are opaque and therefore block visibility to surrounding trenches and architecture. Also, observing color or texture ranges in different loci was awkward because the opacity of layers and architecture eclipsed the view to those underneath and behind. Therefore, despite our attempts to simplify queries so that users could see a range of areas easily, the current color blocking and texture mapping methods still prevented users from seeing key features under or behind an immediate trench.

## 4.7 Lessons

Although archaeologists were thrilled by the ability to reexperience the site and view special finds in their *in situ* locations, analysis using these methods was not yet facilitated. This was due to the fact that the archaeologists had not yet been provided with an accurate context for observing the site data nor had they been provided with adequate tools to visualize and interact with it to perform analysis tasks. The following is a list of issues and goals for improvements.

**Use in situ architecture for context:** Archaeologists were greatly impressed by this prototype's ability to simulate the experience of being on site with the life-sized architectural and archaeological context. However, because we strove to provide a realistic context for the site data, the reconstruction of the temple needed to be changed to a more representative, *in situ* example.

**Provide both life-size and miniature models for navigation and interaction.** Interacting and navigating in the model at life-size scale is suitable for a general site tour, but it is not always optimal for observing trench loci or finding patterns throughout the site. In many cases, users wanted to look at the site at a reduced scale in order to see the relationships between the various areas.

**Provide ways to synthesize a series of viewpoint observations:** In looking at the trenches, loci, bulk finds and special finds, archaeologists generally concluded that it was very difficult to visually process the pottery find values in the different loci because they were not visible from a given vantage point. For example, it was difficult to compare several trenches and their relative loci without moving around to new areas. In doing this, the user forgets what he/she has seen in the associated areas and cannot synthesize the findings effectively. Therefore, we needed to find a way to present more evidence at once or devise a way to enable archaeologists to synthesize a series of viewpoint observations.

**Provide a visual grammar to look at multiple entities together:** Archaeologists had a very difficult time understanding the correlation between pottery and bone finds. This was due to the fact that, while they could easily recognize high concentrations of pottery by color, they could not recognize the range represented by the texture mapping nor could they correlate the two together. Since we wanted to be able to visualize all the artifacts together, we needed to find a way to represent many different data types together.

## 4.8 Conclusions

Implementing the third prototype in an IVR environment was invaluable for providing archaeologists with different aspects of the site data in a realistic context. It was also very useful for evaluating archaeologists' responses and supplying feedback to design and integrate new features. However, in order to investigate the site data in a more useful format and provide ways to answer key questions about the record, there are several aspects of the prototype that need to be improved.

In conclusion, after assessing many of the findings derived from evaluation and observation of the first three prototypes we made plans to develop a fourth prototype. Chapter 5 will outline many of the features added to provide an environment where archaeologists can perform the tasks hypothesized.  It will also present key findings from watching archaeologists using it for analysis.

# Chapter 5: The Fourth Prototype:
Analyzing Lamps in Context at Petra

By designing and building each prototype we learned a great deal about the issues related to processing physical components of the archaeological record. Specifically, in attempting to provide a method to link objects via their spatial attributes, we realized the importance of accommodating visual properties. Next, by providing a more accurate context in a GIS for the architectural components, trenches, loci and artifacts, we concluded that there were a variety of interaction, navigation and visualization tools needed to perform analysis tasks with the record. Finally, we specified a new context (an immersive virtual reality environment) to facilitate the visualization of spatial properties and developed some preliminary tools to interact with the record.

In the process of observing archaeologists using the third prototype, we concluded that some basic improvements were needed to enable them to perform real analysis tasks. This chapter will outline how we incorporated new visualization and interaction features (see Figure 33) and what happened when archaeologists used the new prototype in the context of the Brown University Cave.

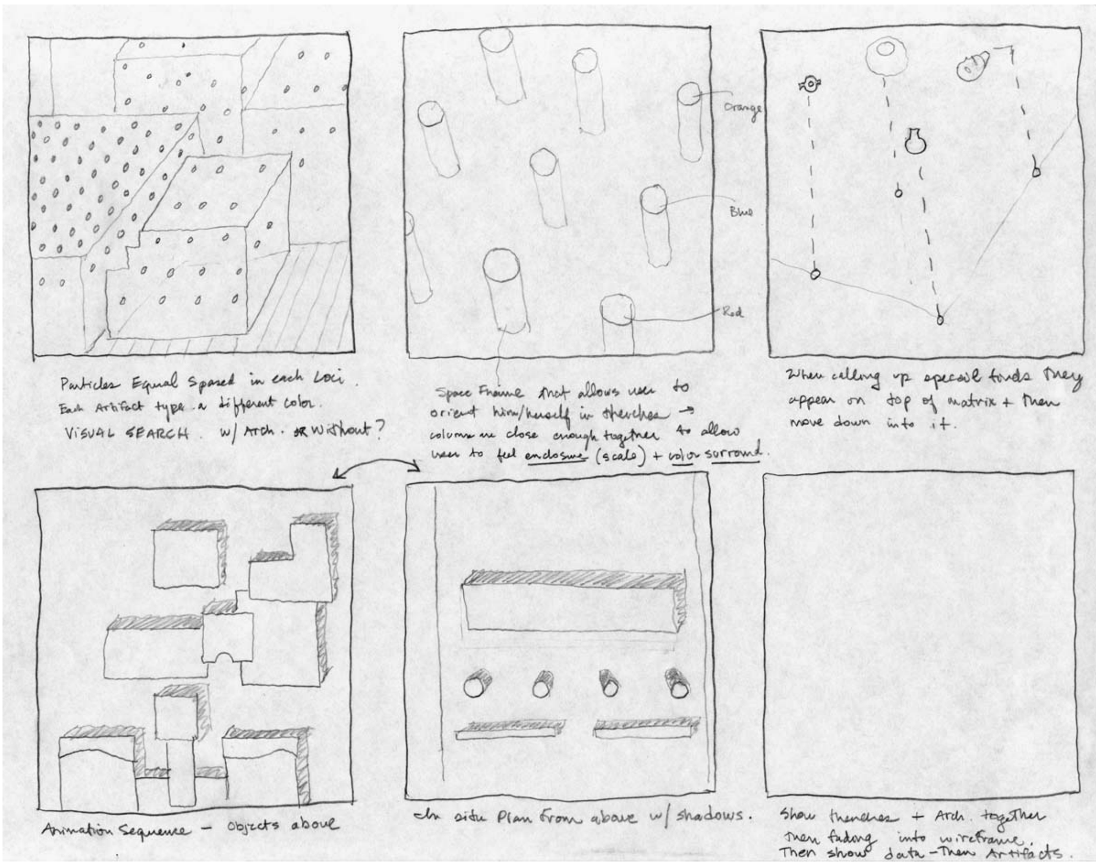



*Figure 33 Concept sketch showing new visualization and interaction features.*

## 5.1 The Fourth Prototype

### New Visualization Design

**The Context:** The site context provided in the third prototype was not effective. For example, archaeologists need information about the existing site findings that is more specific than a reconstruction of the temple and a few basic trenches. Therefore, a more accurate context was provided in this prototype by building a model of the existing *in situ* architectural remains using digital and photogrammetric site survey data and hand-drawn elevations, sections and photographs (see Figure 34). It was then necessary to build a representative sample of the excavation trenches. Essentially, since each trench is made up of irregular layers or loci, we had to refer to the site trench notebooks for measurements of each locus of sediment removed and build the trench so that it represented the whole process of excavation.[36] Figures 34 and 35 show the distribution of seventeen trenches that were built with information from the trench notebooks in the region straddling the upper and lower temenos and branching slightly into the temple proper and theatron. This model of the *in situ* architecture and trenches served as the basic context to test a variety of hypotheses posed by archaeologists (see evaluation section below). It also provided a structured way to index the range of finds associated with each trench locus and to test some new visualization paradigms.

**The Entities:** A major problem that archaeologists had with the first prototype was their inability to understand the pottery ranges in the trenches because the "color blocked" regions obstructed visibility. In addition, methods for representing multiple entities such as pottery and bone were not effective. Therefore, a better visual grammar was needed to enable users to visually isolate important regions, detect anomalies in a group of objects and look at multiple artifact types at once.

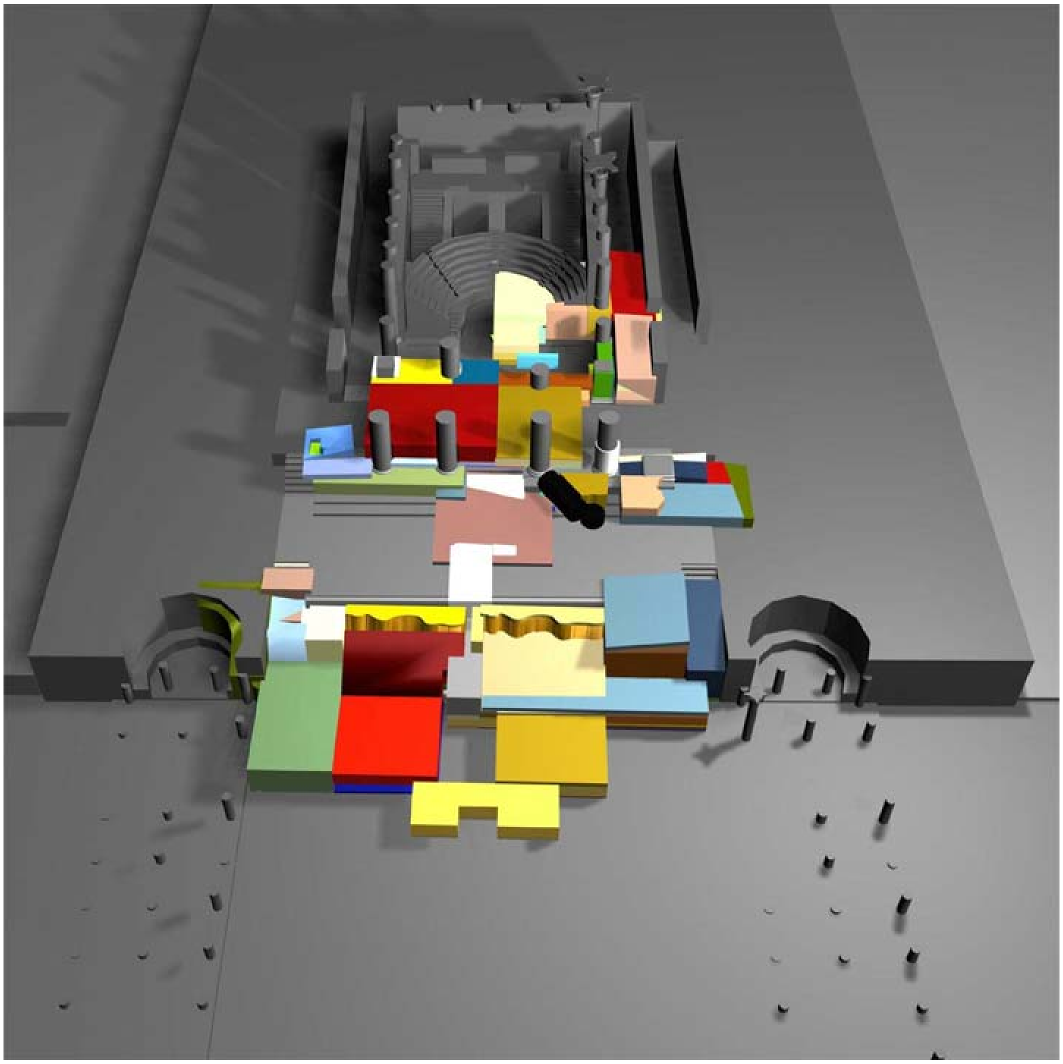


***Figure 34*** *Gray areas represent the in situ architecture while the colored boxlike regions show seventeen key excavation trenches, specifically all loci.*

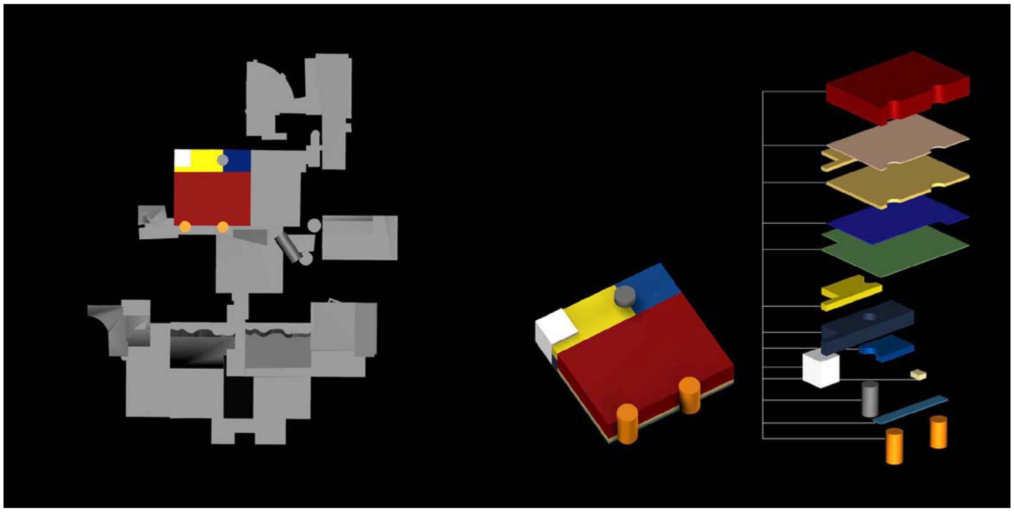


***Figure 35*** *(left) Top plan showing the distribution of the seventeen trenches without an architectural context. (right) Trench 24, on the right, an exploded axonometric shows each significant locus in the trench.*

Researchers in Cognitive Science and Information Visualization have isolated some visual grammar paradigms that allow the human eye to detect variables more easily. In mitigating a few of our visualization issues we were interested in providing the user with visual entities that can be pre-attentively processed. According to Colin Ware:

> "Certain types of shapes and colors "pop-out" from their surroundings. The theoretical mechanism underlying pop-out is called pre-attentive processing because logically it must occur prior to conscious attention. In essence, pre-attentive processing determines what visual objects are offered up to our attention." [37]

Features that are pre-attentively processed can be organized into a number of categories based on form, color, motion and spatial position. We used form, color and spatial position to organize the visualization of disparate physical parameters from the excavation record including: in situ architecture, trenches, loci, special finds and bulk finds (see Figure 36). Because the whole visualization was meant to focus on those elements that archaeologists cannot currently observe, (i.e., trenches and their related finds), we assumed that the site and *in situ* architectural finds should act as a base environment for visually processing those objects. Therefore, the architecture is visualized in a low saturation dark gray color to contrast with the other elements (see Figure 36, top right).

