

3D imaging of Skoteino Cave, Crete, Greece: Successes and difficulties

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Interpreting cave use, especially from antiquity, requires the perception of subterranean space in all dimensions (floor to ceiling to lateral extent) including spatial variability resulting from geological factors. Subterranean conditions, coupled with variable atmospheric conditions, create a special environment not readily conveyed by conventional mapping techniques limited to two-dimensional floor plans. Skoteino Cave in north central Crete, Greece was used as a ritual and refuge site in the Bronze Age and later. Mapping of the cave attempted to depict and interpret prehistoric and historical use of this space by employing two mapping techniques: EDM total station mapping and terrestrial/point cloud laser scanning. Comparisons with earlier methods used to map cave show the advantages and disadvantages of various mapping schemes. To date, this was the first use of three-dimensional (3D) scanning to explore the complex shapes and space of a subterranean archaeological site on Crete (and the second such use in Greece), and this use demonstrates its own consequent successes and difficulties.

Keywords: Crete, Greece, Skoteino Cave, tape and compass mapping, two-dimensional and three-dimensional mapping, EDM total station mapping, terrestrial/point cloud laser scanning

Introduction

Caves present unique challenges to archaeological and geoarchaeological studies. How do environments influence cultural use? In contrast to sites on the surface, subterranean sites include features such as floors, walls, and ceilings that create narrow passageways, chambers, and niches. Mineralogical adornments draping surfaces such as speleothems add to the beauty of this environment. Limited light conditions help to create a special sense of space. All this, coupled with atmospheric conditions that can be uncomfortable, if not toxic, to human occupation for extended periods, define a unique archaeological setting.

These subterranean features present a specific challenge to those who wish to understand cultural attraction, use, and perception an underground setting. Chief among the difficulties involved in mapping such a space is the fact that the traditional floor plan, fundamental to an archaeological interpretation of space, is limited and insufficient as it represents only a two-dimensional (2D) rendition of the three-dimensional (3D) qualities of a cave. Unlike features on the surface, the entire subterranean environment is an interior space and must be treated as such if we are to gain a full understanding of its use and meaning. This is the challenge that we have faced

in studying the prehistoric and historical use of Skoteino Cave on Crete.

Two seasons of attempting to map features of a subterranean environment using traditional cartographic techniques resulted in limited success, so we turned to the technology of 3D terrestrial laser scanning, which produces point cloud datasets, in order to create a more accurate model of the site. As a result, Skoteino Cave has now been mapped using three different techniques, and therefore stands as an exceptional case study for comparing the benefits and drawbacks of each when used within a subterranean space. As we continue to research the environmental conditions and setting and their influence on human use within, each technique is proving to be useful in different ways.

Archaeology and Geology of Skoteino Cave

Located 16 km east of Herakleion in north central Crete (FIG. 1), Skoteino Cave (“Dark Cave” in Greek) holds a place of considerable importance among the subterranean archaeological sites of Crete. Since Sir Arthur Evans’ first excavations in the early 20th century (Evans 1921: 163; Faure 1964: 163), this cave has been studied by a number of archaeologists and speleologists, including John Pendlebury in 1933 (Pendlebury 1939: 177) and Paul Faure in 1953–1959 (Faure 1964: 162). Most notably, in 1962, in response to persistent looting, Costis Davaras carried out a series

