Discovering Petra: Archaeological Analysis in VR

Eileen Vote, Daniel Acevedo Feliz, David H. Laidlaw, and Martha Sharp Joukowsky
Brown University

In field archaeology, analysis of an excavated region is a meticulous process requiring exploration at a variety of levels. While the act of excavation offers the best way for archaeologists to monitor close-range details, they can use empirically based analysis to analyze only the findings to which they themselves have been exposed. With a team of people excavating, synthesizing the wealth of observation from one year to the next is difficult. Archaeologists also use quantitative methods to compare findings throughout the site over time to pinpoint base trends among recorded artifact typologies.[1] Quantitative approaches, unfortunately, are often limited because they lack a spatial component—explicit information about the physical 3D relationships among the excavated objects and the site.

New tools give archaeologists access to formerly inaccessible parts of the archaeological record. The result is a demonstrably improved model for inquiry to pose, and answer, important research questions.

In this article, we chronicle a collaborative effort (from 1997 to the present) with Petra Great Temple archaeologists to augment traditional analysis approaches. We introduce new archaeological analysis tools that combine novel visualization and interaction techniques within a Cave Automatic Virtual Environment (CAVE).[2] These tools

- give archaeologists access to formerly inaccessible parts of the archaeological record;
- support navigation and interaction with virtual trenches, stratigraphy, artifacts, and architecture; and
- preserve and display the spatial relationships present before excavation.

Using an iterative approach and working with archaeologists from the Brown University-sponsored excavations at Petra, Jordan, we built four successive prototypes, each of which refined tools from earlier prototypes and added new tools to help users query, navigate, and explore site findings in three dimensions and at different scales. The tools incorporated new visual representations for the many data values associated with each artifact to highlight patterns and anomalies in the record.

Evaluation of the fourth and final prototype shows that our system provides an environment and tools that facilitate empirical analysis by familiarizing team members with data from many years. It also lets multiple team members corroborate observations while examining the record together. Finally, it provides a model of the excavation site where quantitative results can be visualized in context with other aspects of the data collected on site. The "Related Work" sidebar discusses other researchers' efforts to develop similar tools.

Petra Great Temple

Figure 1 shows Jordan's Petra Great Temple site, which was the underlying focus of our archaeological tool development. Some of the most important research questions archaeologists at Petra ask during excavation and site analysis include these:

- What's the chronology of the architectural phases at the Petra Great Temple precinct?
- What was the temple's function?
- What did the Temple look like before it was destroyed?
- During what time period was the temple and its precinct in use?

Archaeologists establish hypotheses and use a variety of on- and off-site inquiry methods to answer these questions, as the "Archaeological Analysis: Current Practice" sidebar (on p. 40) explains. Unfortunately, it isn't always possible to answer them using traditional approaches alone. If given new methods to analyze aspects of the archaeological record that are currently difficult to analyze, archaeologists' ability to resolve crucial questions will be enhanced.

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Related Work

The search for new methods to analyze excavation findings began around the time that archaeologists standardized data-collection processes for cataloging field information in the latter part of the 20th century. Archaeologists quickly adopted quantitative methods to analyze their findings because they now had immense amounts of physical data. Yet most of these approaches failed to use the 3D components of the archaeological record for postexcavation analysis.

Early approaches

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 findings. He developed Grafland, a simulated excavation tool consisting of a series of topological layers with various features cut into them.[1] This tool was intended to demonstrate that archaeologists can produce realistic records of the data destroyed during excavation and employ improved methods for managing and interrogating the data for postexcavation analysis. However, because of inaccuracies in how the data were recorded, Grafland was used primarily as a teaching and simulation tool, not for the specialized research tasks archaeologists perform as described in this article.

CAD and GIS

More recently, archaeologists have begun to integrate physical aspects of the excavation by employing methods derived from geographic information system (GIS) and CAD-based applications. Unfortunately, because many of these application methods have been adapted from those created for disciplines such as geography, meteorology, and physics, for example, they don't give access to the tools archaeologists need to effectively manage conditions peculiar to archaeology.

A number of visualization systems employing immersive virtual reality (IVR) have attempted to use GIS to handle large data sets such as those presented by climatological data and the urban environment. Sandbox, for example, was developed as a VR tool to let an investigator visualize the contents of a climatologic database while retrieving data.[2] The tool is significant because it gives scientists a means to interact with a variety of data using visual clues. However, it focuses on completing tasks with a 2D climatology data set. Although this system gives users a way to explore and interact with data, the research problems addressed differ markedly from the ones archaeologists face in dealing with data having a strong 3D component.

Karma VI is a VR interface for ESRI's Spatial Database Engine that supports powerful visualization, manipulation, and editing of standard GIS data in a VR environment.[3] Users of this interface can walk through 3D environments, see planned buildings, and view changes in the landscape. The tool lets users experience the data set at close range and access important statistics. However, these IVR applications weren't developed for archaeological inquiry and therefore don't consider the specific research tasks archaeologists need to perform.

The research reported in this article builds on the methods developed in GIS and CAD packages. It also incorporates the spatial paradigm employed in recent visualization projects to facilitate the interrogation of 3D attributes from the archaeological record.

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2. A. Johnson and F. Fotouhi, "The SANDBOX: A Virtual Reality Interface to Scientific Databases," *Proc. 7th Int'l Working Conf. Scientific and Statistical Database Management*, IEEE Computer Soc. Press, Los Alamitos, Calif., 1994, pp. 12-21.
3. R. Germs et al., "A Multi-view VR Interface for 3D GIS," *Computers & Graphics,* vol. 23, no. 4, pp. 497-506.

Photo courtesy of Brown University/John Forasté

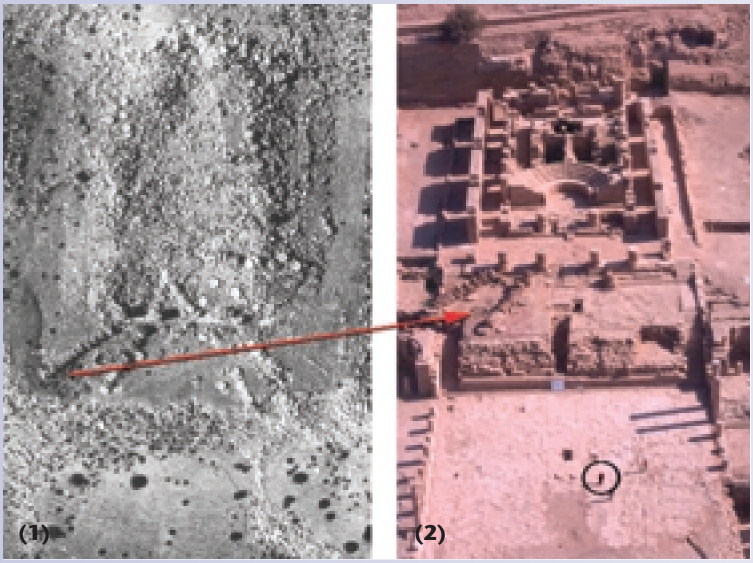
1 Archaeologists working in a Petra excavation trench that measures approximately 10 meters deep. Findings from each sediment layer (locus) must be carefully indexed for off-site analysis. Once away from the site, archaeologists typically have no way to access the spatial relationships that are important for analysis.