Because it is important to visually differentiate the seventeen excavation trenches from base architectural finds, they are modeled in white (Figure 36, middle right). However, since archaeologists need to understand the loci or layers of excavated remains and the physically indexed finds inside, the trenches can be modified on the fly from a highly saturated value to a barely visible transparent white.

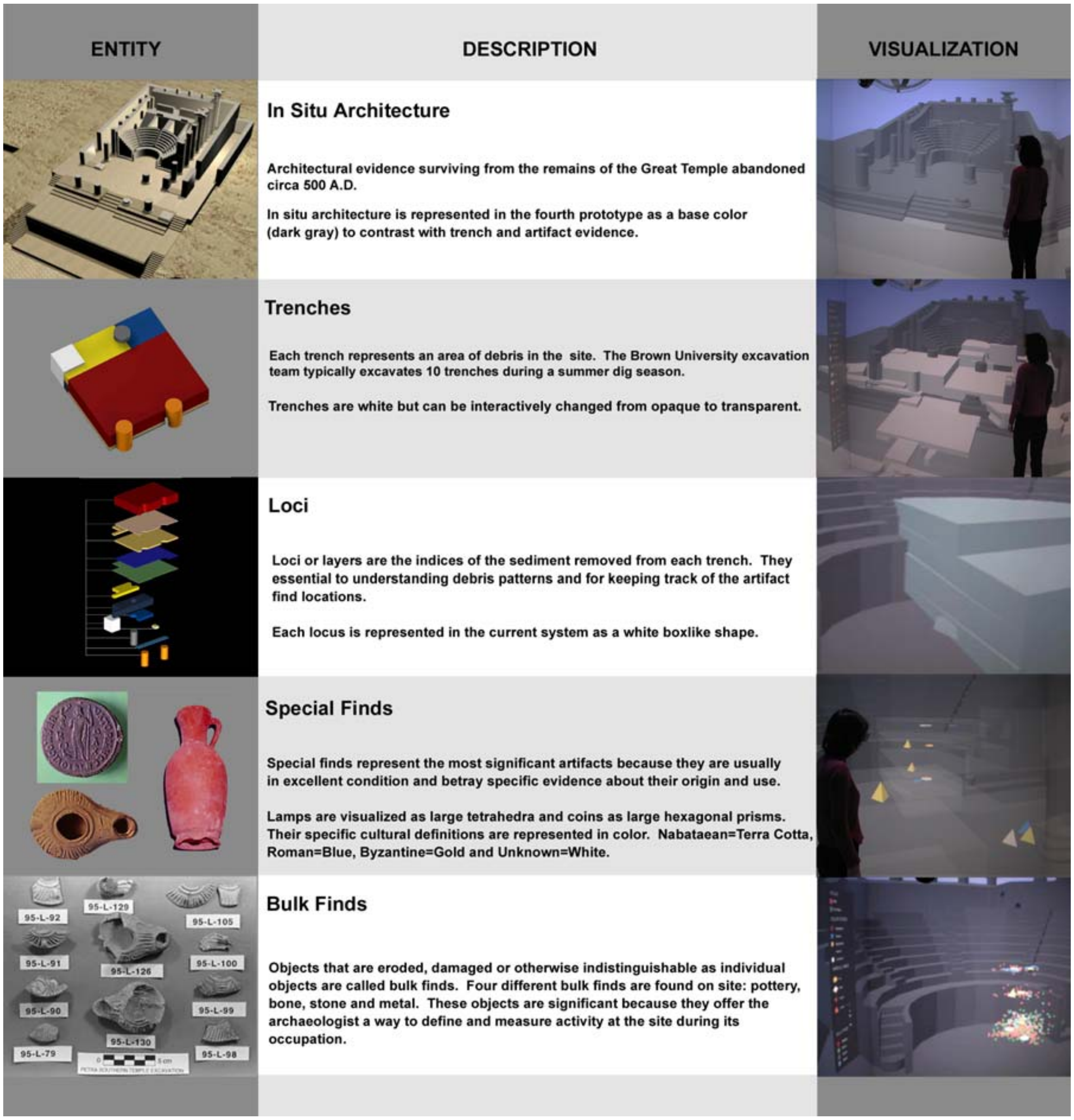



***Figure 36*** *Chart showing all the physical variables provided in the fourth prototype.*

**Artifacts:** When special and bulk find artifacts are added to the base composition (gray) they contrast with it due to their color and saturation (see chart, Figure 36). However, archaeologists needed a way to examine bulk finds and special finds together so that they could recognize the differences between them. This was accomplished by modifying their shapes and sizes. For example, special finds exist as distinctive shapes such as tetrahedra (lamp finds), hexagonal prisms (coins) and spheres (pottery) (see Figure 37). Users can identify special finds in relation to bulk finds by size; bulk finds (small tetrahedra) are approximately one quarter of the size of special finds (large tetrahedra).

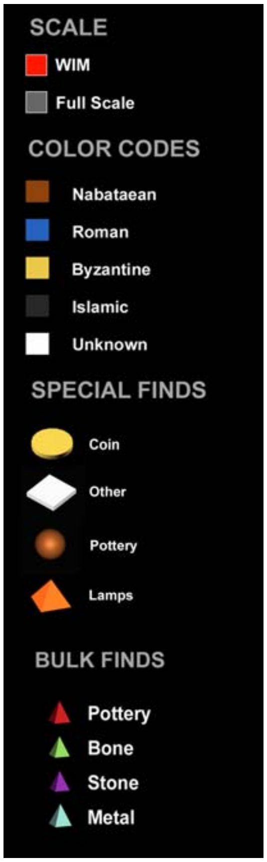



*Figure 37 The visualization key provides users with an accessible reference to the range of objects that they are seeing while studying the site.*

**New Interface Design**

Along with the need to visually refine the system, it was also necessary to improve the user's physical interaction with it. Therefore, we designed custom navigation and interaction techniques in order to perform many of the tasks required for analysis of three-dimensionally referenced data.

The ideal user interface is undetectable and unobtrusive to users while they maintain involvement in a task's completion. Unfortunately, many of the general user interface techniques do not facilitate investigations of the excavation record. For example, without control of the scale of the environment and movement, the user must navigate a very large area, approximately the size of three football fields. In addition, unless the user is quite familiar with the site, it is easy to get lost.

**Navigation Aids – Miniature Site Model:** A miniature site model (see Figure 38) can be accessed for navigation, thereby allowing the user to investigate a reduced version of the site in order to select areas to focus on at life-size scale. In addition, to introduce new users to the system and acquaint them with the site layout, a basic map of the site (with labeled regions of interest) is projected on the floor (see Figure 38). After looking at the site map, users are introduced to the *in situ* architectural remains in the context of the miniature model. Once the user has chosen an area to focus on, he/she is automatically relocated to that position in the full-scale model for more detailed exploration. In the context of the full-scale model, he/she can begin moving and interacting with excavation data via a mouse and pinch glove. The mouse is used to move, select and turn objects on and off. The glove can be used to access a virtual widget to initiate queries of six different bulk finds.

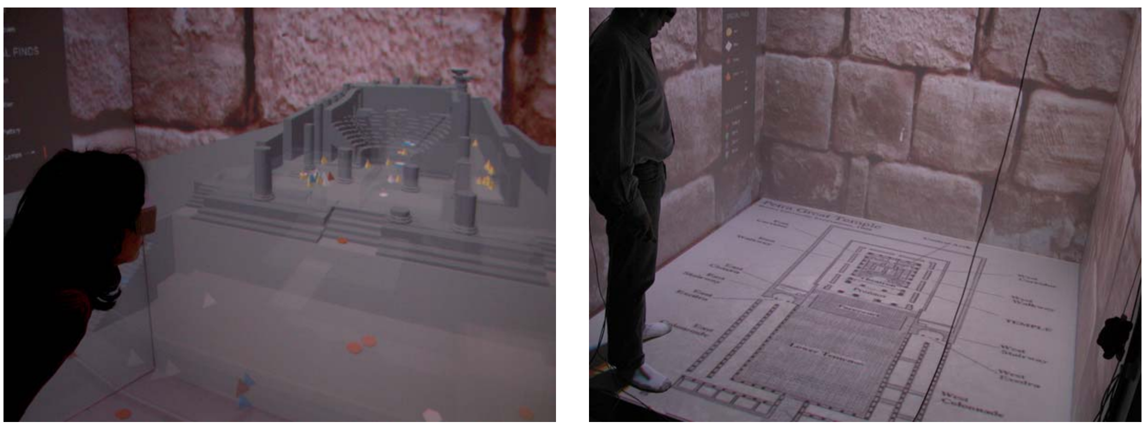


***Figure 38*** *(left)Miniature model of the site in context with the map underneath. (right)User being introduced to the system with a site map.*

**References – Palette, Maps:** Movement and interaction with the model is generally a very new phenomenon for users. The visualization process introduces additional "foreign" concepts. A site map (shown on the floor of the cave, see Figure 38) and key are provided to acclimate the user in the event that he or she becomes confused.

Most users have commented that the key provided with visualization symbols is extremely useful for referencing the various objects that they are trying to identify (see Figure 37). The key is projected on the left wall of the Cave so that it is visually accessible but does not obstruct the user's peripheral vision.

### Next Steps

After performing preliminary tests using some of the new features, team archaeologists were more comfortable using this system to navigate and interact with the model to observe the excavation record. Specifically, the basic features provided for navigation (miniature model, full-scale model and map) gave the archaeologists useful options for viewing and interacting with the site data and the visual grammar (size, shape, color, hue/saturation and solid/transparency), while allowing them to isolate the variety of features presented in the model.

At this point, we consulted with the Petra Great Temple team archaeologists about using the model to explore some of their own specific research questions. They outlined the key questions that they needed to answer for their research, questions which they had difficulty answering using the site database and trench notebooks. We made plans to observe them while using the fourth prototype for these research questions.

## 5.2 Evaluation

The fourth prototype was developed to implement comprehensive visualization and interaction techniques to examine the different types of objects collected over the course of the Petra Great Temple excavations in progress since 1993. It was also meant to afford archaeologists a way to conduct research and perform analysis tasks with site data that had not been possible using 'traditional' paper-based and quantitative analyses.

Specifically, using the research model incorporated into the system, it was posited that site archaeologists would be able to:

1.) Observe relevant objects and associated finds in their *in situ* (excavated) positions and in the context of the site.

2.) Trace relationships between trenches, trench loci, and artifacts.

3.) Examine stratigraphy and relationships between loci throughout the site.

4.) Look for relationships between different types of artifacts, i.e. coins and lamps.

5.) Test current "archaeological" hypotheses and formulate new ones and finally.

6.) Find anomalies in the data set.

In order to investigate this list of hypotheses we needed to observe the team archaeologists using the prototype.

**Testing Method**

To evaluate the prototype we reviewed some of the analysis and visualization tasks that archaeologists conducted while comparing it to traditional analysis processes (implemented at the Petra Great Temple site). Two user tests were performed to observe the archaeologists, to prompt them to answer different questions and to determine what sorts of analyses they could perform using the prototype in its current form.

Three non-archaeologist observers prompted the users with questions about their research aims and their level of comfort in using the prototype. The archaeologists were also asked to comment on the visualization, navigation and interaction methods. To make the users more comfortable with the interface, a non-archaeologist became the defined navigator. The same person was also in charge of instantiating the users' artifact and model visualization commands (i.e., transparent and opaque definitions for the *in situ* architecture to help the users focus on different features or artifact queries). It was posited that in this way the archaeologists would be less constrained by the interface and could concentrate on observing features and relationships and comment on their own research questions.

The first test employed archaeologists A and B. This test focused on evaluating the users' general observations in looking at the site data. Later archaeologists B and C used the system and were prompted to perform a series of specific tasks based on their own research initiatives. As they mastered its use, they were questioned about ways to adjust the performance that would aid them in their own research initiatives. The following discussion will focus on observations that were made in the latter test with B and C.

**The Research Questions**

Before beginning the test, B and C were both asked general questions regarding their own research and what they expected to find while using the prototype. Some items in the following list cannot be studied using the current methods but could be explored at a later time provided that additional information (specific object attributes such as pottery typologies or physical evidence from lamps) needed for a critical understanding of object associations were to be provided. This capability could be implemented fairly easily by extracting those attributes from the site database.

The fact that each archaeologist had well-formulated questions about the site findings was especially striking. In earlier discussions and user tests, the same archaeologists had had considerable trouble devising ways to use the spatial understanding and investigative features provided by the system. Their initial experience with the system model helped them to formulate new questions by providing additional contextual information about objects that they had been attempting to analyze discrete from the entire site.

Archaeologist B's research questions included observing the following:

1. Occupation patterns segregated by period, i.e., Nabataean, Roman and Byzantine.
2. Occupation patterns by area: i.e., theatron, western aisle or exedra.
3. Relationships among the loci in each trench and associated objects in the different levels.
4. Function of an artifact related to its find location and its loci location.
5. The relationship between coins and lamps; this can help validate the date of the lamp.
6. Contrasting lamps with an 'x' marking on the bottom to unmarked lamps in various find spots; this might help explain the connection between lamps used for religious function and those used for domestic purposes.
7. Broken pottery: was it ritually broken for sacrificial purposes? (This idea was generated from earlier tests using the system.)

Archaeologist C wanted to perform the following tasks:

1. An overview of the site with trenches and artifacts. She felt that she did not have a good understanding of the trenches and artifacts, especially those that she did not personally excavate.
2. Locations where high densities of glass existed.
3. Glass find locations in relation to other objects. Currently it is very difficult for her to compare other objects with glass finds. Performing this task without the methods presented here would require her to read through the trench reports to understand what each trench looked like. In addition, she wanted to query the database for evidence about the objects found in each locus.
4. The function of the Great Temple as opposed to the adjoining Petra Small Temple. This could be determined by comparing finds from both areas.