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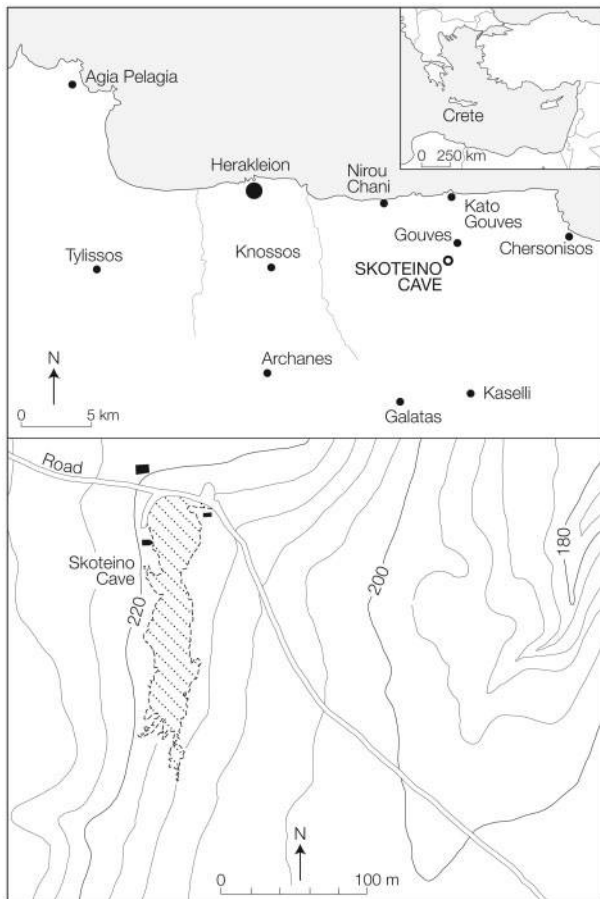


Figure 1 Location of Crete (inset) in the Eastern Mediterranean. Location of Skoteino Cave in north-central Crete (top) and topography (bottom) surrounding the cave area (contour interval = 4 m; topography from IGME 1989). The outline of the cave system is depicted by dashed lines. Modern structures are shown in black: buildings on the left are churches, the building on the right is a shed. Figure modified after Tyree et al. 2005–2006: 52, fig. 1.

of small excavations for the Greek Archaeological Service in a number of different locations within the cave (Alexiou 1963a: 312; 1963b: 398; Davaras 1969: 621–622). Later, to better understand the relationship between these areas of ancient activity, and realizing the deficiencies of existing cave maps, a survey team under the direction of Loeta Tyree and Athanasia Kanta began a project to map the interior of the cave using more accurate digital techniques (Tyree et al. 2005–2006). The initial results of these surveys were presented by Frey and colleagues (2009).

Excavations in Skoteino Cave indicate that the first cultural utilization of the subterranean space was as a Bronze Age ritual and refuge site with additional use in Roman and later times (Tyree et al. 2005–2006). The artifacts indicated mixed contexts mainly from Middle Minoan III through Late Minoan IIIB (ca. 1750/1700–1200 B.C.) and Roman periods (2nd and 3rd centuries A.D.) (Tyree et al. 2007; Tyree et al. 2008). The main period of Bronze Age use was during the New Palace period, i.e., Middle Minoan III–Late Minoan I (ca. 1750–1450 B.C.) when the cave was a



Figure 2 Entrance to Skoteino Cave showing the collapse doline that allows access into the cave. From this opening the cave plunges 20° to a subsurface depth of 70 m. Trees in foreground are approximately 2 m tall. Photograph by L. Tyree taken in 1970.

place for ritual, as evidenced by three bronze anthropomorphic figurines of the “votary” type and ceramics that are more restricted in shape than those from contemporary domestic assemblages. Specialized pottery vessels include chalices, a Linear A-inscribed cup, and libation vessels with pierced bases. The consumption of liquids was an important part of the ritual, judging from the presence of approximately 2000 cups, a considerable number of pouring vessels, and transport jars. The consumption of food is also indicated by the presence of preparation, cooking, and serving vessels as well as storage vessels. A broad, flat-topped stalagmite, located in the main ritual area, may have been an altar (Tyree et al. 2005–2006: 55). Visitors consider it as such today, leaving pinecones, leaves, replica medallions of Athena, etc., on the stalagmite. Post-antiquity use of this cave is indicated by inscriptions dating back to the 15th century A.D. as well as undated burn marks on walls from open-flame torches (Tyree et al. 2011: 727).