Archaeological Analysis: Current Practice

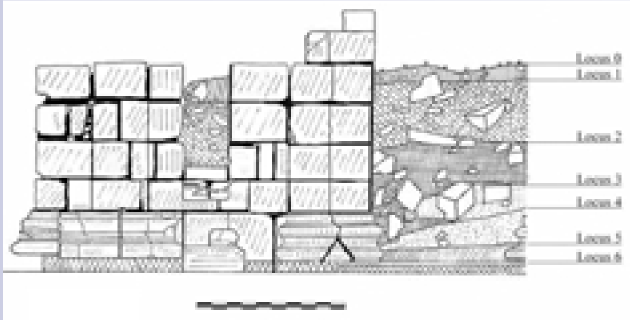
Archaeologists are concerned with maintaining accurate records of the material unearthed during excavation because when excavation is completed, the site is essentially destroyed (see Figures A1 and A2). The archaeological record generally comprises items in diverse media such as paper-based records (maps, plans, elevations, sections, and drawings), photographs of artifacts and architectural finds, digitally preserved survey data, and detailed statistics on artifacts stored in a site database.[1] During postexcavation analyses, archaeologists attempt to synthesize their on-site observations with details contained in these records.

Much of the data collected on site isn't used during the final analysis process because the spatial components of individual artifacts, architectural finds, and site features aren't adequately synthesized. For example, although there may be relationships among the artifacts found in an adjoining trench, if the two trenches were excavated separately by different archaeologists during successive field seasons, the relationships will likely be missed. Figure B shows the different loci, or sediment layers, at an excavation that could represent work done by half a dozen different archaeologists over as many different years. Trends that connect the trenches can only be identified if the same archaeologist is involved to visually identify them. In the postexcavation process of analyzing artifacts, their connection can be correlated only if their in situ spatial relationship is understood.

The difficulty in relating findings that are inherently three-dimensionally linked is hard to alleviate using current methods. Such methods would require an enormous amount of time to physically correlate artifacts and associated finds inside a trench with those in adjoining trenches.[2,3] Archaeologists who want to explore these relationships must first search for the relevant objects from specific locations in the site database. Next, they must investigate the physical information about the trench and trench loci using the site notebooks. Finally, they must apply strategies to understand the spatial connections among the objects and trenches with the existing site features recorded in the digital survey. Even if it were possible to understand the data's spatial aspect, it would still be difficult to consider the other attributes (such as shape, color, and decorative markings) associated with the data that provide additional clues.



A **(1) Aerial view of Petra Great Temple precinct section, preexcavation 1993. After excavations conclude (right), the site is essentially destroyed because physical associations among sediment, architectural fragments, and artifacts are lost. Arrow view shows where the Petra Great Temple's monumental columns were found. The columns were left in place after excavations concluded (right). (2) Aerial view of Petra Great Temple precinct section, postexcavation 2001. Excavations to date span eight field seasons (or years) and have uncovered an enormous amount of physical evidence. The entire excavated region is roughly the size of three football fields and measures approximately 7,560 square meters. The dark circle shows a human's scale. (Figure A1 courtesy of J. Wilson Myers. Figure A2 courtesy of Artemis A.W. Joukowsky.)**



B **Section through a trench showing the sediment layers (loci) and in situ architectural findings that must be carefully indexed during excavation. Artifacts must be recorded by the find location in a locus.**

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Prototype one: A conceptual model

We created this first prototype to index many of the architectural fragments unearthed in Petra to investigate the research question, What is the chronology of the building phases of the temple and its precinct? We designed the conceptual plan to consider a set of variables present in the site databases, along with 3D models of objects, drawings, and photographs for new comparisons and to establish links among objects.

Our design goals were motivated by the need to establish a chronology of architectural phases among the Petra Great Temple areas. This complex problem can be solved only by relating small finds such as coins and oil lamps with monumental architectural fragments, in situ remains, and site features. Currently, the archaeological team attempts to establish building dates for each area of the temple by comparing observations and physical evidence collected during excavation.[3] At the end of each season, the team meets to assign phases to each architectural area by reviewing notes and comparing individual observations. The process somewhat resembles forensics because each site detail is potentially an important clue.

The fundamental relational aspect of the physical evidence challenges archaeologists because their current methods can't rigorously compare evidence from successive excavation years. Therefore, it's difficult for them to recall the many relationships in the site record they've observed during excavation. Also, because multiple archaeologists excavate the site and witness important aspects of the record, synthesizing their observations is inherently problematic.

Design goals

Based on these observations, we established the following design goals for our first prototype:

- Provide a way to relate smaller artifacts such as coins and oil lamps with their associated architectural fragments (see Figure 2).
- Attempt to assign relative dates to three-dimensionally linked objects.
- Relate evidence from datable stone-cutter markings on the architectural fragments at remote sites to help assign dates to architectural fragments with similar markings at the Petra Great Temple.

System development

In 1997, we built a conceptual prototype guided by our design goals. We posited that if each architectural feature were given an exact or relative date based on associated datable evidence, we could ultimately evaluate an architectural region by examining the resulting associations. We specified a framework in which archaeologists could index architectural fragments with distinguishable stone-cutter markings with other objects such as coins (already assigned absolute and relative dates; see Figures 2 and 3 on the next page).[4] We also developed ways to correlate the in situ find locations for objects with physical characteristics that can provide clues for comparing the objects.

Photos courtesy of Artemis A.W. Joukowsky

2 Examples of the artifacts archaeologists use to assign dates for areas of the temple. Top: a jug, an oil lamp, a coin, and a sculptural fragment. Middle: a column base with stone-cutter markings and a section of a column capital with sculptural detail. Bottom: small bulk-find pottery and oil lamp fragments.

Evaluation

We spent six weeks on site at the Petra Great Temple in 1998 and received feedback from the team that necessitated fundamental changes in our prototype. We determined that automating the process of assigning dates to architectural regions by using datable objects exclusively would severely limit our results. Datable objects are problematic because many of the Temple's architectural components—such as columns, walls, and floors—are so badly eroded that they can't yield adequate datable evidence for our relational model.