**Observations**

In general, it was observed that the archaeologists used the system for three general types of tasks:

1.) Making broad observations of the entire data set.

2.) Performing specific queries to answer key questions.

3.) Forming new hypotheses.

The next three sections will outline these research tasks. Chapter 6 will present results from performing the tasks and will contrast them with 'traditional' on- and off-site analysis processes.

**Task One: General Observation of Field Data**

Initially, the archaeologists used the methods employed in the system (i.e., the ability to visualize objects in three dimensions, to isolate different types of finds and to change scale from the miniature model to full-scale interaction) in order to understand the site findings more fully. They achieved this by navigating existing architectural remains, by looking at the trenches and by viewing the trench loci and artifact types in various combinations. During this process they observed and, with help from the non-archaeologist navigator, interacted with the site data by moving from the miniature model into the full-scale site. They also moved about at various levels and orientations, from flying above the site to small movements on the ground or within the trenches.

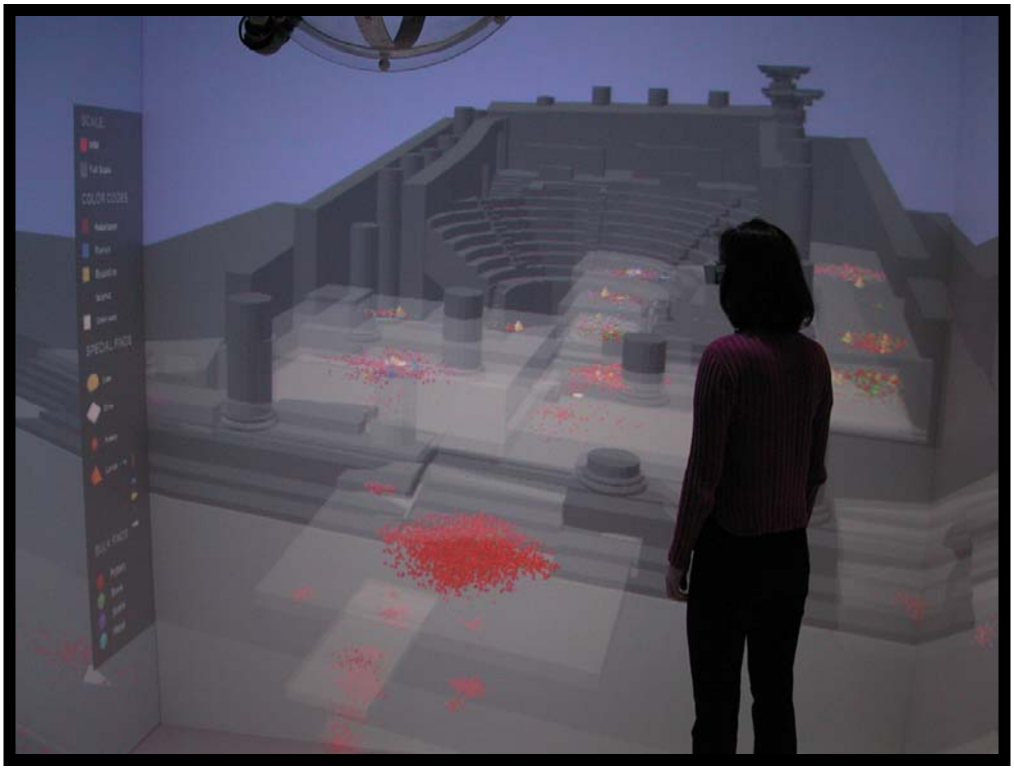


*Figure 39* *User observing the entire upper temenos region with trenches (semi-transparent areas) and all special and bulk finds in situ. Archaeologists used the ability to visualize and query the data in three dimensions in order to understand the site better. This allowed them to synthesize disparate elements observed over many years of excavation.*

**Synthesizing On-Site Observations:** In employing these methods they were able to synthesize observations with on-site findings. The ability to perform this task is significant because, while excavating at the site, they are often constrained by excavation procedure that requires them to document the trench and its associated objects. B commented that it is difficult to synthesize findings since, "You can't see the trees for the trees..." In essence they expend much of their energy in documentation tasks that limit their ability to conduct general observations about the context. In addition, it is often difficult for them to understand inter-trench relations. C noted that even by exploring those relationships through weekly on-site tours, the archaeologist was still unable to form a comprehensive picture of trenches that other members of the team had excavated.

**Finding Anomalies:** B wanted to examine the objects in the central stair area (trench SP 4) and noticed some features that did not agree with her memory of excavating the trench in 1996. Moreover, after querying the lamp finds from the upper temenos, she was quickly able to isolate a cache of Byzantine lamps in the middle loci of trench 29 (right next to trench 45) in the western corridor. This finding suggests that there might have been activity in that area during the Byzantine occupation of the site. Because she had not personally excavated trenches 29 and 45, she was neither familiar with the lamp find locations, nor was she aware that Byzantine lamps (excluding Roman and Nabataean) were the only kind found in that general area. This observation became a particularly striking curiosity and perhaps a vital clue regarding Byzantine site use, which would have been missed without the method of visualization, observation and interaction provided by prototype four.

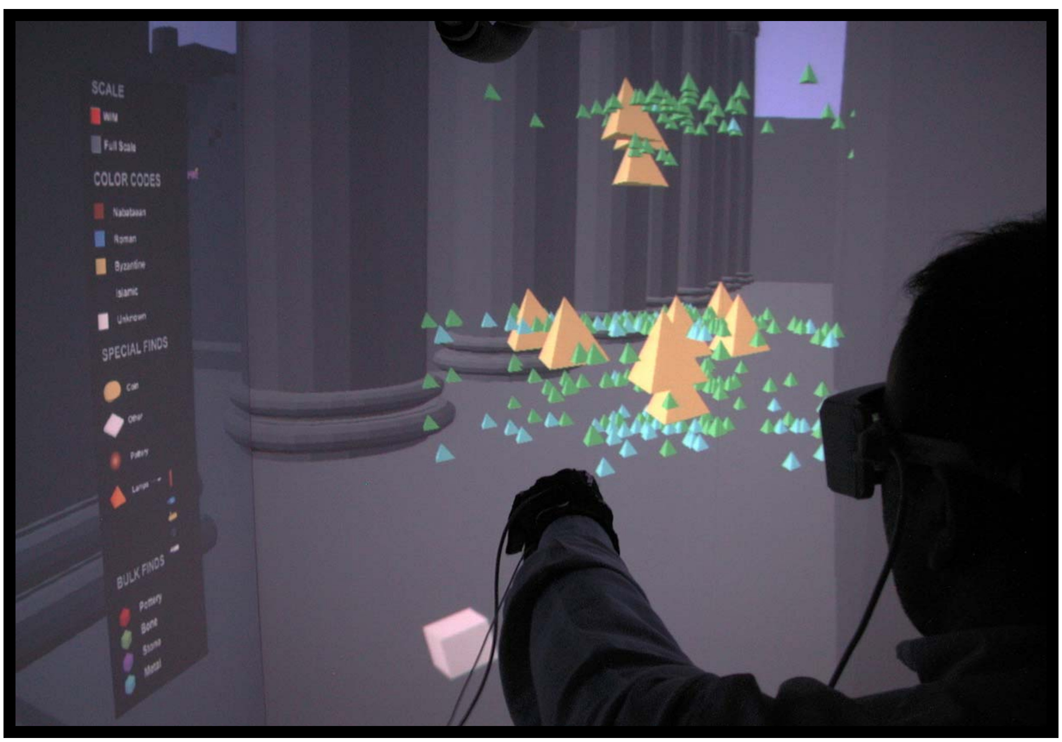



***Figure 40*** *User looking at lamps (large yellow triangles) in the western aisle. The small green (bone) and blue (metal) triangles represent bulk finds found in the same trench.*

**Confirmations of On-Site Findings:** In an earlier test, archaeologists A and B confirmed on-site findings regarding areas of mixed deposit by looking at the trenches and their associated finds in the context of the site. During excavations it was suspected that earthquakes, which ravaged the site in 363 and 551 CE, along with heavy annual rains, had disturbed the layers of sediment covering the building and its environs. As a result, the stratigraphic sequence became "mixed," making difficult the relationships between the various trenches, loci, and artifacts. This finding helps provide tangible proof for empirically derived excavation results and it produces information to document the relationships among site deposits and objects that can be used in performing analysis tasks. It is also significant because it confirms some of their longstanding suspicions about the various levels throughout the site.

**Synthesizing On-Site Findings:** These methods of observing the patterns in field data, although not always of significance in solving specific hypotheses, are nonetheless important features. Because many excavations take years to conclude and involve many people, allowing archaeologists to synthesize findings from a variety of trenches and over the span of the excavation is extremely valuable in providing an accurate context, helping resolve questions about the whole data set and forming new questions and observations.

### Task Two: Hypothesis Formation

Typically, archaeologists derive new hypotheses in the process of observing the physical evidence while they are excavating. However, the fact that they cannot personally excavate each trench means that they also cannot be exposed to all the site evidence and therefore, are not synthesizing the full record comprehensively. Using the research model, archaeologists can conduct empirical analysis much as they do on site, but with a much more complete data set.

Indeed, the archaeologists who were tested using this prototype were able to formulate new hypotheses because they had access to a more complete record of the site findings.

**Az Zantur Site:** In the process of doing queries to look at the architectural remains and special and bulk finds, B and C began to form personal hypotheses about what they saw. For example, after observing the placement of coins and lamps together, B posited that the finds at the Petra Great Temple precinct might be physically related to the Az Zantur Nabataean housing site immediately behind it. This idea might explain the seemingly random pattern of objects from different cultural periods at the ground levels of the trenches. To explore this hypothesis further and to attempt to prove her idea that heavy rains caused an overflow of objects from the Az Zantur site, earlier findings could be compared with these findings using the system.

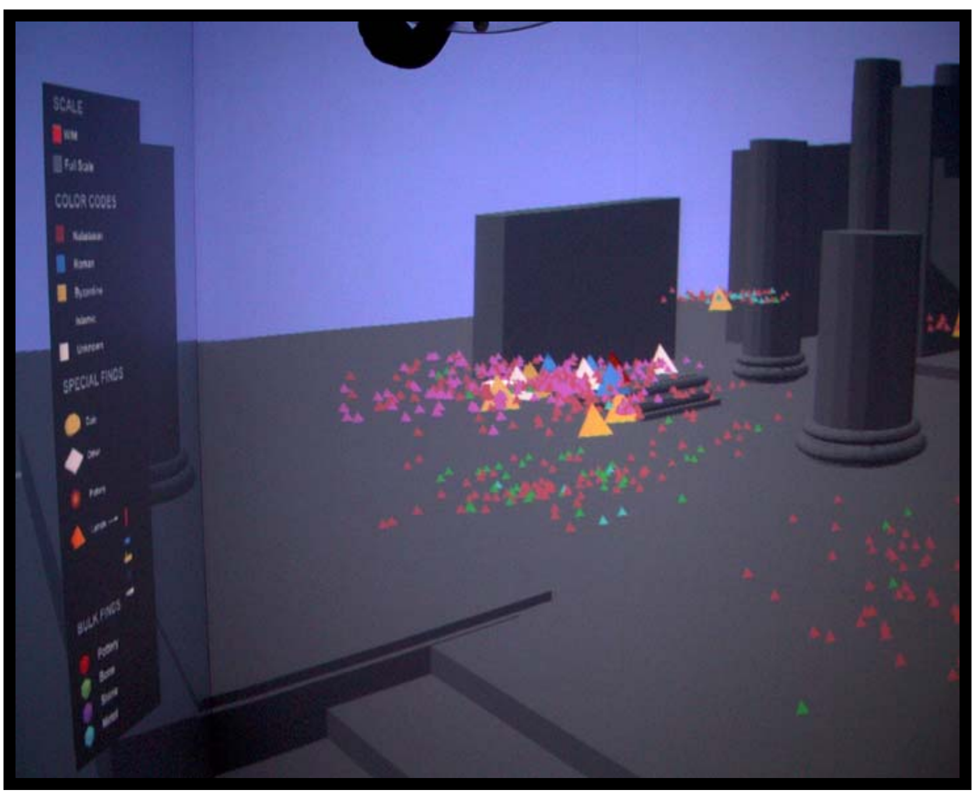



***Figure 41*** *Figure showing mixed concentrations of finds in the Pronaos region of the temple. Note the mix of lamps from different cultural periods in the center.*

**Metal Finds:** C was interested in some of the metal finds from the site. While looking at bulk finds in combination, she hypothesized that the metal fragments might correspond with doors or windows because, when the wood disintegrated the metal hardware would remain. Although it's fairly easy to find high concentrations of metal using merely the site database, it is not easy to associate a specific layer with its architectural component.

C queried the database for metal finds and observed them in the life-size model. She thought it was surprising that all the metal in the theatron and in the western aisle was at ground level. In looking at the metal in the western aisle she observed that it was aligned with the doorframe on the west side. She also posited that another cache of metal found in the lower levels of trench 47, in front of the theatron, could have come from old wooden banisters that lined the theatron circulation routes. Again, if this were to be the case, after the wood had disintegrated the metal hardware would have remained.

C encountered a problem in proving this hypothesis because the metal objects she found did not have additional attribute information such as shape or function (currently accessible only from the original database). Integrating more physical attributes from the database for these objects would allow her to investigate this hypothesis further.

**Task Three: Performing Hypothesis Testing Via Specific Queries**

Hypothesis testing is an inferential procedure used to offer support for a hypothesis or educated guess. Archaeologists often form personal hypotheses about the physical record from on-site observations or by looking at specific objects unearthed outside of their find context. Utilizing some of the methods provided in this prototype could potentially allow archaeologists to check objects of interest in their on-site setting and provide evidence (via graphic means) to clarify the findings.

**Sacrifices:** B wondered whether sacrifices were conducted in front of the temple or inside it. To investigate this hypothesis it was necessary for her to query and observe bone and pottery finds both by themselves as well as in combination with other objects. She also needed to examine some of the different types of objects in the upper temenos forecourt, pronaos and theatron (see Maps). The investigative process included moving around in the model at full scale and in the miniature model to find the highest concentrations of bone finds. In addition, B believes that certain types of pottery were used in conjunction with bone for sacrificial practices. Therefore, she queried pottery finds and attempted to visually isolate areas where there was a strong combination of bone and pottery. Both B and C concluded that it was necessary to examine the finds from a variety of viewpoints in order to understand the concentrations and combination of finds, i.e., from above the trenches, on the ground at life-size scale, rotating around the trenches to understand the relationships between loci and finally, hovering above the miniature model to get an overall impression of major artifact concentrations.