The cave is readily accessed today, and likely was in antiquity, through a depression that resulted from the dissolution and collapse of the limestone ceiling (doline) to form an entryway (FIG. 2). Although it is short (207 m from the entrance to the farthest accessible chamber) in comparison to many Cretan caves, Skoteino Cave is one of the largest walk-in caves in Crete. In plan view, the cave forms an elongated oval. Its longitudinal profile follows a regional fault line in a north-south alignment (FIG. 3). The cave’s interior space is separated by a series of discrete steep slopes (or small escarpments) of the floor, zones of speleothems, and other features such as breccia accumulations that together partition the cave into five distinct topographic levels (labeled Levels I–V in FIG. 4; also see FIG. 3). With the exception of the transition from Level IV to Level

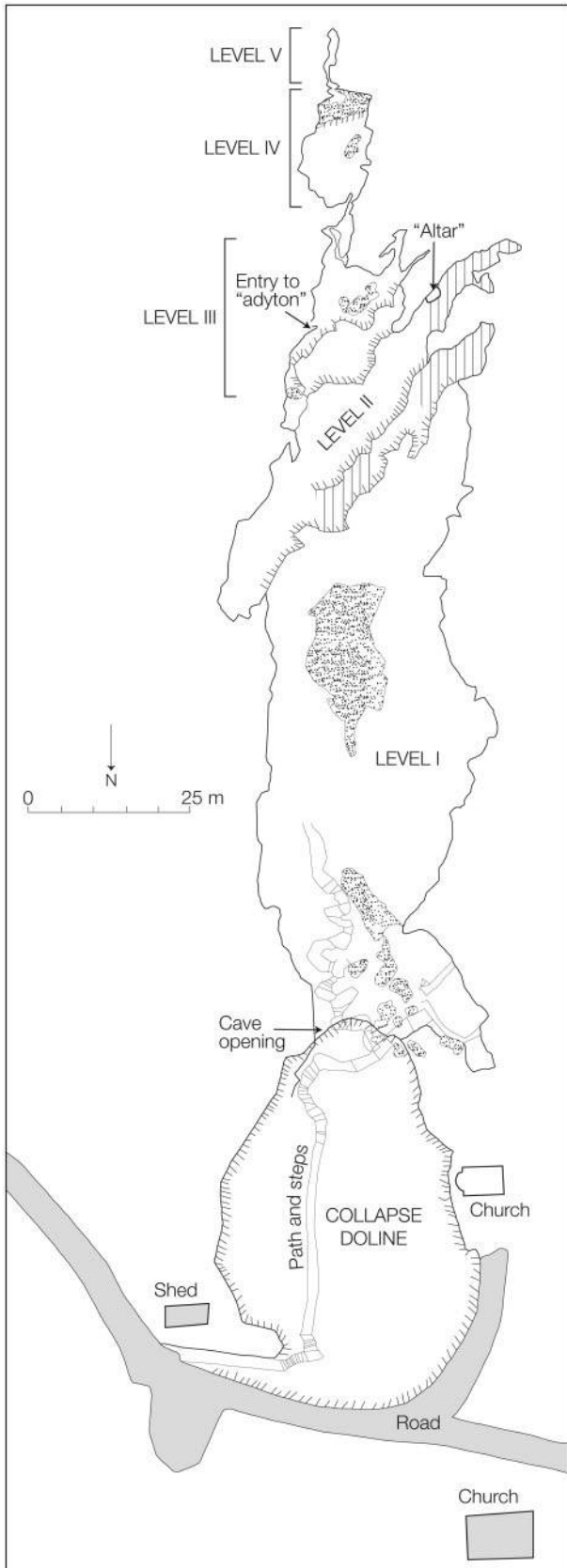


Figure 3 Ground plan of Skoteino Cave identifying the five topographic levels within the cave. The stippled patterns identify stalagmites, large pillars, or accumulations of collapsed debris. Hatchures identify scarps and steep slopes. Vertical lines indicate the Bronze Age ritual areas. Paths and steps are depicted within the access doline. The southwestern end of Level II, to the west of the “altar,” is the view plane shown in Figure 8. Created by A. Stamos, June

2006, with a TopCon GTS-303D EDM Total Station. Data processed using Tripod Data Systems Foresight 2.2.1, AutoCAD 2000, and Surfer 8.0.

V, each level represents a downthrown fault block that marks a fault scarp. These steep descents are slippery, rocky, and difficult to negotiate, especially between Levels III and IV at the bottom of the cave.