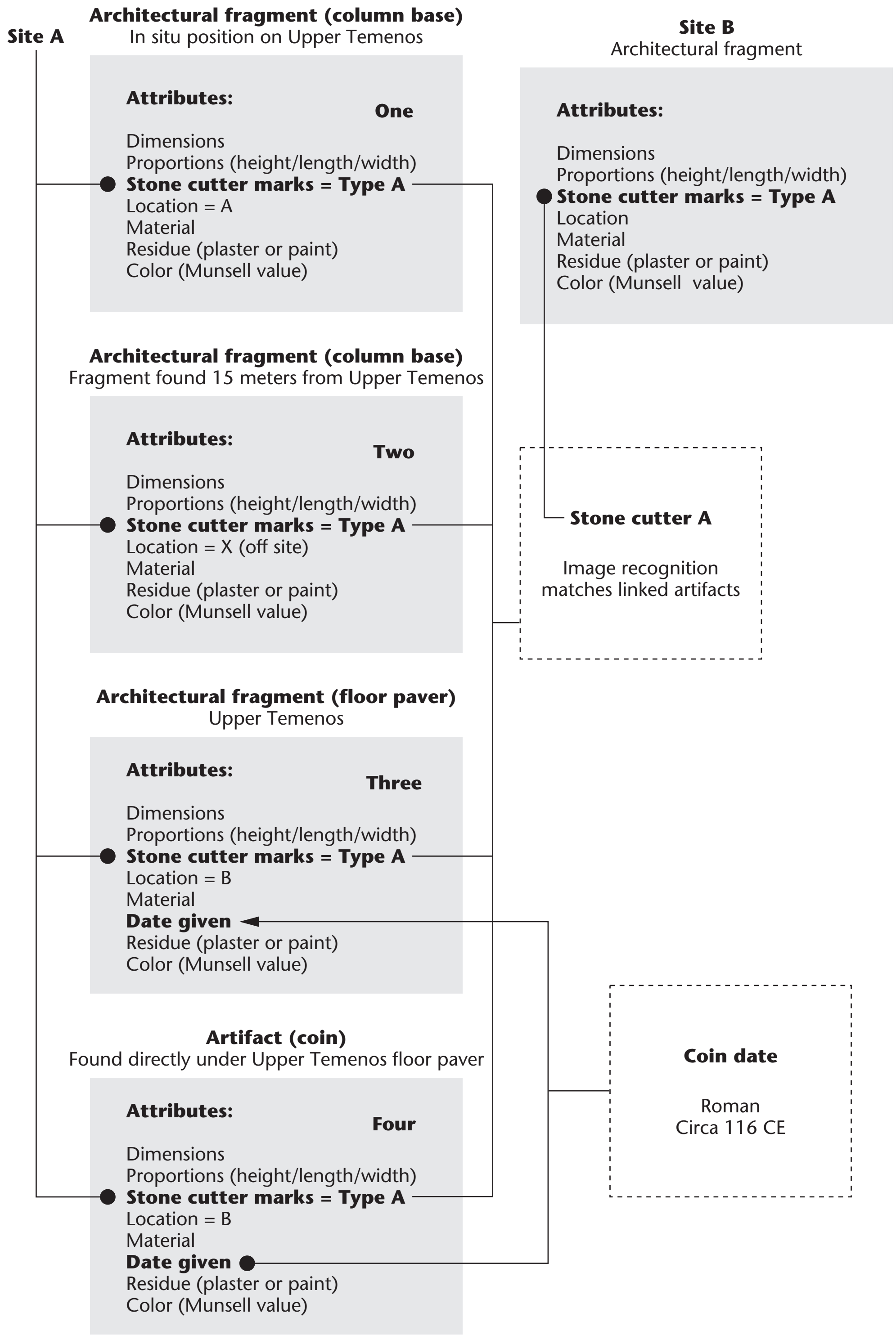
Prototype two: A test using a geographical information system

After evaluating the first prototype, we concluded that we couldn't use the system to synthesize the architectural findings and provide a chronology for the temple's building phases. However, in the process, team archaeologists helped us analyze the temple in terms of its function, use, and appearance.

Petra has been ravaged by several devastating earthquakes, so many of the architectural components such as column capitals and wall friezes have either been destroyed or displaced.

Archaeologists investigate these questions with empirically based observations. They consult with the excavation team to compare findings and analyze the statistics derived from the site databases. However, because the record's physical components are diverse and difficult to synthesize, archaeologists often rely on their memory for details and spatial relationships in formulating hypotheses.

Before implementing prototype two, we posited that



3 First conceptual diagram developed in 1997. It shows a framework for archaeologists to index datable artifacts and other finds based on their relative find location.

we could help archaeologists solve some of these research questions by providing new methods to investigate the parts of the record with which they aren't well acquainted. To do this, we used input from the excavation team to specify some simple tasks they would need, including these:

- The ability to reinvestigate and become better acquainted with the range of on-site findings, all excavators' discoveries, and data from many years of excavating.
- Ways to understand the spatial relationships among objects and features within or among excavation trenches.
- Methods to investigate, correlate, and provide evidence for sitewide artifact concentrations.
- The ability to generate evidence about the basic composition of the sediment removed during excavation.

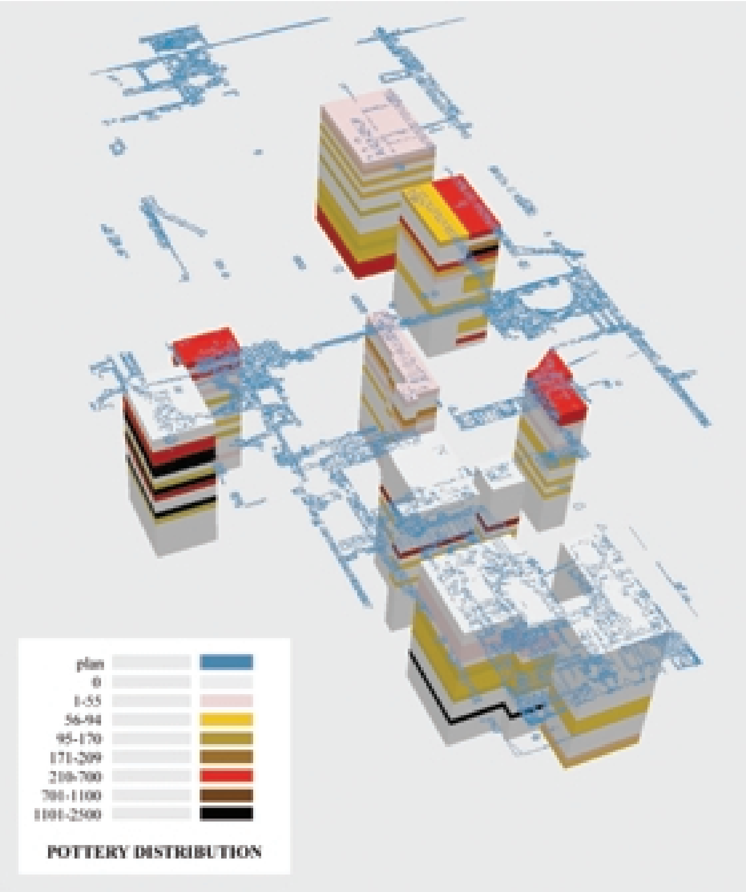
Design goals

To give archaeologists a means to perform these tasks, we established the following design goals:

- Implement tools and features to perform specified research tasks.
- Test some preexisting features in commercial geographic information system (GIS) software to see if it provides visualization or interaction methods adaptable to our purposes.