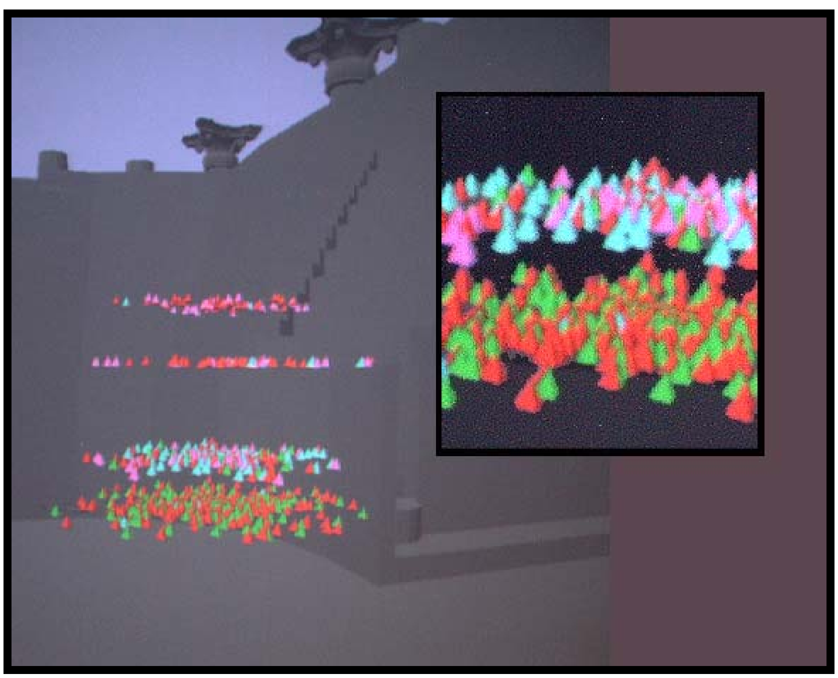


***Figure 42*** *Bone and pottery finds in the area just in front of the theatron, trench 47.*

B observed that there was a high concentration of bone just in front of the theatron in the lower levels of trench 47, near the floor (see Figure 42). She also isolated a combination of bone and pottery near the stage area in trenches 23 and 24. This was an interesting result because she had predicted that there would be more bone and pottery in the temple forecourt, (just in front of the temple, since that's traditionally where sacrifices were performed) not in the theatron where the high concentrations of bone and pottery were actually found.

In order to clarify this result, she wanted to understand if the pottery found in combination with bone in trench 47, was coarseware or fineware. She commented that: "Perhaps they (the Nabataeans, Romans or Byzantines) were cooking there or, it could be that they were performing sacrifices." She suggested that, "They may have used a particular type of pottery for sacrifice in this area that we won't see in other areas of the site."

Unfortunately, at this point, additional pottery attributes like color, painted or non-painted, material, shape, part, are not accessible. Significantly, this information has been recorded in the site database but has not been indexed for use by the system. In the future, additional pottery attributes could be made accessible for queries and presented in the system along with the present features. Having this additional information would allow B to isolate the painted pottery (of Nabataean origin and seldom used for cooking purposes) and compare it with coarseware (of mixed origin and typically used for cooking).

**Lamps:** To complete a thorough investigation of lamp finds and to tie them into the cultural periods of the site's occupation, B wanted to consider their find locations and relationship to other relevant and dateable objects such as coins, pottery and architectural fragments.[38] She utilized the system's ability to query those artifacts in combination with the lamps in order to observe links between them.

She began her analysis process by examining the lamp finds (see Figure 43). Lamps are oversized triangles and their color indicates in which cultural period they originated (Terra-cotta=Nabataean, Blue=Roman, Gold=Byzantine, White=Unknown). B wanted to look at the lamps with the trench and loci (trench layer) information so that she could determine the location where they were found within the trench, since, a lamp found in a locus close to the opening of the trench (the top) can sometimes be considered a "surface find." Surface finds are often discovered on the ground during the field walking process, just before excavation begins, or immediately after a trench is opened. These objects generally arrive in this placement when the soil is irrigated during heavy rains and therefore aren't generally used to help describe a cultural level. As a result, if a lamp is considered a surface find, it can't be used in dating, or otherwise describing, the level of stratigraphy in which it was found.

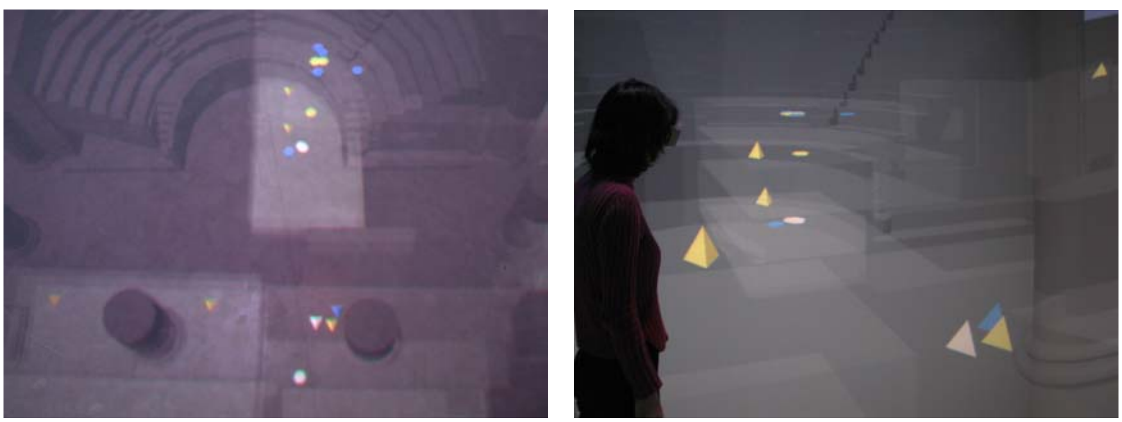


***Figure 43*** *Two separate views showing lamp and coin finds in the region in front of the theatron. It is often useful to change perspective from above the model (left) to ground level (right).*

After B observed the lamps in their find locations and the associated trenches, she asked to see the coin finds. Even though B is an expert on ancient lamps and can determine quite a lot about them from their shapes and stylistic markings, she cannot always be certain that the date of manufacture established for the object will share the find locus date. One way to verify that the lamp find layer is indeed the same as the lamp origin date is to perform a cross check with associated dateable objects such as coins.

In her own research she has not yet compared the lamp finds with spatially related coins because it would require too much work (see Figure 43). To accomplish such a task, B would need to trace all the coins that are spatially related to the lamps by looking them up in two separate databases ("Grosso Modo" for the lamps and the" Special Finds" database for the coins). Next, she would have to use an associated trench notebook to attempt to understand the spatial composition of the trench and the individual loci where the objects were unearthed. This process would have to be repeated for every lamp and coin *in situ* location. In addition, she would have to try to determine supplementary descriptive information about the find layer such as whether it was a sealed cultural level, to determine if she could indeed trust the assigned dates.

In summary, the visualization and interaction methods employed in this prototype simplified the analysis process. Using a three-dimensional visualization of lamps and coins together allowed B to understand their spatial connection and it helped her to determine whether their cultural origins were similar. Furthermore, after looking at the seventeen trenches in the context of the site, she was able to determine that there was no clear agreement between the cultural origins of the lamps and coins. This finding did not surprise her because she had predicted that most of the deposit at the site was mixed. However, her conclusion is significant because it confirms the state of the site deposit and provides proof of her hypothesis (through graphics generated from screen grabs) for dissertation research, site reports and other analysis proceedings.

## 5.3 Conclusions

In conclusion, with a number of improvements implemented in a fourth prototype, users were finally able to perform a number of analysis tasks. Specifically, they were able to make general observations of the field` data, formulate new hypotheses and test existing ones.

Also, in the process of performing user tests, archaeologists began to see a number of new possibilities for analysis that they had not previously considered. This was due to the fact that they were given a means to examine the site record without constraint, something they could not formerly do.

The following chapter will assess some of the tasks that archaeologists performed using the fourth prototype and compare the results with those derived using traditional analysis processes. It will also outline some issues with the current process and additional features that archaeologists require to perform other forms of analysis.

# Chapter 6: Results and Discussion

In this chapter we review and summarize the research tasks conducted using the new methodology implemented in the fourth prototype and discuss their effectiveness compared to traditional on- and off-site methods for archaeological analysis. We will also summarize major visualization, interaction and navigation issues that were observed during the testing process. Additional features that archaeologists require to improve their performance in completing these tasks will be presented, along with new tasks they would like to conduct in the future. Finally, a summary of results will be presented.

### Initial Hypotheses

The hypothesis we tested assumed that, given a comprehensive, three-dimensional representation of the entire excavation site record and an environment for examination and interaction with it along with ways to perform essential analytical tasks, archaeologists would be able conduct new and more effective types of research and analysis. In the process of adapting a series of prototypes, a methodology (best embodied in the fourth prototype) was created to test this hypothesis. It is significant that while using the fourth prototype, archaeologists who were tested were able to accomplish the following:

1. Observe relevant objects and associated finds in their *in situ* (excavated) positions and in the context of the site.
2. Trace relationships between trenches, trench loci, and artifact finds.
3. Examine stratigraphy and locus relationships throughout the site.
4. Look for relationships between different types of artifacts, i.e. coins and lamps.
5. Find anomalies in the data set.
6. Form new hypotheses.
7. Test current hypotheses.

In order to evaluate the effectiveness of the methodology, we need to compare it with traditional approaches. The following two sections will present a comparison and assessment of tasks performed using each method.

## 6.1 Time Requirements for Each Method

The time required to perform comparable tasks using traditional and new methods is presented in Figure 44. Although the new method involves an initial time investment to extract and build trench and locus dimensions from the trench notebooks, the net time requirement (approximately 20 minutes) is still much less than that required to perform the same task using traditional approaches (approximately 15 hours to trace ten objects). This is due to the fact that, if archaeologists were to attempt to conduct the task using their own current site methods (in the form of databases, maps, plans, sections, etc.), they would be faced with a cumbersome procedure that would take hours of work. Specifically, in order to understand the placement of a representative sample of lamps and coins in a three-dimensional context, the archaeologist would have to: find all the related objects in the database, isolate their specific find locations by trench and locus, and extract physical information about the related trenches and loci from the trench notebooks. Immediately after this process he/she has to attempt to determine the three-dimensional relationships between the finds with an assemblage of maps, drawings, and sections as well as notes derived from the examination of the trench notebooks. Even so, it would be almost impossible to derive a comparable environment to that granted by the new method.

| Analyzing Lamps and Coins Together | Time to Complete Task |
| --- | --- |
| **Traditional Method**<br>1. Find relevant objects in the database.<br>2. Using trench notebooks for each object.<br>• Find physical information about trench and locus.<br>• Find location of object within the locus.<br>3. Attempt to understand the relation among objects, loci in relation to architecture. | (Approximately 10 Objects)<br>**15 hours** |
| **New Method**<br>1. Query coins and lamps.<br>2. Examine them in relation to one another and site record. | **20 minutes** |

***Figure 44*** *Figure showing the comparison of time required to complete a task using both methods. Note: Building the trenches and loci using the trench notebooks is an initial time investment for the new method.*

## 6.2 Comparison of Task Performance using Traditional vs. New Methods

In comparing new and traditional methods we considered three of the tasks that archaeologists accomplished during the testing process, specifically, general observations, hypothesis formation and hypothesis testing. We then assessed the relative difficulty and effectiveness when tasks were performed using traditional vs. new methods. We also reviewed what sorts of results were obtained with a combination of both.

When archaeologists perform **Task One** (General Observations, see Figure 45) on site, they do so by assessing the physical evidence during the excavation and exchanging their observations with the other site archaeologists. If necessary, they can refer to the trench notebooks or site databases to attempt to confirm these observations. However, it is not always easy to confirm general site trends since personal (empirically-based) observations are limited.

| **Task One: General Observations** | Using Traditional Methods | Using New Methods | Using Both Methods Together |
|---|---|---|---|
| **Task is performed by:** | Empirical observations, discussing observations with colleagues, site database reports, trench notebooks, plans, maps, drawings. | Observations of all finds together through navigation and interaction with the record, queries showing specific objects. | Must perform tasks for both methods. |
| **Difficulty:** | **High** | **Low** | **High** |
| **Effectiveness:** | **Moderate** | **Good** | **Excellent** |
| **Comments:** | Cannot see all objects together in their find locations. Cannot synthesize findings from all years. Can see things that do not make it into the record. | Provides a way to synthesize all findings. Cannot see all attributes at this point, more detail is needed. Find location is not exact. | Comes with the ability to make empirically based observations on site but can check them out with more comprehensive information. |

***Figure 45*** *Task One – General observations about the site record.*

Archaeologists perform well by employing the new methods since they are given a more thorough representation of the excavation record. As a result, they have the ability to observe features that were found in areas of the site that they did not personally excavate and can synthesize all findings together in a manner that is not possible using traditional approaches. Yet they are still not able to see details and object attributes like those in the real record, for example, specific bulk find pottery attributes such as color, texture, painted vs. non-painted, etc. In addition, the in situ find locations represented in the fourth prototype are not exact so it is not always possible to trust these attributes. Nonetheless, in employing both methods together, archaeologists gain a considerable edge over previous strategies because they gain the capability of performing tangible observations on site with a way to synthesize all findings together.

| **Task Two: Forming Hypotheses** | Using Traditional Methods | Using New Methods | Using Both Methods Together |
|---|---|---|---|
| **Task is performed by:** | Empirical observations, discussing observations with colleagues, database reports to augment other methods, trench notebooks, plans, maps, drawings. | Observations of all finds together through navigation and interaction with the record, queries showing specific objects. | Must perform tasks for both methods. |
| **Difficulty:** | **High** | **Low** | **High** |
| **Effectiveness:** | **Moderate** | **Good** | **Excellent** |
| **Comments:** | Observations with tangible evidence are difficult to replicate in system but cannot be synthesized well here. | Can synthesize all findings *in situ*. Not enough attribute data, sometimes results can be misleading because in situ location is not exact. | Requires more work but can produce a very effective way to establish and check hypotheses in both contexts. |

***Figure 46*** *Task Two – Forming hypotheses with the site record.*

When archaeologists perform **Task Two** (Forming Hypotheses, see Figure 46) on site, they do so by assessing the physical evidence during the excavation and by participating in team site tours and phasing meetings. Also, when they observe trends or unusual patterns among the physical record, they have the ability to discuss these observations with colleagues. Even so, by using the new methods provided here, they are far more likely to gain a clear picture of the compendium of site findings. Furthermore, they can look at the findings unencumbered by features that are distracting such as architectural or trench components.