Given the complex tectonic fabric that has created this cave’s physiography, combined with geochemical processes that have added spectacular secondary carbonate deposits as a variety of speleothem structures, this cave is a challenge to map regardless of the chosen method, and therefore has served as a rigorous testing ground to compare the efficacy of several different mapping techniques.

Cave Mapping Techniques

Tape and compass technique

No maps are known from the earliest post-antiquity access that left the 15th century and later wall inscriptions. The earliest attempt to map and portray Skoteino Cave’s dimensions, topography, and morphology was by Platakis presumably using common mapping tools such as measuring tapes and a magnetic compass (Platakis 1962: 36) (FIG. 5A). While this technique is inexpensive and requires a small field crew (two people can accomplish the work), the resulting map presents an inaccurate, limited, and skewed overview of the cave system. Fortunately, the host rock at Skoteino Cave is limestone and this seems to have caused minimal magnetic compass deviation. Errors in distance, however, are inherent when measurements are taken on steep slopes and then plotted as horizontal distances on maps without slope

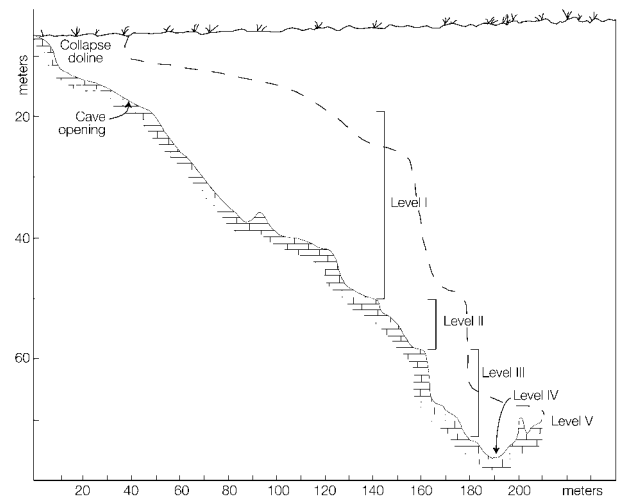


Figure 4 Cross-section through Skoteino Cave. Elevations of the roofline (dashed line) are estimated. The vertical scale is exaggerated (2.5 ×) to emphasize topographic changes marked by fault scarps separating levels.