System development

We began implementing a second prototype on a desktop computer using GIS software called ArcView by Environmental Systems Research Institute (ESRI). We also used the 3D Analyst extension, which links the excavation database to a 3D viewer program. We started by integrating the 3D survey of architecture and site features with 2D shape information for approximately 50 trenches. The result resembled a site map with blocks representing trenches, as in Figure 4. When we loaded the site databases with more than 15 artifact typologies, we were quickly able to index bulk artifact find concentrations by trench. The result was a 2D visualization of an artifact typology (such as pottery) by a color scale (white to black). This wasn't very helpful because it displayed only the bulk concentration of pottery in the trench and gave no information about where inside the trench the pottery was found.



4 **Rendering from the 3D Analyst viewer. The trench layers (loci) are represented as boxes. Color ranges indicate the relative concentrations of pottery finds in the various layers.**

Next, we used the 3D Analyst viewer to look at the pottery ranges inside each trench by locus. Because we didn't have digital 3D information about each trench layer, we had to approximate the layer thicknesses. This time-consuming process yielded a somewhat inaccurate representation of the excavation layers. Finally, we used the visualization tools to assign a color range that represented the pottery concentrations in individual loci throughout the site.

Evaluation

During evaluation, team archaeologists found the prototype's 3D visualization difficult to understand. The rendering of this attempt shows a relative spatial distribution of pottery in the site trenches that, as Figure 4 shows, looks much like a 3D bar chart. The resulting depiction of the site and trenches gives the misleading impression that each trench layer is equal. Additionally, when querying in the viewer, we could examine only one artifact type at a time (such as coin, pottery, or sculptural finds).

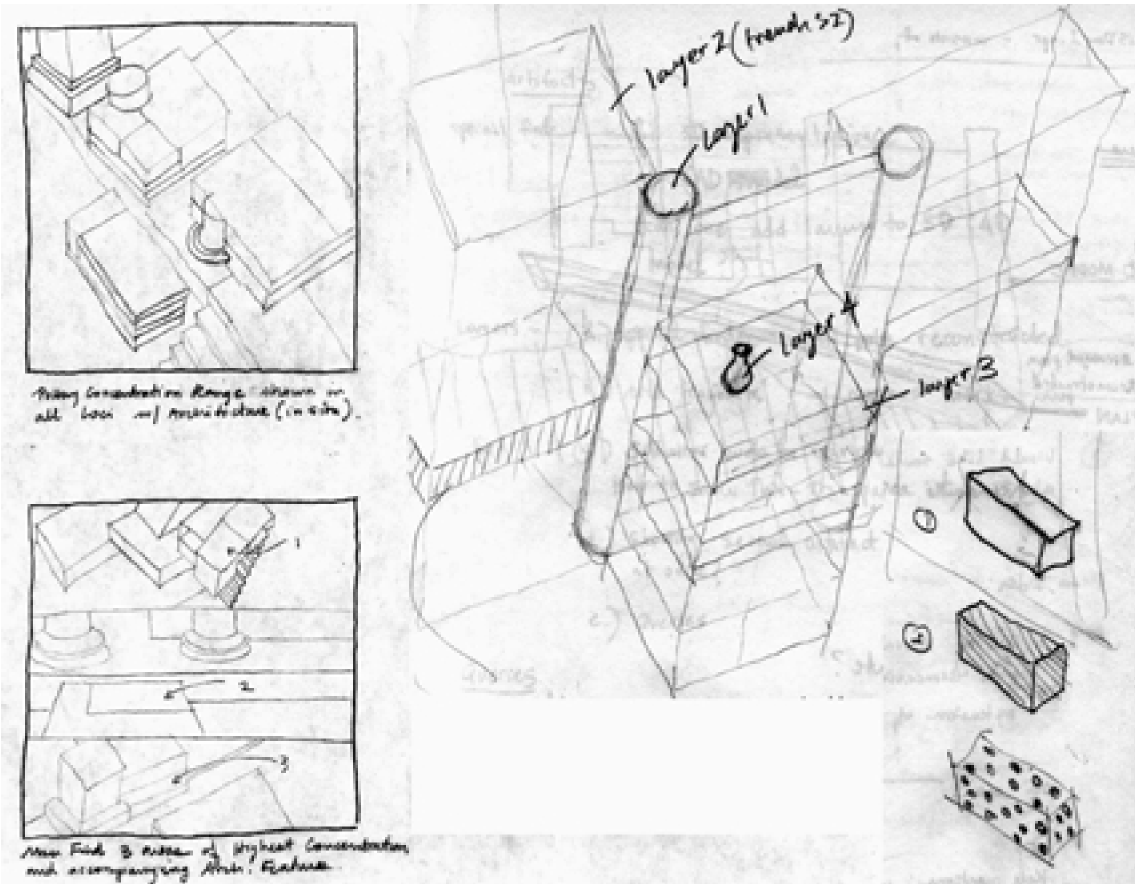
Although our test GIS offered a novel interface by which a variety of 2D data types could be correlated, it wasn't sophisticated enough to give a thorough description of height relationships among the spatial entities, nor did it give us adequate tools to examine multiple artifact types together. Finally, since we had only a rotation wheel and zoom tool with which to examine the site, we had trouble referencing occluded objects and remote features within the 3D viewer.

Prototype three: An inquiry model

Our test GIS prototype provided a 3D model with visualization and interaction methods. Team archaeologists appreciated the ability to visualize and explore the 3D components of the record but wanted additional features unavailable in GIS-based software. In response to their tests, team members described their ideal inquiry model for the analysis process. The sketch in Figure 5 (next page) illustrates how a more complete 3D visualization and interaction paradigm might enable archaeologists to interrogate important physical aspects of their site data.

We planned to build prototype three with some data visualization methods and user interaction and navigation tools to simulate the natural inquiry process occurring when the archaeologist is in an excavation trench or moving about the site.