Archaeologists have a considerable edge when they combine the tasks they perform using the new methods with those derived on site. However, there is not yet a good degree of detail provided within prototype four to allow descriptive observations to be made. For example, even though archaeologists can determine that there is a mixed deposit in certain regions of the site, they must be able to observe more specifics about the objects in those areas in order to decide how and why the deposit collected. Integrating more object attributes and providing ways for archaeologists to visually process those characteristics together can allow them to investigate these specifics and solve the mystery.

| **Task Three: Testing Hypotheses** | Using Traditional Methods | Using New Methods | Using Both Methods Together |
|---|---|---|---|
| **Task is performed by:** | On-site observations combined with evidence from database reports. | Observations of all finds together through navigation and interaction with the record, queries showing specific objects. | Must perform tasks for both methods. |
| **Difficulty:** | **High** | **Low** | **High** |
| **Effectiveness:** | **Poor** | **Good** | **Excellent** |
| **Comments:** | Database reports are 2D-based | Provides a way to pose hypotheses that are difficult to investigate otherwise | Provides evidence for hypotheses |

***Figure 47*** *Task Three – Testing hypotheses with the site record.*

When archaeologists perform **Task Three** (Testing Hypotheses, see Figure 47) via traditional methods, they do so by combining observations from the excavation record with those derived from database reports. Yet, after looking at the results from database reports in chapter 1, we concluded that they are largely 2D based. In particular, the specific find locations of the objects in the Z dimension are not considered. Therefore, it must be concluded that, while archaeologists may believe that a hypothesis is correct based on empirical evidence, it is considerably more difficult to validate that hypothesis using a database approach.

In employing the new methods, they can investigate their hypotheses in a much more rigorous way. Also, by visualizing aspects of the site record they can generate "evidence" for hypotheses (in the form of screen grab footage or other graphics of queries that are conducted). Finally, the method provides a way for them to test hypotheses that are difficult to investigate otherwise. Because they are afforded a comprehensive configuration of the site findings, and the ability to understand many of the spatial linkages between objects, it is much easier for them to test experimental hypotheses. For example, there were a series of roof tiles found throughout the site. Archaeologist A first believed that they had a relationship with the temple proper alone, not other areas of the precinct. This hypothesis cannot presently be substantiated with the site database because the evidence produced from it is not descriptive enough. But, because the objects can be examined in their relative in situ locations using the new method, a substantial picture is provided to elucidate their associations with the architecture as well as the rest of the site.

In conclusion, when the same task is performed with a combination of old and new methods, the results are comparable to those achieved for task one and two. For example, consistently excellent results are achieved when given the ability to perform on-site observations with the tangible aspects of the record, as well as the ability to synthesize the three-dimensional components for a variety of evidence from many years. These results suggest that the new methods provided in the fourth prototype would be best implemented to accompany current on-site excavations and observations.

## 6.3 Strengths and Limitations

In assessing the user performance of the new method in comparison to traditional approaches, we encountered strengths and limitations that must be considered in future implementation processes.

### On-Site Empirically-Based Findings

When archaeologists excavate a site, they become well acquainted with many of its artifacts and site characteristics. Therefore, even though they won't be able to remember every feature and object in a particular trench, they have a good understanding of site trends. For example, since it is not yet possible to depict subtle variations in color and texture in a series of trench loci using the model currently running in the Cave, observing these details on site is necessary. Also, although archaeologists, A and B noticed that the site had a mixed deposit from earthquake and rain damage while using the system, they had initially observed this feature on site. The lesson here is that, on-site observations provide detail that simply cannot, at this time, be replicated using the proposed methods. Therefore, in integrating the new methods with current on and off-site research and analysis processes, an individual method's strengths and weaknesses should be considered.

On-site, empirically-based findings have several deficiencies that the new method addresses. In particular, when three-dimensional artifact attributes are used in conjunction with site and trench features, a comprehensive picture of the findings emerges that cannot be derived from on-site observation (see Figure 48). The picture allows researchers to find connections and isolate anomalies and patterns, and perform basic comparative analyses with the combination of features.

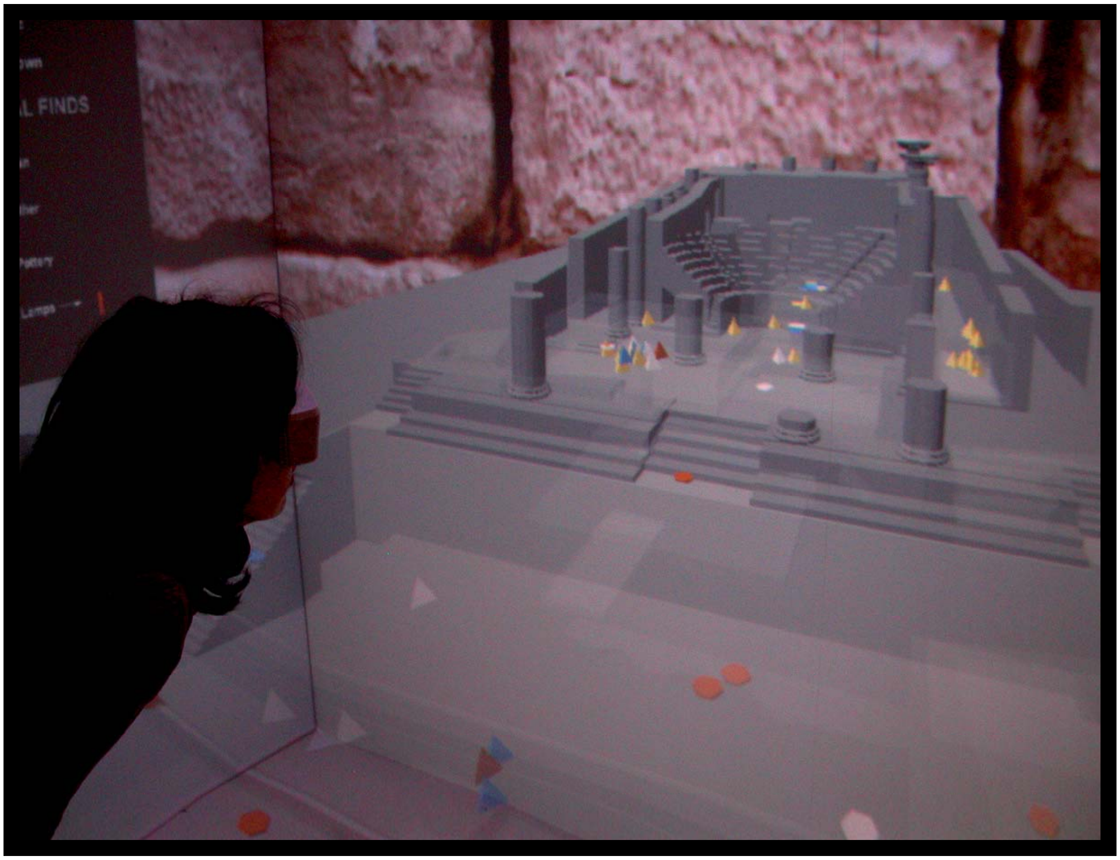


***Figure 48*** *User observing lamps and coin finds in the miniature model. This feature allows archaeologists to synthesize on-site findings in a more rigorous way. However, it cannot provide the same level of detail as the on- site observations.*

**Quantitative Analyses using the Site Database**

The site database alone can be used to generate reports on the percentage of lamps that are Roman vs. Nabataean, Byzantine or Unknown. It can also allow the excavation team to determine how many elephant-headed column capitals were found in various regions of the temple precinct. This information is most useful in providing quantitative proof for hypotheses.[39]

Statistics about site finds such as *pottery* or *bone* and the percentage of each in various areas of the excavation can also supplement on-site findings to the extent that they facilitate new hypothesis formation.

However, given the additional level of insight provided by seeing the objects in their physical locations, those statistically-based perceptions are transformed. Although the site database does not allow archaeologists to understand the attribute variations inside an object group, (i.e., architectural fragment attributes like: Corinthian capital, elephant head, elephant trunk, wall frieze, wall stucco, column fluting), it is possible to derive statistical breakdowns about the distribution of architectural fragments among large areas of the site, e.g., propylaeum, upper temenos, or lower temenos. However, these statistics do not begin to describe an object's physical attributes or its find location. For example, one cannot determine that the artifacts were, in fact, elephant head fragments in the triple colonnades or Corinthian capital fragments in the upper temenos. Visualizations that present the whole context with a variety of objects attributes offer the comprehensive picture of site conditions that archaeologists require. For example, seeing all architectural fragments in their find locations throughout the lower temenos can help support theories on how earthquakes effected the region.

The methods described and tested in this research have several strengths over quantitative methods. To begin with, quantitatively-derived variables and their associated physical information can be visualized together using the new method. Effectively, the current database functions are available along with the other features. Also, an archaeologist can quickly identify the location of a coin or artifact and its relationship to other features and objects. The database alone preserves the find location but not the associated spatial context. Traditionally, since the physical information about the trench is kept in a separate source (the trench notebook) the find location is not currently useable without significant effort.

## 6.4 Visualization, Navigation and Interaction Issues

### Visualization Issues

The archaeologists tested commented that they felt comfortable identifying different variables using the current visualization design. In particular, it was noted that the color and saturation levels chosen for the *in situ* architectural finds (effectively subduing those features) greatly enhanced the users' abilities to focus on the excavation trenches and finds. Yet in looking at bulk finds and special finds together, there was confusion regarding the differences between the two (they were both represented as tetrahedra) even though the lamps were much larger than the bulk finds. One proposed method for eliminating confusion when similar shapes are viewed together is to modify individual shapes. Specifically, for future improvement in this area, we propose developing a more refined visual grammar for artifact types. In particular, we would like to present "accurate" three-dimensional models of lamps, coins and other special finds (i.e., sculpture and pottery objects such as vessels and bowls). It may also be possible to implement a "level of detail" function to instantiate additional object detail as the user interacts with the objects.

### Navigation and Interaction Issues

A non-archaeologist acted as the navigator and performed many of the interaction commands necessary for inquiries using the system. Although the archaeologists (users) were able to focus fairly well on the objects they saw, they were timid about making dramatic movements into new investigative areas. They also had to be prompted to reorient themselves when they arrived in the new areas. For example, we suggested that they look at some of the bulk find combinations at the ground level rather than from above. They commented that they could see more relationships between the different loci from the new viewpoint, lower down and closer to the trenches. However they had to be prompted to performing these multiple perspective investigations.

In the future, we believe that users can have a greater degree of autonomy while using the system if they are given more control of navigation and interaction functions presently controlled by us, the veteran users. Considering that during the excavation process they extract information through direct physical contact with the excavated material, eliminating that possibility here inhibits their natural inclination. Therefore, in the future, we will consider training archaeologists to perform many of the interaction and navigation commands themselves.

## 6.5 Additional Visualization, Navigation and Interaction Features Archaeologists Require

During the process of testing, archaeologists provided feedback about the types of visualization and interaction features they felt they needed to accomplish new tasks. The following is a list of features that could be added.

- Users sometimes need exact quantitative results. If two trenches have high pottery concentrations, users need to visually compare the quantities in each trench. It's not enough to look at them together. Therefore, the user needs a way to ask for exact numbers when viewing specific regions (i.e., 62 pieces of pottery per trench, or 580 pieces in upper temenos vs. lower temenos).

- Users need access to additional variables for some of the objects, i.e., Bulk finds = Pottery = Coarseware or Fineware, Painted or Non-Painted. Users need to understand the variations in the types of pottery represented.

- Users need additional tools to process visual information. Archaeologist A commented that she needed ways to keep track of different features she looked at over the course of examining the site data. This might be resolved by providing screen grabs of significant features to refer back to when needed.

- Archaeologists also need ways to annotate the site features and artifacts to build up a knowledge base that can be shared between users. To achieve this goal, they could be provided with tools to visually annotate features and to save those alterations for other users to access and build upon.

## 6.6 Additional Tasks Archaeologists Would Like To Perform

After testing the system, archaeologists gave suggestions for new tasks they would like to perform. The following list (see Figure 49) includes some of the tasks that could be accomplished in the near future, especially when some additional features like those above are incorporated into the current system design.

| Task: | What's Needed to Complete It: |
|---|---|
| **1. Observe Stratigraphy.** | Current trenches have information on soil type. If more trenches are added a consistent reading of stratigraphy across the site could be provided. |
| **2. See architectural fragments in their original locations to understand how the building collapsed and also where the roof fell.** | This would require the integration of an additional database (the architectural fragment database). |
| **3. Bring in the western exedra trench.** | Modeling additional trenches with survey data and measurements from the trench notebooks. |
| **4. Looking at the different characteristics of the pottery, coarseware and fineware to observe grouping trends.** | Integrating new variables from the site database. |
| **5. North/South artifact distribution patterns using additional trenches.** | Model additional trenches and observe sediment patterns. |
| **6. Roof tile distributions to help determine which sections had roofs.** | Model additional trenches and integrate the architectural fragments database. |
| **7. Elephant-headed capital distributions. Allow archaeologists to obtain clear evidence for hypotheses.** | Model additional trenches and add architectural fragments database. |
| **8. Cryptoporticus under the lower temenos. When was it built, what was found there and what was it used for?** | This will require modeling the trenches in lower temenos and the observation of artifacts in the area. |

***Figure 49*** *Chart presents new tasks archaeologists would like to complete with some additional features added.*

## 6.7 Summary of Results

In the beginning of this chapter, we reviewed a new method for conducting research tasks and compared their effectiveness to traditional on- and off-site methods of analysis. It was found that numerous tasks that are difficult to perform on site were completed with ease using the new method. Because archaeologists were provided with a good visual interface, they successfully performed specific research tasks (synthesizing on-site findings, formulating hypotheses and performing hypothesis testing) with the excavation data.