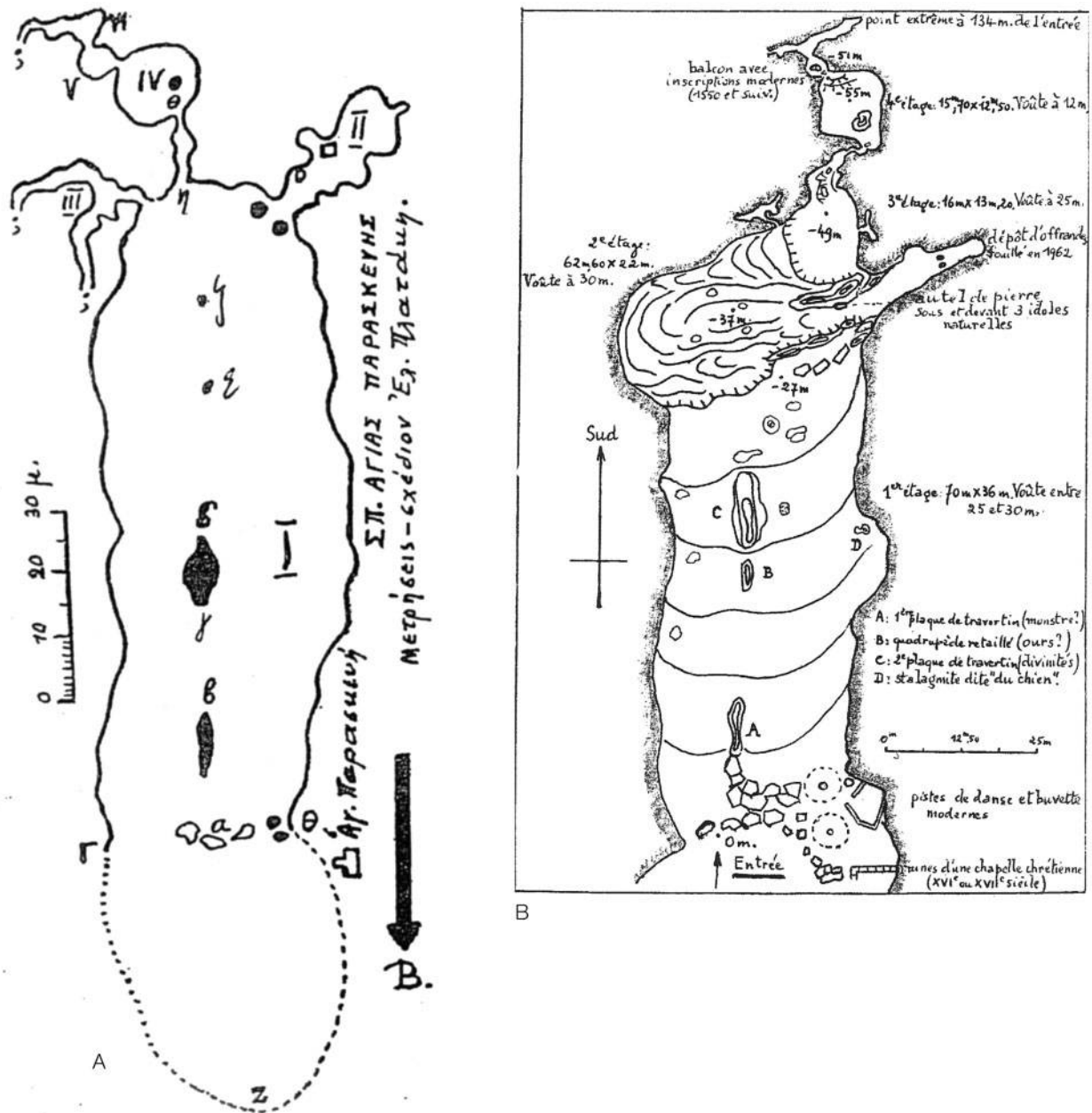


Figure 5 Comparison of two early maps of the floor of Skoteino Cave at approximately the same scale. Note that north is towards the bottom. A) Map by Platakis (1962: 36). Roman numerals identify “levels” (sections) in the cave. Image reproduced by permission of the Greek Speleological Society (Δελτίον της Ε.Σ.Ε.); B) Map by Faure (1987: v. 2). Plan courtesy of the City of Herakleion: Vikelaia Public Library (Δήμος Ηρακλείου: Βικελαία Δημοτική Βιβλιοθήκη).

corrections. Accordingly, the relationship between cave physiographic and anthropogenic features was similarly limited and, at best, Platakis’ map presents a rough but still useful outline of both the cave system and the cave floor.

Later mapping projects (FIG. 5B) (Faure 1987: v. 2) added floor topography to the Platakis map, determined by crude leveling techniques. Floor relief was sketched, but again without depiction of walls and ceilings that would allow appreciation of spatial relationships likely important to ancient perceptions and uses of the cave. Platakis and Ioannou improved on prior techniques by applying leveling techniques (Ioannou 1970: 62) (FIG. 6A). The differences between

maps in terms of scale, cave outline, and cave physiography are dramatic.

EDM total station technique

The limitations of existing maps constructed by these earlier techniques and equipment, coupled with rapid advances in cartographic technologies and software that allowed for an easier mapping and plotting experience, inspired surveys by the authors in 2005 that created an entirely new map of Skoteino Cave using a TopCon GTS-303D Total Station and Recon Data Collector. A total station measures distances by accurately timing laser beam transmissions to and from a reflecting glass prism. The latter is positioned in the field atop features being mapped, while the