We wanted a 3D visualization interface because it would let us add realistic visualization features and interaction tools. Moreover, it would provide a way to implement a range of inquiry methods in an intuitive user interface. We posited that the immersive VR inter-



5 Sketch of an inquiry model that integrates novel visualization methods to facilitate the analytic tasks archaeologists want to perform.

face offered by a CAVE would be an optimal environment in which to perform these inquiries. An IVR interface is particularly well suited to archaeological visualization and interaction tasks because it provides the visual range that "... help(s) provide situational awareness and context, aid(s) spatial judgments and enhance(s) navigation and locomotion."[5]

Recently, researchers have attempted to compare the results that can be achieved in immersive versus nonimmersive systems.[6] However, most studies admit that we still lack an adequate evaluation of IVR's specific capabilities. To date, the consensus is that certain specific tasks (that is, navigation and object manipulation) can be completed more comfortably in an IVR environment; other tasks are more effective in fishtank VR systems, using a stereo-capable desktop display with head tracking.[7]

Design goals

We began the design process for our third prototype by specifying four categories of tools that archaeologists need:

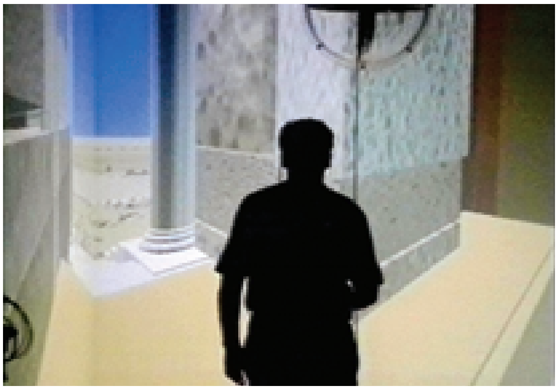
- *Specialized interface*: to use immersive VR in a CAVE to facilitate exploration and analysis tasks.
- *Visualization tools*: to search for artifact concentrations, differentiate among artifact types, and isolate anomalous conditions in a visual field with multiple attributes.
- *Navigation/interaction tools*: to let users interact with the 3D findings.
- *Examination/inquiry tools*: to observe the data at multiple scales (both at close range inside a trench and with overviews of the whole site).

System development

Because we intended this prototype to let archaeologists view and interact with a variety of entities simultaneously, we presented the data entity types with graphical rendering methods. We categorized the data types as follows:

- *Site features and architecture*: We provided a realistic 3D reconstruction of the Petra Great Temple as a base context/interface in the CAVE at life-size scale, as Figure 6 shows.
- *Trenches and loci*: We integrated some excavation trenches in a concentrated region of the temple. Each trench is broken down into a sequence of layers (excavated loci), as Figure 7 shows.
- *Artifacts*: Users send queries to the site findings database. Local concentrations of specific artifact types appear when each locus becomes a solid color (for example, white indicates minimum concentration, dark red indicates maximum concentration). When two artifact queries go to the database, the results appear in combination. Color indicates the first artifact concentration, and texture indicates the second artifact concentration, as Figure 7 shows.
- *Special artifacts:* The most significant artifacts such as a sculptural mask can be displayed in their 3D find

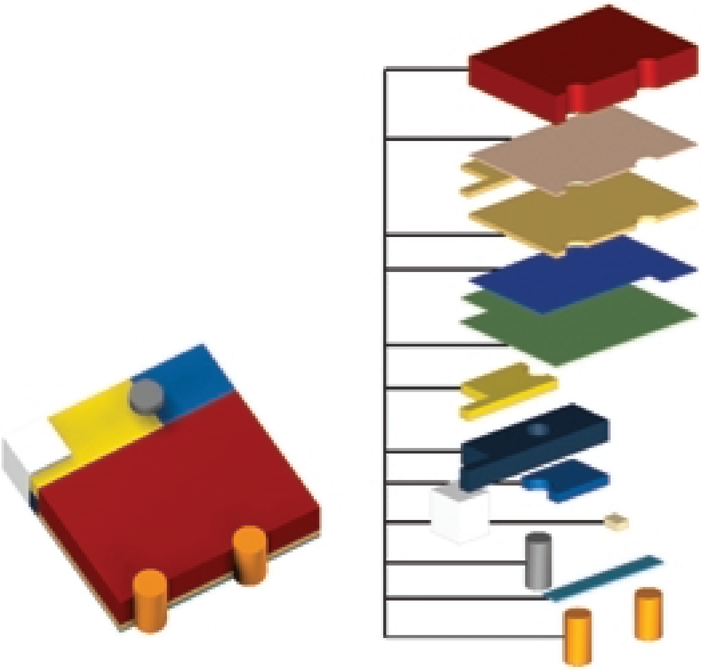
6 **Users navigating in the life-size Petra Great Temple reconstruction that serves as a base context for exploring site findings in prototype three. We built this model with data from a digital survey compiled from several sources.**



7 **User interacting with an excavation trench in prototype three. Each locus is expressed as a block of sediment. Pottery concentrations are plotted as color ranges (white equals low, red equals high). Bone concentrations are expressed as texture (loose equals low, dense equals high).**

locations inside the trenches. Users access them by turning the trenches off or dimming existing queries to see inside loci.

We also developed two sets of tools in this prototype. First, we developed tools for interaction and inquiry, with which new elements (trenches and special finds) can be added to the scene and queries sent with button interactions on the computer mouse. Second, we developed tools for navigation, with which users move in the IVR environment by using a tracked wand equipped with a trackball. The trackball lets users "walk" (move freely on the ground plane) or "fly" (move freely, unconnected to the ground plane).



8 **The colored regions on the left are the individual loci (from trench 24 at right) 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, and so on) or an important artifact.**

Evaluation

Implementing this prototype in a CAVE provided archaeologists with a realistic inquiry environment similar to the one they establish on site but without physical impediments such as dirt and heavy objects. The team appreciated the ability to reexperience the site at life-size scale and observe artifacts in their in situ locations. However, team members still had difficulty performing research tasks because they lacked refined, flexible visualization and interaction techniques.

Over a six-month period, we collected feedback from archaeologists on the general problems they encountered with this prototype. They felt that the temple reconstruction wasn't an accurate research context to explore excavation features because it didn't represent their raw find data and was visually distracting. They wanted to experience the site at life-size scale but also wanted to "shrink" it so that they could look for features common to different areas. Finally, artifact concentrations were difficult to observe because the trenches occlude one another, and the method of integrating multiple artifact types with color and texture was too visually complex.