Many of the visualization problems encountered while testing the system were resolved by modifying the imaging techniques, e.g., color, saturation, shape and form. We were also able to provide users with a few necessary features (miniature model, map and key) to mediate navigation and interaction issues. In the future, we would like to give archaeologists a greater degree of autonomy by allowing them to personally control navigation and interaction.

It has been shown that the methodology is made even more effective when used along with traditional approaches (see Figures, 45, 46 and 47). Implementation of this methodology can have a direct impact on existing site findings and analysis. In spite of its current limitations, it still offers archaeologists a better understanding of the archaeological record when compared to traditional on-site findings alone.

Significantly, after using the fourth prototype, archaeologists were anxious to have additional features implemented so that they could perform a wider range of analysis tasks. In the process of presenting them with the spatial components of the record and by illustrating a variety of high-level analyses, they became convinced of the value of changing their excavation and recording methods (see Appendix A). If archaeologists employ more precise excavation and data extraction methods to record site findings, they will have a greater opportunity to perform high-level analyses using the new methods offered here.

## 6.8 Final Conclusions

Within this body of research, we assessed current methods for archaeological analysis and provided a new method based on the implementation of visualization, interaction and navigation techniques. During the process, several prototypes were built to mitigate specific analysis problems in archaeology. With each successive prototype, new and useful features were added and evaluations were conducted to isolate the issues and implement further improvements. As a result of this iterative process, a final methodology was produced (prototype four) to explore the spatial links in excavation data in an immersive virtual reality environment.

In order to evaluate this method, archaeologists were encouraged to use the research model presented here to observe the record from the Petra Great Temple site and to perform different types of investigations based on their personal research interests. It was observed that during the user tests, the archaeologists were able to substantiate patterns that they had observed while excavating on site and identify new patterns and anomalies in the excavated record. Significantly, they would not otherwise have been able to make these observations. We also found that they performed these tasks with a low degree of difficulty.

The tests demonstrated that employing traditional and new methods together produced the most effective results. In conclusion, although there are some observations that can only be made with the tangible evidence witnessed during the excavation, the methods described here can play a significant complimentary role in analyzing the components of field data that are difficult to understand on-site. In addition, as three-dimensional data acquisition of field data becomes faster and more affordable, the research model presented here will provide a way for archaeologists to manage the new complex spatial characteristics more effectively.

# Appendix A

| Task: | Can Be Completed Using Traditional Methods: | This Method Augments Traditional Methods: | This Method Provides New Information: |
|---|---|---|---|
| **1. Observe associated finds in their *in situ* (excavated) positions and in the context of the site.** | Not Well (empirical observation only) | Yes (but cannot see all attributes at this point, more detail is needed) | Yes (provides a way to synthesize all excavation findings for new types of analysis.) |
| **2. Trace relationships between trenches, trench loci, and artifacts.** | No (trenches are located randomly throughout the site, not together.) | N/A | Yes |
| **3. Examine stratigraphy and locus relationships throughout the site.** | Yes (but only in trenches that were personally excavated.) | Partially (only locus relationships) | Partially (only locus relationships) |
| **4. Look for the relationships between different types of artifacts, i.e. coins and lamps.** | Yes (through the excavation process) | Yes (connections between trenches and the site) | Yes (with a comprehensive group of objects in all areas but without many physical attributes attached.) |
| **5. Discover anomalies in the data set (i.e., Byzantine lamps in the Western Corridor)** | Sometimes | Yes (provides a way to synthesize bulk and special finds) | Yes |
| **6. Formulate new hypotheses based on physical associations.** | Yes | Yes | Sometimes (more detail is needed) |
| **7. Test current hypotheses using the site findings.** | Yes | Yes | Yes (provides proof for hypotheses) |
| **8. Synthesize Data from Years of Excavating:** | Not Well (currently through quantitative reports.) | Yes | Yes (because the excavators aren't familiar with all trenches and artifacts.) |
| **9. Finding patterns in the field data.** | Sometimes | Yes | Partially (more variables such as material and typology are needed.) |
| **10. Perform comparative analysis with objects in physical relationship to research objects. (Coins and lamps)** | Not Well (only compare object typologies and physical features.) | Yes | Yes |

***Figure 50*** *This chart presents additional archaeological research tasks performed using this method and a description of how well they are achieved using traditional and new methods. The middle column indicates whether the standard archaeological method is improved when coupled with the new method.*

# Appendix B

## Standard Methods for Data Capture/Recording

> "The first challenge in heritage work, whether virtual or real, has always been to gather data of existing conditions."[40]

In this appendix, I'd plan to outline some of the new close-range methods emerging for data acquisition that will allow archaeologists and scientists to establish a new paradigm for excavation and analysis. Traditional methods of data capture such as tapes, rulers and digital surveying using a theodolite, although certainly precise, convenient, cheap and mobile, are extremely slow and only the latter method provides measurements in a digital format. More importantly, each of these methods requires the user to register each point separately. In the case of manual measurement using tape, measurements must later be registered digitally, adding another cumbersome step to the entire process. Digital Survey Theodolite and Global Positioning Systems offer speed, mobility and flexibility, but still require the user to register points one at a time by physical contact with the target object.

In the following discussion I will outline some of the traditional methods for data capture and compare them with some of the new, 'contact' and 'non-contact' approaches such as Photogrammetry and Digital Scanning. Perhaps, in the near future, portable and affordable surveys will incorporate this technology and allow site and artifact data to be rapidly captured and recorded. Also, what will be the implications of some of these new methods?

## Digital Survey

A comprehensive field strategy was developed at the Petra Great Temple site at the beginning of excavations in 1993 to provide quantitative, spatial-formal relationships leave architectural, artifactual and ecofactual records. The result was the application of a careful archaeological field method to unearth the edifice and its accompanying artifacts as well as the use of the most up-to-date scientific data retrieval techniques to assure accurate and consistent field data. The data acquired thus far consists of maps, datum and sub-datum points, topographic features, and trench maps with loci. All elevations are being recorded by electronic distance measuring equipment (EDM) and scaled plan drawings are made of all deposits and architectural features. Vertical balks were also recorded by section All of these were recorded with both black and white print and color slide photography.

Field strategy at the Great Temple site relies on Digital Survey equipment to map site features, architecture plans and trench outlines. All other measurements are recorded by individual surveyors using manual measurement techniques such as tape, rule and calipers to capture elevations, trench plans, sections, layers and individual artifacts.

## Plane Survey

Traditional surveying is called plane surveying, which does not take into account the curvature of the earth. For most surveying projects, the curvature of the earth is slight enough that the effects can be ignored, greatly simplifying the calculations involved. In larger surveyed regions, such as the area surrounding Petra, geodetic surveying or surveying which takes into account the earth’s curvature must be used to ensure accuracy and measurement agreement between different surveyed regions.

In plane surveying, measurements are typically gathered with a *theodolite*, an instrument that is set up over a recoverable point. The theodolite combines the capabilities of a telescope (to span large distances), a ruler (to derive measurements) and a protractor. The telescope is used for sighting over a range of distances and has much greater precision than the unaided eye. In modern equipment a laser works with the prism to capture measurements.[41] The laser is used in conjunction with the prism to measure slope distances and a digital readout provides angular measurements of the horizontal and vertical planes. Using trigonometry, these measurements can be used to derive x,y,z coordinates for each point measured. The vertical angle and slope distance are converted from polar measurements (angle and distance) to provide a difference in elevation (delta Z coordinates) and horizontal distance. The horizontal distance and horizontal angle are converted from polar measurements to rectangular coordinates (delta X and Y coordinates). Using the digital survey equipment to measure points, the surveyor can generate different types of maps for different purposes. For example, a topographic map represents the three-dimensional aspects of terrain. Surveying at the Petra Great Temple site coupled a Topcon laser transit station with the COMPASS/Foresight program, a survey data acquisition and plot program that was developed at the University of Pennsylvania Museum.[42]

Accuracy and speed using plane survey methods and a theodolite, although faster and more accurate than hand-measure, are extremely slow and cumbersome. Estimated time using a manual measurement technique (hand measure, tape, ruler, calipers) runs around 0.01 points taken per second, with a range up to 50 meters and accuracy around 1mm. Time using digital survey with theodolite is around 1 point per second, with a range up to 1000 meters and accuracy about the same as by hand at 1mm.[43]

Generating low-resolution topographical maps or digital terrain models can be done fairly easily using digital survey methods. However, where more detail is needed, i.e., architectural and other important excavation features, the time needed to take each point and process coordinates to generate a plan is so time consuming that important detail is often left unrecorded (i.e., individual stones or floor detail, see Figure 51). [44] In the recent history of Brown University excavations at the Petra Great Temple, surveying has played a central role in excavation planning and recording strategies. During this time, surveying has focused on producing top plans of the architecture and trench outlines. Essentially, the surveyor spends time shooting in points, one at a time, to build a highly-detailed top plan of *in situ* architecture in the Petra Great Temple region and in the immediate vicinity.

The objective of the survey is to provide highly accurate measurements of the temple precinct and surrounding area so that all associated data, (drawings and objects) can be properly placed in the matrix of the site. Individual excavation teams augment this effort with scaled drawings showing a top down view (and sections of architecture and balks) of their trench and the region directly surrounding it. The drawing of the theatron in Figure 51 was produced as an addition to the surveyed features. In this case, a great deal of detail in the areas between surveyed walls and floors was added. The estimated time spent to produce a drawing like this is equal to the surveyed time needed to collect 4,556 vertices plus the time it took the archaeologist to draw the top plan with the added detail.

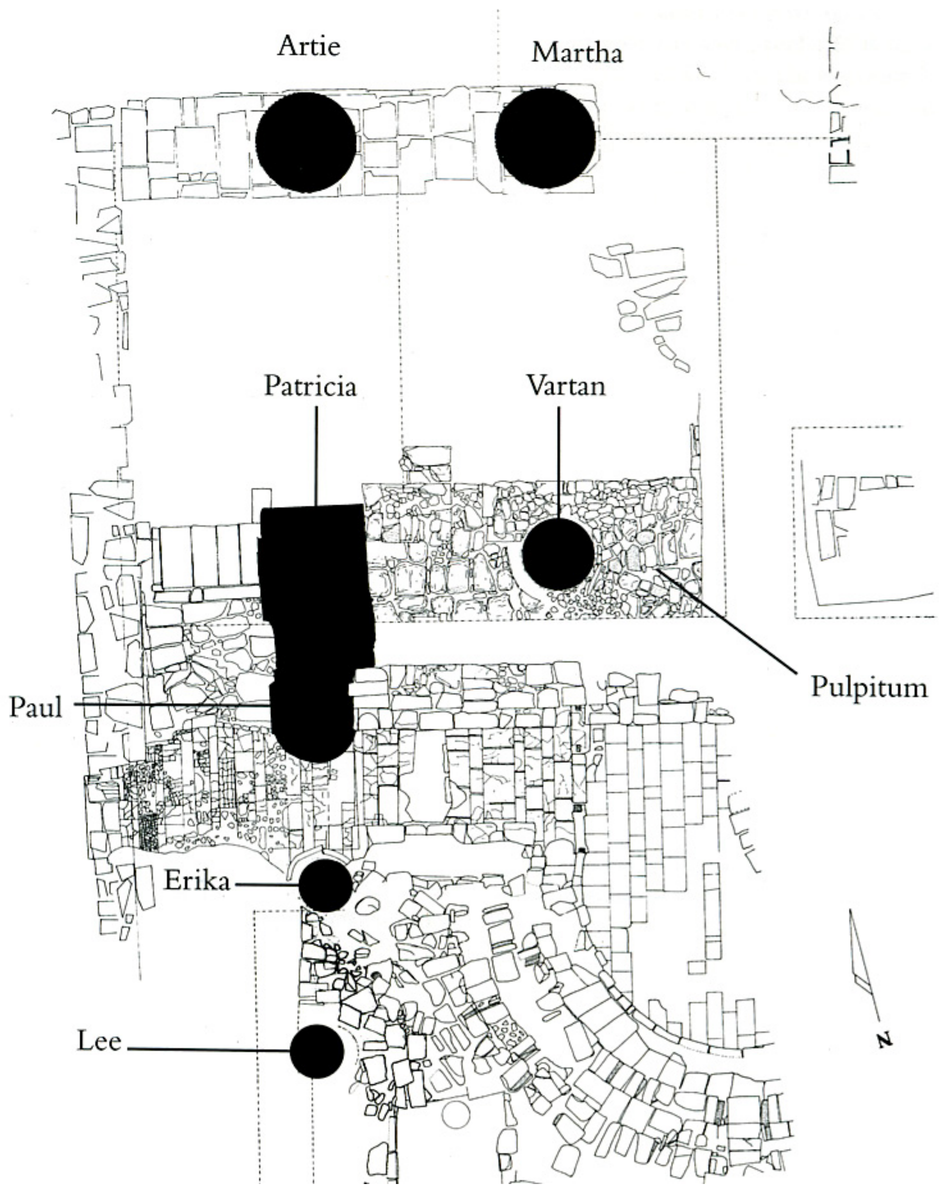



***Figure 51*** *Top plan of the theatron and immediate surroundings. Drawing by Martha S. Joukowsky, 1997.*

**Global Positioning Systems**

The Global Positioning System has become a popular survey option because it is mobile, efficient and easy to use. The Global Positioning System is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. The system was built and is maintained by the United States Department of Defense to communicate global location for navigation and mapping measurements and recording. In the early 1980s, the U.S. Department of Defense began to deploy the satellites intended for U.S. military use to obtain accurate navigational and positional locations. The satellites broadcast a coded signal that can be accessed with a receiver by air, water and ground location. Four GPS satellite signals are used to compute positions in three dimensions. Receivers can accept several grades of signals, which vary by accuracy and cost. Civil users can access SPS grade GPS signals without charge or restrictions. Most receivers are capable of accepting and using the SPS signal. The SPS accuracy is intentionally degraded by the Department of Defense by the use of Selective Availability. This essentially means that a degree of artificial error is introduced into the signals projected to reduce the accuracy to potential hostile users. Accuracy is reduced for SPS users to 100 meters. Commercial or Survey grade GPS units have accuracy ratings around 20 meters but are expensive. DGPS improves the accuracy of the GPS positions to about 10 meters.