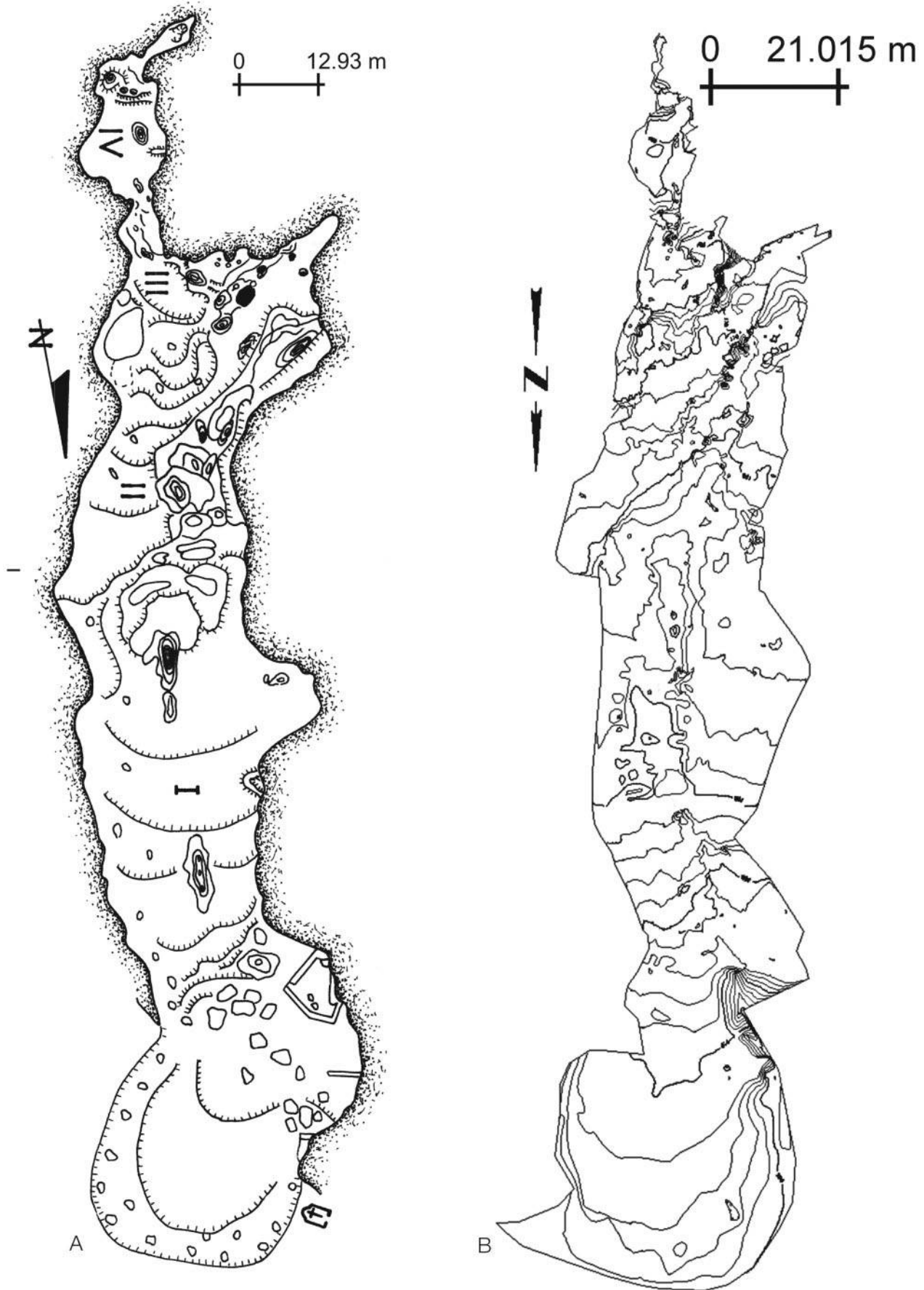


Figure 6 Comparison of two maps of the floor of Skoteino Cave using modern techniques. Note that north is towards the bottom. Scale here is approximately the same between the two maps. A) Map from Platakis and Ioannou (Ioannou 1970: 62). Roman numerals identify “levels” (sections) in the cave identified during this mapping. Map reproduced by permission of the Greek Speleological Society (Δελτίον της Ε.Σ.Ε.). Redrawn by Roxana Docsan; B) Topographic contour map of Skoteino Cave, created with a TopCon GTS-303D EDM Total Station (A. Stamos, June 2006). Data were processed using Tripod Data Systems Foresight 2.2.1, AutoCAD 2000, and Surfer 8.0. The contour interval is 5 m: uppermost contour is 223.044 m; lowermost contour is 149.084 m.