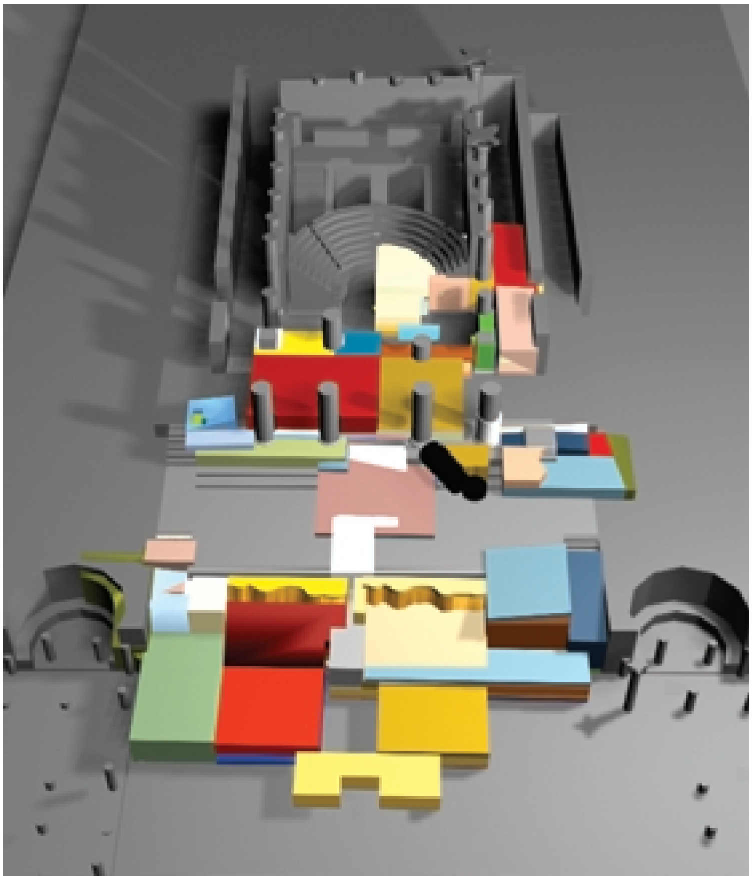
Prototype four: Refinements

In our final prototype, we integrated essential refinements so that two team archaeologists could evaluate it by investigating specific research questions.

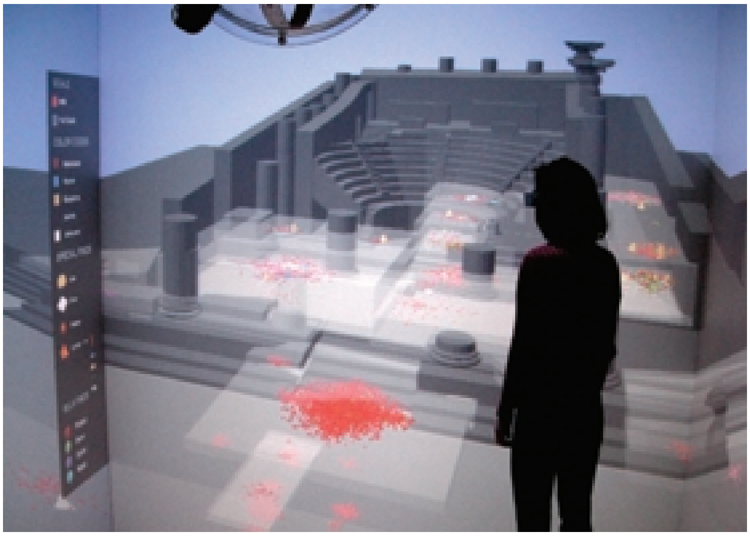
Design goals

To refine the visualization and interaction methods in prototype three, we created a wish list of changes for our final prototype:

- Create an accurate research context with only in situ site findings, as Figures 8 and 9 (next page) show.



9 Three-dimensional model with in situ site and architectural remains (gray) and 17 test trenches (multiple colors). This model provides an accurate context for archaeological inquiry.



10 User examining the entire Upper Temenos region of the temple with trenches (semitransparent) and in situ finds. The user can easily pick out high concentrations of pottery (red), bone (green), stone (purple), and metal (blue).

- Develop ways to navigate through the model and change scales.
- Find better ways to look at site features and synthesize findings, for instance, to look at multiple artifact typologies together and understand patterns or anomalous conditions.

In planning improvements, we incorporated these three items and applied perceptual rules for observing and interacting with the site record.

System development

Our development dealt with both new visualization and interaction tools.

Visualization. The visual perception literature outlines general rules for building visualizations that exploit strengths of the human visual system. To mitigate the complexity of our earlier visualization, we gave users some visual entities that they can recognize automatically prior to conscious attention:[8]

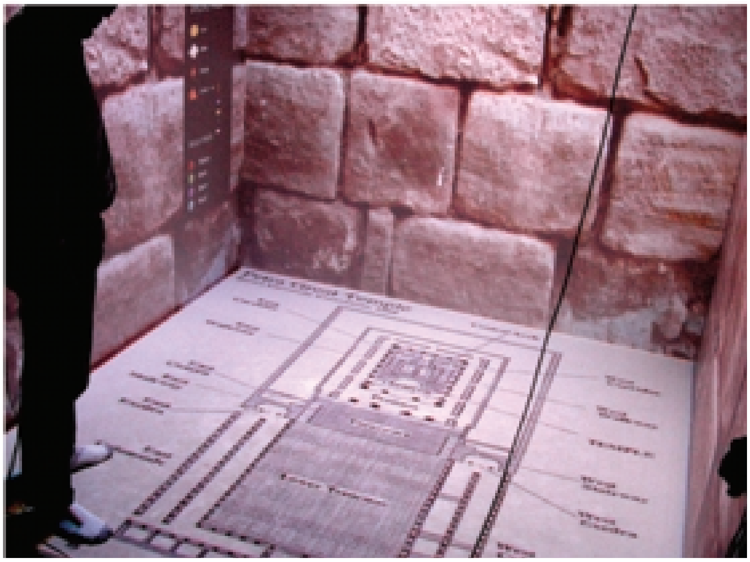
- *Lightness:* We approached the problem of visualizing the site contents (such as architectural finds, trenches, and loci) by composing all the elements in 3D layers and then adjusting their individual properties (color, size, and shape) for users to isolate significant features. For example, we removed the image-map texture and rendered in situ findings in desaturated grayish tones. Then we chose fairly saturated colors with high lightness values for the excavated features (trenches and loci) and artifact typologies (bulk concentrations and special finds). As a result, the base in situ finds now contrast dramatically with excavated features, as Figure 10 shows.
- *Shape and size:* To facilitate discrimination between bulk and special finds, we modified their shape and size. Modifications included, for example, large tetrahedra (lamp finds) and hexagonal prisms—coin finds now stand out visually from small tetrahedra (bulk concentration finds).
- *Hue:* The symbolic use of color lets archaeologists quickly identify bulk finds (red indicates pottery, green indicates bone, and so on).[9] Special finds are also color-coded to reflect their cultural origin (blue indicates Roman, gold indicates Byzantine, for instance); they stand out in the context of bulk finds because they're twice the size. A key to these values is projected on the left wall of the CAVE for easy reference.