Within a measurement project, Global Positioning System devices can be used to shoot approximately 1 point per second, with a range of 1000 meters and an accuracy of about 50mm. Even though GPS receivers offer ease and mobility for the user, they are not more effective or accurate than total station survey equipment. Therefore, at this point, GPS systems are being supplementally used with total stations that produce more accurate global positions.

**Photogrammetry**

Alonzo C. Addison and Marco Gaiani have outlined some of the existing methodologies for three-dimensional data collection, dividing the known strategies into “contact or touch” and “non-contact or camera” methods.[45] Photogrammetry falls into the contact category even though taking photographs of desired locations and objects does not require physically carrying a target or probe to each point or feature. This is so because registering three-dimensional coordinates requires the manual selection of each point in processing the images taken in the field. A variety of products and software now employ photogrammetry for three-dimensional survey tasks. In addition, there have been a number of published archaeological surveys using photogrammetric means to document sites and artifacts (see Gillings 2000; Astorqui 1999; Doneus 1996, Böhler 1996).

The field is generally divided into two categories: aerial photogrammetry (far range) and terrestrial photogrammetry (close-range). Aerial photogrammetry is often used to generate topographical maps and digital terrain models. Terrestrial photogrammetry is commonly used to survey architecture or to document objects within a range of about 100 meters where specific details of scenes and objects can be captured.

Photogrammetry is the science of measuring objects from photographic media (photographs or images stored electronically on tape or disk). Photogrammetry uses the basic principle of Triangulation, to compute the location of a point in three dimensions. By taking photographs from at least two different locations, optical rays or "lines of sight" can be developed from each camera to points on the object.[46] These lines of sight are mathematically intersected to produce the three-dimensional coordinates of the points of interest. By mathematically intersecting converging lines in space, the precise location of the point can be determined. In a three-dimensional Cartesian coordinate system, the origin commonly defines the position of a point in space. The scale and orientation of which can be arbitrarily defined. Therefore, it is necessary to convert all coordinates between systems having different origins, orientations and scales. The coordinate transformations are derived in the photogrammetric process by methods of scale change, translation and rotation.

**A Test Survey:**

A general procedure for documenting archaeological features and producing three-dimensional simulations of those features will be covered here using software that employs the principles of *terrestrial photogrammetry*. The photography for the study was completed during the 1998 summer excavation season at the Brown University excavations at the Great Temple site in Petra, Jordan. During the fall of 1998 and the spring of 1999, photographs were used along with an EOS software package called PhotoModeler Pro to produce three-dimensional models of a section of the pronaos and the West Corridor of the Petra Great Temple site.

The objective of the survey was to determine if a simple, portable and affordable method such as desktop photogrammetry could be used in conjunction with digital survey equipment to document archaeological remains. Currently, archaeologists on site use a cumbersome and time-consuming method of drawing and hand measuring to document architectural finds. This process can take one person up to four hours to document a standard elevation.

***Figure 52*** *Three photographs showing the ring method used for documenting features. These were taken with an "amateur" camera. Notice the four fiducial marks in the corners*

**Photography**

Photographs of the entire project must be taken with the knowledge that, for processing accuracy, one will need three images of elements with a good degree of angular separation between each image. The shots in Figure 52 illustrate the basic method for capturing a simple architectural elevation of the base of a pier in the Temple Proper region of the Petra Great Temple. Each photo is taken at a different position but there is enough overlap to reference features in at least two of the images. For a facade survey it is best to have a minimum of three overlapping images. However, if the project scale is large and it is necessary to capture details at close range, more images will be needed for processing. In this instance it is advisable to take rings around elevations or features to ensure that every section of the edifice is captured. Also, in some cases, it is very difficult to get consistently clear shots of each feature from multiple angles. This sometimes happens because camera settings are set at fixed focal lengths, making it difficult to get good shots, which are still in focus at a variety of target locations. In capturing the West Corridor of the Petra Great Temple, it was necessary to take incremental shots at one-meter intervals to ensure that all areas of the wall would be well documented (see Figure 53).

***Figure 53*** *Shows the West Corridor of the Great Temple. This region is difficult to document because it's not possible to get clear shots of the whole elevation. In this instance it was necessary to take close-range shots of the various sections to ensure that the elevations could be reconstructed with wall detail.*

**Registration, Referencing and Scaling**

After taking photographs (film or digital) of the entire project, images are processed to generate a model. Each image used for analysis must be marked and referenced with all associated photographs. In order to generate an accurate model to use for the archaeological record and for analysis, a fair amount of human interaction is required. Each image must be marked and processed to register the camera's parameters. This step is solved with the help of the fiducial markings in the four corners of each photograph (see Figure 53). After this step three-dimensional points are marked and connected by lines on each image and then referenced by the association of points between images. This can be an extremely tricky process in the event that points and lines connected on the various features are not geometrically regular. For example, in marking the photos of the façade in Figure 54 there was no clear horizontal surface to mark so points had to be chosen along the eroded surface at the top of the pier. Also, it was difficult to align the chosen points in the two photographs because it lacked a clear corner. This problem occurs fairly often when attempting to document aging remains, as they often have sustained damage and erosion. Fortunately, once points are defined and referenced in two images, the related lines are established automatically.

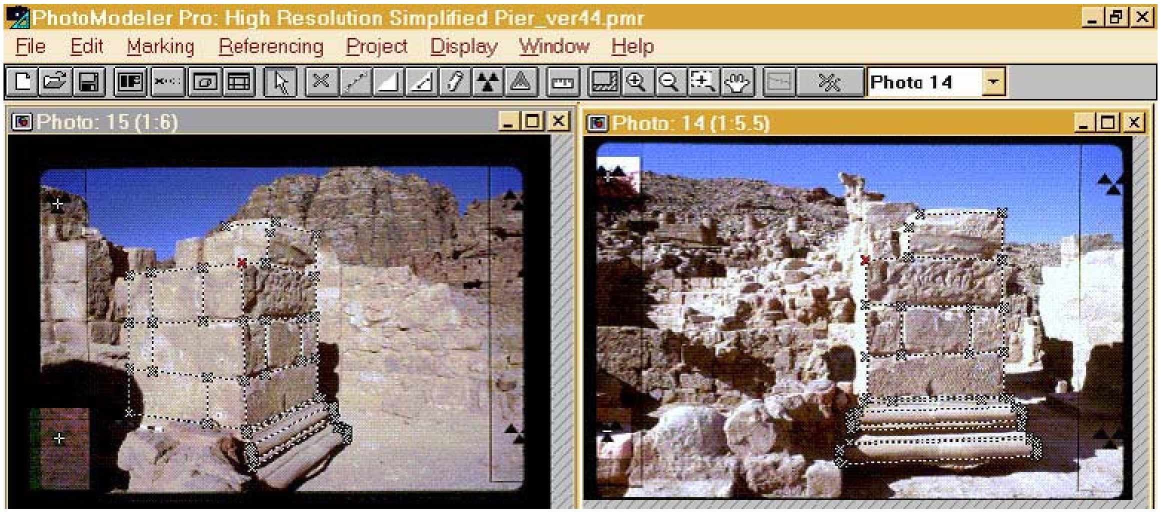



***Figure 54*** *Marking and referencing related photos. The red marks define related points in each image.*

Registering and referencing the various images is by far the most time-consuming part of the whole model-building procedure but there is a third key step in obtaining a full solution. Each set of images must be properly scaled to establish the measured relationships within the triangulation process. This is accomplished by assigning the real distance between three set points in each image. This can also be done somewhat automatically by defining values in one image that are already referenced throughout the set.

One must expect that marking each image, referencing like points on at least three images, assigning a scale and combining the processed images into a set to be solved algorithmically will be a very lengthy and sometimes frustrating process (see Figure 54). For example, unless the images are taken at good angle separation, with an acceptable overlap, it is difficult for the algorithm to generate a solution. When this happens, images are often rejected or left out of the solution. In the survey example, substitute images were not available and traveling back to the site to gather more was not an option.

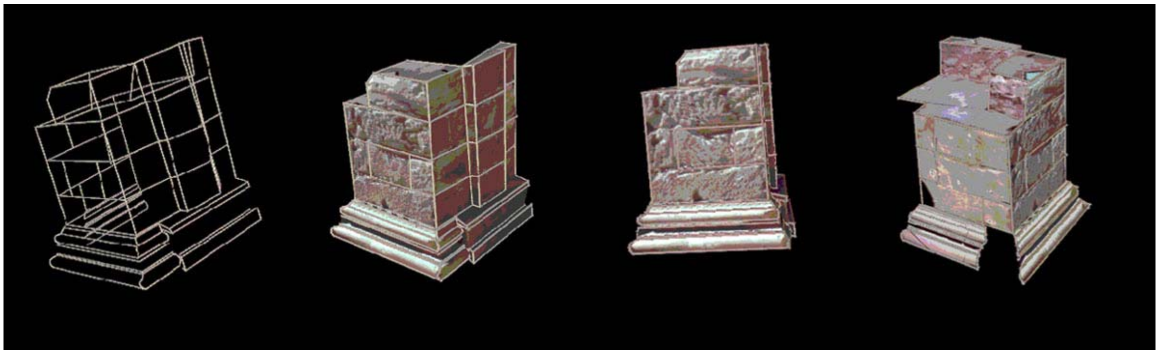


***Figure 55*** *After the images are marked, referenced and scaled a solution model is generated algorithmically. This model represents the pier feature of the Great Temple in the marked photographs from* ***Error! Reference source not found.*** *above.*

After marking, referencing and scaling a small region or feature, it is preferable to initiate the solution process and to generate a model (see Figures 55 and 56). This way, the model can be exported into another Cad-based modeling program and other elements can be added as they are built. By doing this, the user avoids introducing new features into the solution set and risking a failed solution.

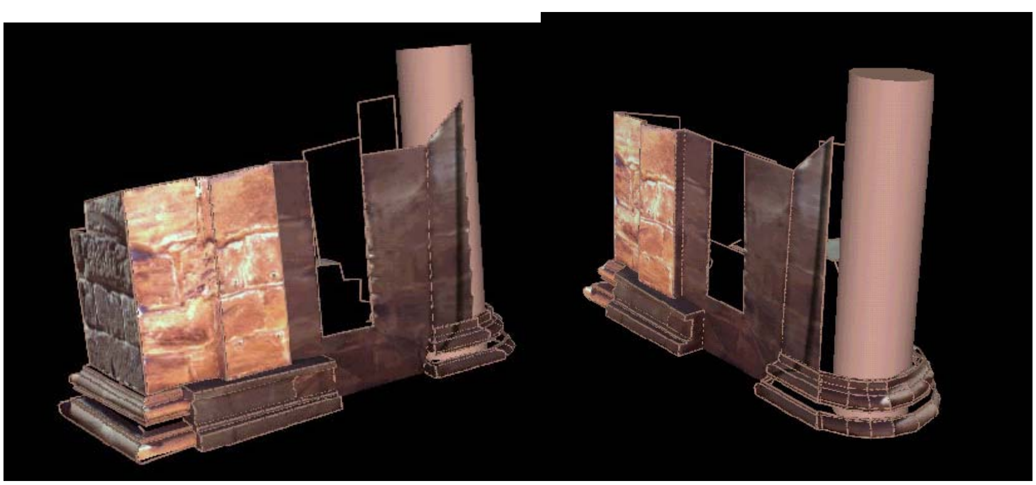


***Figure 56*** *In this model the engaged column and attic base has been added.*

**Results and Accuracy:**

The software literature for PhotoModeler Pro suggests that using photos with sub-pixel level control points, good angle separation, sufficient overlap, high contrast and good camera geometry can produce point accuracies as high as "1 in 20,000" depending on the project size.[47] However, in accuracy studies conducted by Klaus Hanke, point locations generated by metric and 35mm cameras using the PhotoModeler Pro software were compared with those taken by theodolite survey.[48] His summary concludes:

> "The results in general are very promising; the achieved average accuracy for distances between points lies in the range of 1:1700 (7.1 mm) for 35mm camera, with no lens distortion compensation, to 1:6500 (1.9 mm) for a metric camera of the object's size (12m)."[49]

Hanke also derived an accuracy rate in surveying the same points with a Leica T2002 high precision theodolite in a range from 1.0 and 1.5 mm absolute (a similar accuracy rate was derived by Addison and Gaiani 2000).

Ranges derived by EOS Systems:[50]

| | | Approximate Resolution | | Approximate Precision | |
|---|---|---|---|---|---|
| Camera | Pixel Count | Ratio | 50' Object | Ratio | 50' Object |
| PhotoCD / 35mm film | 1536x1024 | 1:1400 | 0.4" | 1:1100 | 0.5" |
| Mid. quality digital | 1500x1000 | 1:1400 | 0.4 | 1:1100 | 0.5" |
| High quality digital | 3000x2000 | 1:2800 | 0.2" | 1:2240 | 0.3" |
| Low-end digital | 640x460 | 1:600 | 1.0" | 1:480 | 1.25" |
| Video camera | 400x300 | 1:380 | 1.6" | 1:300 | 2.0" |

***Figure 57*** *Table from EOS Systems showing equipment expected resolution and accuracy.*

In processing the Petra Great Temple model, point locations had to be compared and produced by the software with those captured by our site surveyor with a theodolite system similar to the one described above. The accuracy of point locations in our model generally ranged from 5 mm or 1:400 in areas where we were able to get clear shots, up to 150 mm or 1:200 in parts of the West Corridor where we had trouble obtaining proper angles separation between photographs.

We concluded that using a desktop method to document the remains at the Petra Great Temple site would only be feasible in areas where there is a clear field of view, or by improving the method with further testing, better camera methods and control-point marking. A similar survey procedure was employed for producing three-dimensional models of the Negotiating Avebury project on the Neolithic henge complex of Avebury, in the southern United Kingdom. In results from that survey it was found that improving target visibility, using hand annotated Polaroid photographs to guide the face creation process of each stone, and ensuring that at least 12 photographs were taken of each feature, improved their results.[51] However, they did not include statistics on the quantitative accuracy of the method. Our survey method did not produce levels of accuracy comparable to the digital survey methods used on site from the beginning. In addition, unless clear evidence documenting a reduced accuracy range in hand measurement methods used for producing elevations is presented, using photogrammetric means will not be practical.