New interaction tools. Along with the need to refine the system visually, we had to improve users' physical interaction with it. Research shows that an undetectable and unobtrusive user interface is important to users in completing a task.[10,11] As a result, we developed the following tools:

- *Introductory portal:* We exploited the CAVE's immersion to introduce the site and acquaint users with the context and tools. They enter the site through an introductory portal, a room with rusticated walls and a map projected onto the floor that helps orient them to the excavated context, as Figure 11 shows.
- *Miniature model:* After looking at the site map, users are introduced to the in situ and excavated remains in

the context of a miniature 3D model,[12] as Figure 10 shows. Users initiate exploration by moving a red block representing the portal to the area of interest. They're automatically relocated to that position in a full-scale model for more detailed exploration. If they're performing queries, they can return to the miniature model at any time for a synthesis of global site features (such as trench data from opposite sides of the site).

- *Interactions*: In this mode, users can begin moving and interacting with excavation data via a wand and a pinch glove. The wand is equipped with a trackball to move (walk or fly), select, and turn objects on and off. Users can wear a tracked-pinch glove to access a 3D virtual widget.[13] Various hand gestures let users choose relevant artifact types—such as bone, shell, and pottery—by rotating the wheel and picking associated colors.



11 **Users enter the site through an introductory portal, a room with rusticated walls and a map projected onto the floor.**

Evaluation of new methods

We originally hypothesized that we could help archaeologists answer key research questions by giving them new methods for examining and synthesizing the record. To test this hypothesis, we asked our team archaeologists to use prototype four to investigate specific research questions. We performed two user evaluations to observe the archaeologists and determine what sorts of analyses they could perform with the prototype.

The first test, with two team archaeologists, focused on evaluating the users' general observations in looking at the site data. In the second test, two other archaeologists (whom we will refer to as users A and B) used the prototype in the CAVE and were prompted to perform tasks to explore their own research questions.

The following discussion focuses not on the testing process but on observations made in the latter test with users A and B.

Preparation

Before beginning the test, users A and B were asked general questions about their own research. We wanted to identify the research questions they would explore during the test and suggest that they focus on those that could realistically be answered given the current state of the prototype.

User A wanted to identify when the temple was in use by assigning dates to her lamp finds. To do this, she planned to examine relationships among lamp and coin finds in different trenches. User B aimed to identify the temple's function and its relationship to the adjoining site, which she is excavating for her dissertation research. She had excavated a few significant trenches at the temple but wanted to observe some trenches she didn't excavate personally.

Observations and discussion

When we encouraged archaeologists A and B to use the system, they performed three different types of tasks.

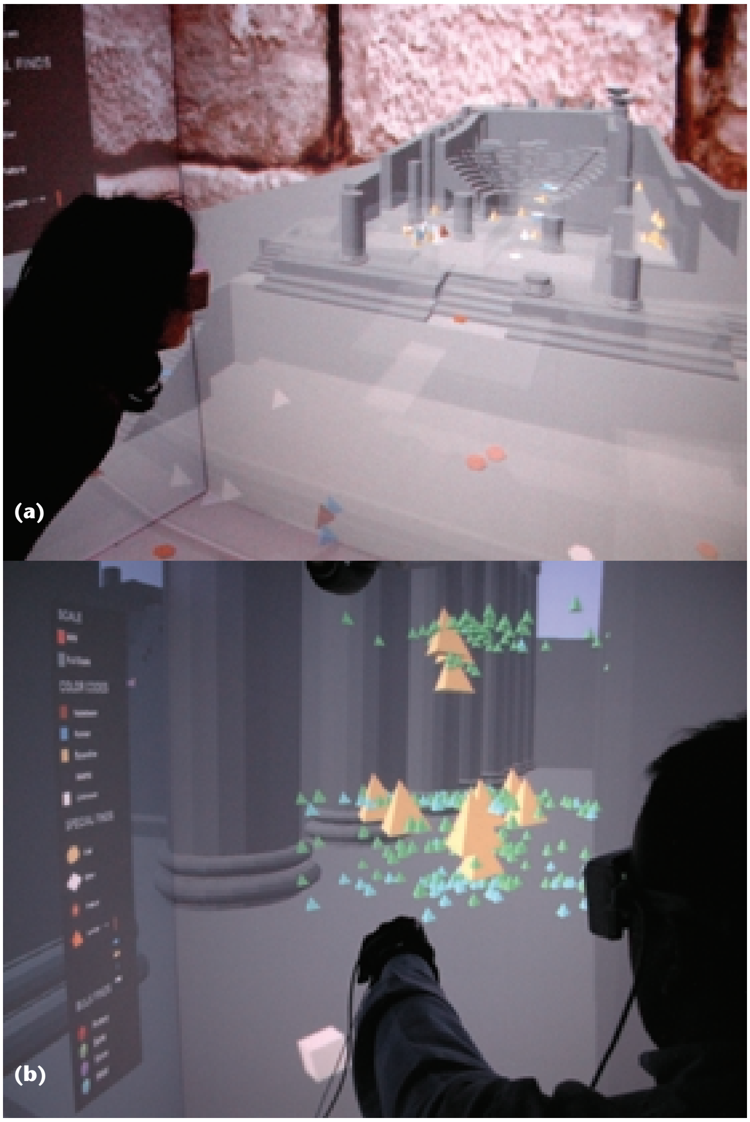
Perform queries with the site information and formulate and explore hypotheses. In the process of making queries to observe the architectural remains with special and bulk finds, users A and B began to form personal hypotheses about what they saw.

User B became interested in some of the site's metal finds. While looking at bulk finds in combination, she hypothesized that the metal fragments corresponded with the frame of a door close by. If the original wood door had disintegrated, its metal hardware would remain.

Although it's fairly easy to find high concentrations of metal using the site database alone, it isn't easy to associate a specific layer and its architectural component. When user B queried the database for metal finds and observed them in the IVR environment, she was surprised to find that all the metal in the western aisle was at ground level. Additionally, she observed that the metal in the western aisle 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 or theater) could have come from the hardware that remained after old wooden banisters lining the theatron circulation routes disintegrated. However, user B was unable to confirm this hypothesis because the metal objects she found didn't have additional attribute information such as shape or function (currently accessible from the site database but not represented in this visualization attempt). In this case, integrating more physical attributes from the database for these objects will let her investigate this hypothesis further.