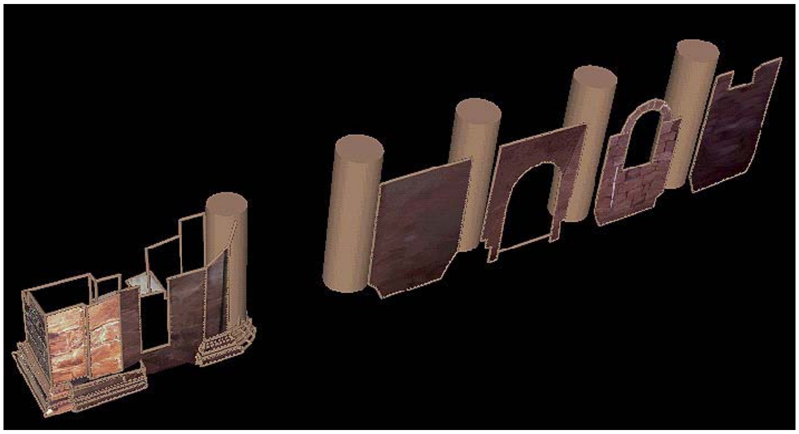


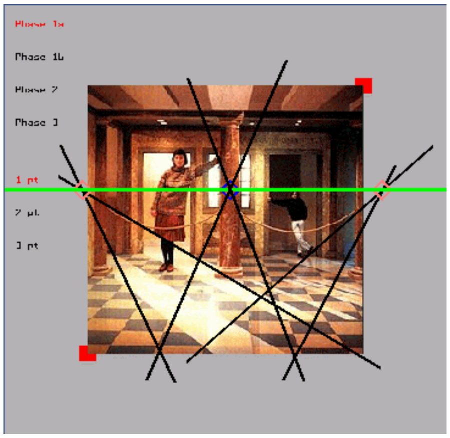
***Figure 58*** *The final model of the West Corridor. Errors in the algorithm solution prevented the modeling of individual stones in the back segments of the hallway. Also, because the photos taken of the back hallway were underexposed, associated texture maps look dark and blurry.*

### SkiP - 3D Reconstruction Using A Single Photograph [52]

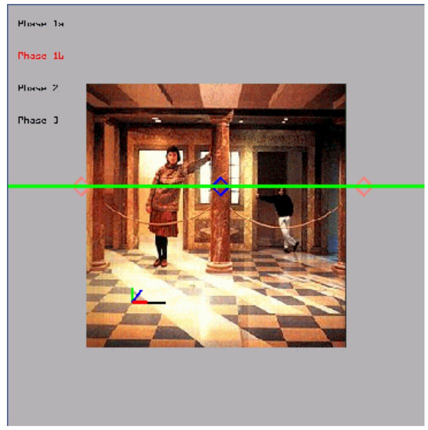
One of the research topics under investigation in the area of Computer Vision, is the ability to fully automate the process of photogrammetry described above. Using an application called SKiP (Sketch in Perspective), developed by the Brown University Computer Graphics Lab in conjunction with the Department of Engineering, a prototype was developed and tested to determine if the automation of the steps necessary using photogrammetry could be bypassed to produce faster yet less accurate three-dimensional reconstructions for archaeology.

There are several steps necessary to produce three-dimensional models with this software but they can be accomplished with fewer interactions than photogrammetry software. Assuming an image was taken with a central projection with no lens distortion, the user can specify camera parameters by interactive extraction (see Figure 59, phase 1a). Next, the user selects a reference frame and metric length (phase 1b). Before starting a reconstruction, the camera parameters are interactively verified and adjusted if necessary. Finally, the user can begin building a reconstruction based on image cues (phase 2 and 3, also see Figure 59). For example, any features in the photograph can be traced or built based on information in the image.

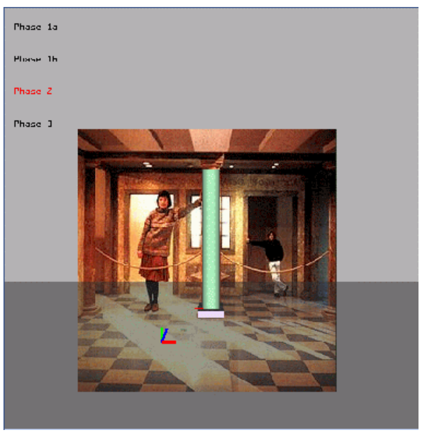
This method of reconstruction offers the advantage of automation with minimal interaction but it is not as precise as some of the other methods reviewed in this section. In addition, objects and features modeled using this method can only be described from one viewpoint. This limits the amount of evidence recorded, and can cause problems in modeling objects with more complex, asymmetrical geometries. However the main advantage is one of simplicity: interaction with a single image at a time. Extending this method and allowing for the use of a sequence of single perspective views "around" an object or scene could achieve better accuracy.



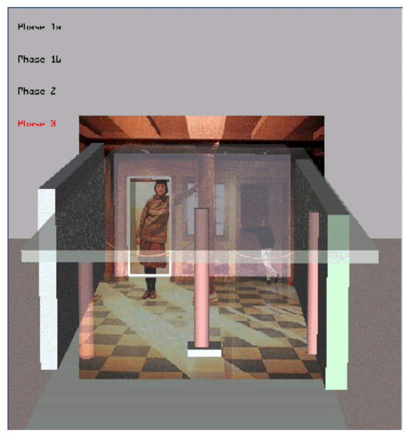
Phase 1a: Retrieve perspective cues for one point central perspective.



Phase 1b: Position reference frame and input metric



Phase 2: Build the central column.



Phase 3: Move columns, walls; roam around.

***Figure 59*** *Three step procedure to process image and begin reconstruction.*

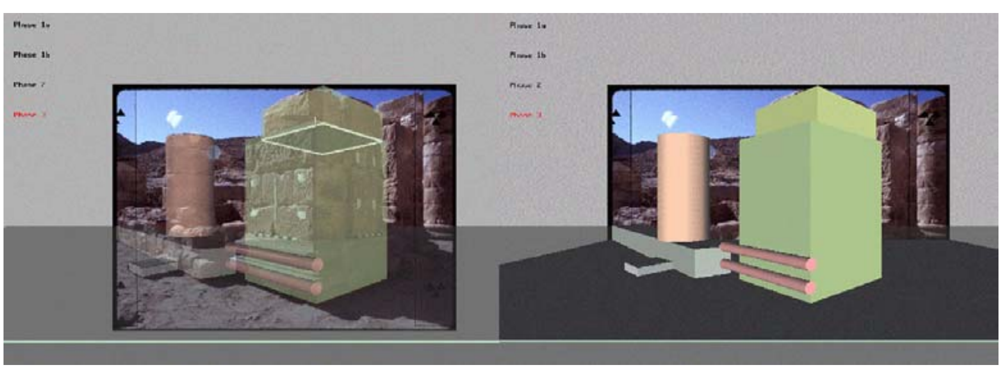


***Figure 60*** *Reconstruction performed using the same image of The Petra Great Temple as was used in the photogrammetric survey above.*

**Three-Dimensional Scanning Technology:**

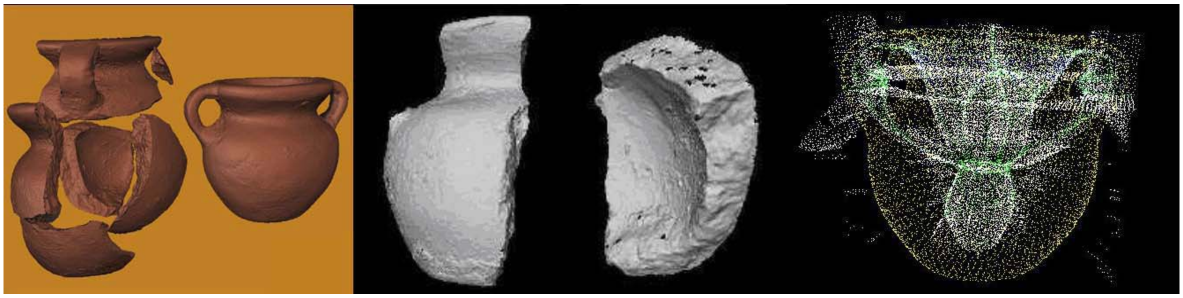


*Figure 61 Three dimensional laser scanning technology can capture up to 15,000 point locations per second. In order to test the system, two jugs were scanned, one complete and another broken (left), to establish whether the vessel could be automatically fit. Several scans of the jug exterior and interior were meshed together to provide a cloud of points (right). Later, photo textures were fitted.*[53]

Current laser scanning technologies employ different methods to acquire three-dimensional point locations from objects, including: structured light, moiré fringe, shape from shading and active stereoscopic. These methods vary in speed, accuracy and cost, as well as in their ability to extract and process data from different types of objects and surfaces. Most of the issues encountered in attempts to record artifacts, architecture and features of the archaeological record via laser scanning technology can be discussed in the following section on structured light methods.

**Laser Scanning:**

The process of laser scanning is similar to methods of image data collection described above in that it also offers a way to measure the distance between two points via optical means. However, it produces three-dimensional points in an automatic way by projecting a pattern of laser light on to an object. A camera works in association with the laser and surface shape is deduced from distortions in the projected pattern. The depth is derived by triangulation.

Current hardware incorporating structured light to capture three-dimensional points in space can automatically extract up to 15,000 points during each 2-3 second scan. The relationship between the gathered points or “cloud of points”(see Figure 61), accurately describe the object being captured.

In contrast to some of the other laser scanning methods, structured light can only be used effectively at close range and offers a fairly narrow field of view. However, it is highly accurate, within the range of .1mm – 1mm, as well as being portable and fast.

**A Highly Detailed Record:**

The additional data points captured by laser scanning techniques provide information on elements otherwise too complex to model using conventional three-dimensional techniques. A number of Cultural Heritage projects use three-dimensional scanning technology because it offers a rich degree of resolution in capturing objects that would otherwise be recorded by less accurate means. Scanning offers archaeologists, historians and conservationists the ability to generate a permanent record of a site.

In assessing the usefulness of scanning technology for recording finds, one might ask why there exists a need to capture additional detail. The project initiated by a Chinese team to document The Terra Cotta Warriors and Horses seeks to record highly detailed scans of the Terra Cotta figures to establish a record of the unearthed state of the objects and to facilitate preservation.[54] In this case, objects are captured by scan technology in their *in situ* locations so that the team can attempt to reconstruct damaged figures interactively with derived three-dimensional models. Therefore, additional detail is needed to establish clues for refitting. Furthermore, research has shown that some of the difficulties they face in matching and refitting remotely are alleviated in cases where excavators have attempted to refit on site. This fact leads them to believe that greater and more realistic detail is needed in laser documentation efforts.

**Issues:**

Unfortunately, capturing excessive detail (both point locations and color associations) come challenges current data storage capabilities, as well as the equipment necessary to use the resulting models (both hardware and software). Also, it is not always prudent to capture the same level of detail for all objects (for example, architecture and site features vs. sculpture and pottery). In considering these issues, it is most practical to consider alternate data acquisition methods for tasks that do not require the level of detail that scanning can provide.

**New Methods, Implications of New Technologies for Fast and Affordable Data Capture:**

In reviewing some of the more standard data acquisition technologies used in excavation procedures, it is obvious that no one method can provide a global solution for all the different data types encountered on site. This is especially so in cases like the Petra Great Temple where it is not only necessary to gather general site and architectural features but also, details of small scale finds in the excavation trenches such as pottery, sculpture, coin and bone. However, it is not difficult to see that the current methods employed are inadequate both for capturing important information and for providing a dataset that can be analyzed properly in post-excavation procedures. In addition, in the words of lead Archaeologist, Martha Sharp Joukowsky:

> "The process of conducting measurements manually and recording the details in the excavator's unwieldy field notebooks is time consuming, tedious and subject to inaccuracies." [55]

Financial considerations prevent researchers from obtaining equipment and the associated means to upgrade current methods. In looking at many of the new techniques evinced in the variety of published case studies, these processes are certainly not any easier, faster or cheaper than current paper-based means of record keeping. This is, however, no real argument because we have seen that paper-based data recording strategies do not augment real scientific method.

During various discussions regarding "ideal method" for data capture and record keeping, the possibility of automatic or semi-automatic, high-accuracy, fast and affordable methods have been described. One possible scenario for the process would include a means to capture site features and geography without the time-consuming and labor-intensive plane survey method described above, as well as a means to capture three-dimensional information about the individual trench and all associated layers and finds as it is excavated. A proposed solution is presented in a paper called "Acquisition of Detailed Models for Virtual Reality," by Pollefeys, et al. [56] They describe two methods, the first of which is a surface reconstruction method using a one-shot range sensor and a three-dimensional reconstruction from uncalibrated image sequences. The latter method presented describes a process similar to desktop photogrammetry but which is far more automatic (with minimal human interaction) and facilitates the gathering of three-dimensional information and texture from a sequence of photographs or video. The method gives archaeologists a way to generate three-dimensional information about the site from unregistered aerial photographs for general site information, and models of architecture and trench information from photographs taken at a closer range. Although there are several problems with the method (models generated with this method are still too coarse to be used as records of site and objects), its continued development could lead to several possibilities for improved site recording and analysis. For example, if three-dimensional information could be recorded easily with digital or film cameras, a system of four cameras (set to take exposures every few minutes) could be set up above a trench to capture information as it is excavated thus alleviating the need for excavators to stop for recording every time an object is unearthed.

**Final Thoughts:**

In considering the implications of some of the methods described in this section, it is obvious that applying new and better methods for data acquisition could open possibilities for improved archaeological discovery and analysis. If, as it has been shown, data recording strategies consume such a large percentage of site excavation efforts, implementing faster and more accurate methods could allow excavations to produce a larger and more diverse archaeological record. In addition, better strategies for data recording will directly affect analysis possibilities proposed in the new research methods outlined below.

Many of the current methods of data recovery and recording represent solid progress in the battle to document complex physical associations that exist in the archaeological record. Significantly, in developing new analysis methods using scientific visualization and interaction techniques, we are forced to consider the constraints imposed by current data recovery and recording strategies. However, it should be noted that as new data recovery methods are implemented in the field, larger and more complex datasets will result. Therefore, in the near future, visualization solutions will become more and more necessary to make sense of the increased complexity.

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