Investigate site data and find patterns and anomalies. User A wanted to consider the oil lamp find locations in relation to other relevant and datable



12 **(a) User examining lamp and coin finds in the miniature model. Lamps are tetrahedra and coins are hexagonal prisms. These shapes are easy to identify because they're quite a bit larger than the clustered bulk finds in Figure 7. Here the colors indicate the cultural period of the objects (blue equals Roman, gold equals Byzantine, red equals Nabataean, white equals unknown). (b) User examining a cache of Byzantine lamps (large yellow tetrahedra) in trench 29, in the western aisle. The small green (bone) and blue (metal) tetrahedra represent bulk artifact finds.**

objects, such as coins and pottery. In her research, she hadn't yet compared the lamp finds with spatially related coins because this would be too laborious with existing methods.

User A used the visual query tools to view the lamps in their find locations (see Figure 12a). Next, she queried the coin finds to observe them together. After querying the lamp finds from the Upper Temenos region, she was able to isolate a cache of Byzantine lamps in the middle loci of trench 29, bordering trench 45 in the western corridor (see Figure 12b). This finding suggests that there might have been activity in that area during the Byzantine occupation of the site. Because she hadn't personally excavated trenches 29 and 45, she was neither familiar with these lamp find locations nor aware that Byzantine lamps were the only kind found in that general area. This observation became a particularly striking curiosity and perhaps a vital clue regarding site use during the Byzantine period.

Confirm on-site findings and proof for hypotheses. User A found several areas with mixed deposits by looking at the trenches and their associated finds along with the site features. (During excavations, it was suspected that the heavy annual rains and earthquakes that ravaged the site disturbed the sediment layers covering the building and its environs. Consequently, the stratigraphic sequence became mixed, making it difficult to determine the relationships among various trenches, loci, and artifacts.) For example, after observing the placement of coins and lamps together, user A posited that the finds at the Petra Great Temple precinct might be physically related to the Nabataean Az Zantur, a domestic excavation site to the immediate south. That is, heavy rains might have washed surface objects down into the temple precinct. This supposition might explain the seemingly random distribution of objects from different cultural periods located on the surface layers of most trenches.

In interacting with a range of data from the Petra Great Temple site, user B derived initial proof to support her hypothesis regarding metal findings. The metal objects she located close to the ground near a door frame could certainly have been used for door hardware. This result would have been extremely difficult to investigate using traditional approaches alone because the artifacts were likely removed from the ground without this observation. This method of inquiry allows their relationship with the find context to be preserved.

These findings help provide tangible proof for empirically derived excavation results because archaeologists now have additional documentation (in the form of screen shots and renderings from observations made in the CAVE) of results. They're also significant because they confirm some of the archaeologists' longstanding suspicions about the sedimentary levels throughout the site.

Discussion

In our evaluations of prototype four, we observed that the two team archaeologists initiated queries with the new interaction features and by navigating freely using the mouse and pinch glove. In addition, the improved visualization methods helped them identify important patterns and anomalies in a visual field with many diverse elements.

The experience essentially changed their perception of the site by exposing them to a much wider range of physical data and acquainting them with site areas, artifacts, and features previously unfamiliar to them or excavated by other team members. Their observations let them check existing hypotheses and formulate new ones with physical evidence not otherwise accessible. They also commented that the application will help them share findings with colleagues from related sites by providing tangible evidence for their hypotheses.

At the beginning of our collaboration, team archaeologists had expressed interest in new techniques to help answer the difficult research questions about the Petra Great Temple site. Traditional methods helped them in performing some research tasks but prevented the collection of evidence sufficient to substantiate hypotheses about the larger research questions. We believe that they will soon be able to generate this evidence using additional excavation features, not present in the fourth prototype, to describe a greater number of attributes from the excavation record, for example, specific physical details of smaller artifacts such as pottery and bone and more precise in situ location. We are currently developing features to provide greater amounts of artifact detail with additional visualization tools linked to the site database; however, specific information about the artifacts' in situ location must be collected on site. In the future, with slight adjustments to current field recording methods (to integrate more 3D attributes), we can improve the capabilities of our current prototype.

We're encouraged by the fact that, after evaluating the fourth prototype, team archaeologists became convinced of the value of modifying their data-recording methods and are working with us to integrate new standards for digital recovery and record keeping.

Conclusions

In this body of research, we created an archaeology-specific application to augment the analysis methods employed by the Petra Great Temple excavation team. To accomplish this, we built four prototypes that address archaeologists' important research questions and specified some analysis tasks they need to perform in order to answer them. Through an iterative process, we added a series of tools and techniques to help them interrogate aspects of the site record and perform the research tasks.

Our final prototype four provides a greatly improved model for inquiry. According to our team archaeologists, in evaluating prototype four they could accomplish many of the research tasks we specified. For example, in exploring the site findings they had been exposed to while excavating, they were able to acquire proof for hypotheses they established on site. They were also able to explore site areas they had not personally excavated and so were able to formulate new hypotheses using data derived from those areas.

The archaeologists used the tools in prototype four to query, navigate, and explore the Petra Great Temple site as if it had never been excavated and the sediment still remained. The prototype application also provided a venue for collaboration among multiple archaeologists and the possibility of sharing data among remote sites. Although many observations are best made with tangible evidence derived from the on-site excavation, our approach can play a significant complementary role in the entire archaeological inquiry and analysis process. ■

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Eileen Vote *is a postdoctoral fellow in the Computer Science Department at Brown University. Her research interests include scientific visualization in VR environments, 3D user interface design, and art-based visualization of complex data sets. She received an interdisciplinary PhD with the Departments of Archaeology and Computer Science and an MA in the*

Department of Art and Architectural History at Brown University. She also holds a BA in architecture from Rice University.

Daniel Acevedo Feliz *is a PhD student in computer science at Brown University. His research interests include human–computer interaction in VR, scientific visualization, 3D modeling, and intelligent interfaces. He received a BS in civil engineering from the University of A Coruña (Spain) and an MS in computer science from Brown University.*

David H. Laidlaw *is the Stephen Roberts Assistant Professor in the Computer Science Department at Brown University. His research centers on applications of visualization, modeling, computer graphics, and computer science to other scientific disciplines. He received a PhD in computer science from the California Institute of Technology, where he also did postdoctoral work in the Division of Biology.*

Martha Sharp Joukowsky *is a professor, Center for Old World Archaeology and Art and Department of Anthropology, at Brown University and is a veteran of more than 30 years as a field archaeologist specializing in the Near East. Since 1992, she has directed the Brown University excavations at the Petra Great Temple in Petra in the Hashemite Kingdom of Jordan. She received a PhD in archaeology from the Sorbonne after attending Brown University as an undergraduate.*

Readers may contact Eileen Vote at the Dept. of Computer Science, Brown University, Box 1910, Providence, RI 02912, email evote@cs.brown.edu.

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