Figure 7 Using the TopCon GTS-303D EDM total station and prism on uneven ground in Skoteino Cave. Photograph by J. Frey.

total station remains in a fixed position. This system also calculates slope inclination, using the dip of the laser beam, and azimuth by the orientation of the instrument to determine the exact spatial coordinates of any visible object.

More advanced total stations no longer require the use of a prism, but one was not available at the time of our initial mapping. Thus our attempts to survey the cave using this method were, at best, only partly successful (FIG. 6B). Little or no light, confined spaces, speleothems, collapsed debris fields, slippery slopes, and abrupt drop offs combined to make mapping difficult, especially for equipment setup, the determination of necessary sight lines, and the placement of handheld prisms. All of the latter prohibited mapping of cave walls and ceilings, for example. Moreover, while the overall cave data could be tied to regional coordinate systems at the cave entrance using Geographic Positioning System (GPS), inside the cave, a GPS system was ineffective. As a result, coordinates had to be translated into the cave through a complex series of survey control points from the cave mouth to the lowest level. In order to maintain a dependable network of survey markers, each new setup of the instrument over a control point, or benchmark, required a clear view of at least two other control points. While this common procedure is relatively simple above ground, the cave's complex morphology made the search for an uninterrupted line of sight to control points especially challenging. Often the total station had to be repositioned several times in order to establish an acceptable new point for instrument setup.

Accurate recording of features required that the prism be placed directly atop the feature being mapped (FIG. 7). This was especially difficult inside the cave, where stalagmites were often impossible to climb and clearly defined boundaries such as floor/

wall junctions were lacking. Thus, we were often required to make compromises in interpreting and determining mapping points. Furthermore, the person operating the total station often had difficulty locating the small (10 cm diameter) reflecting prism in the dark, especially when the total station was aimed at extremely high and low angles. One improvised method to minimize this problem was to place a larger white background behind the prism that could be illuminated with a flashlight. Once the prism was located by the total station operator, the flashlight was extinguished and the actual measurement taken in the dark. Although factors such as temperature variability (from 15–23°C), the absence of natural light, and wet conditions (87–92% humidity) did not create problems for the survey instruments, they did begin to take a toll on the mapping crew.

Three seasons (2005–2007) were required to survey the cave floor to its farthest and deepest point, 207 m from the mouth of the cave and 70 m below the overlying ground surface. The survey required well over 500 man hours and produced 4250 measurements based on a network of 34 control points. As can be seen from the contour plan (FIG. 6B), the resulting map offers an accurate representation of the cave floor. This technique did not allow the mapping of the entire cave morphology, however, particularly the walls and ceiling. Most speleothems were not represented, and physiographic contacts between features such as floor and wall transitions were indistinct and not clearly defined. In terms of the final product, this mapping technique did not fully and accurately represent the spatial relationships essential for a clearer understanding of the cave setting for ancient and modern ritual or refuge use. While the cave floor topography and physiography were nicely portrayed (FIG. 6B), the shortcomings in using this technology in a speleological survey were apparent.

Point cloud laser scanning technique

Faced with these limitations, the survey team turned to 3D terrestrial laser scanning for accurately mapping the entire Skoteino cave system, from floor to ceiling. Terrestrial laser scanners, also known as point cloud scanners, utilize the same technology as a total station in that a laser beam is broadcast and returned to the instrument by reflecting off a remote surface. The difference lies in the number and range of measurements that can be made: terrestrial laser scanners are capable of collecting up to 12,000 points a second and cover a field of view in a 360° horizontal circle through a 270° vertical arc in each scan. The result is an enormous dataset, a cloud of data points (a typical 20 minute scan can produce about 3,500,000 data points) that digitally creates an accurate model of any scanned surface.

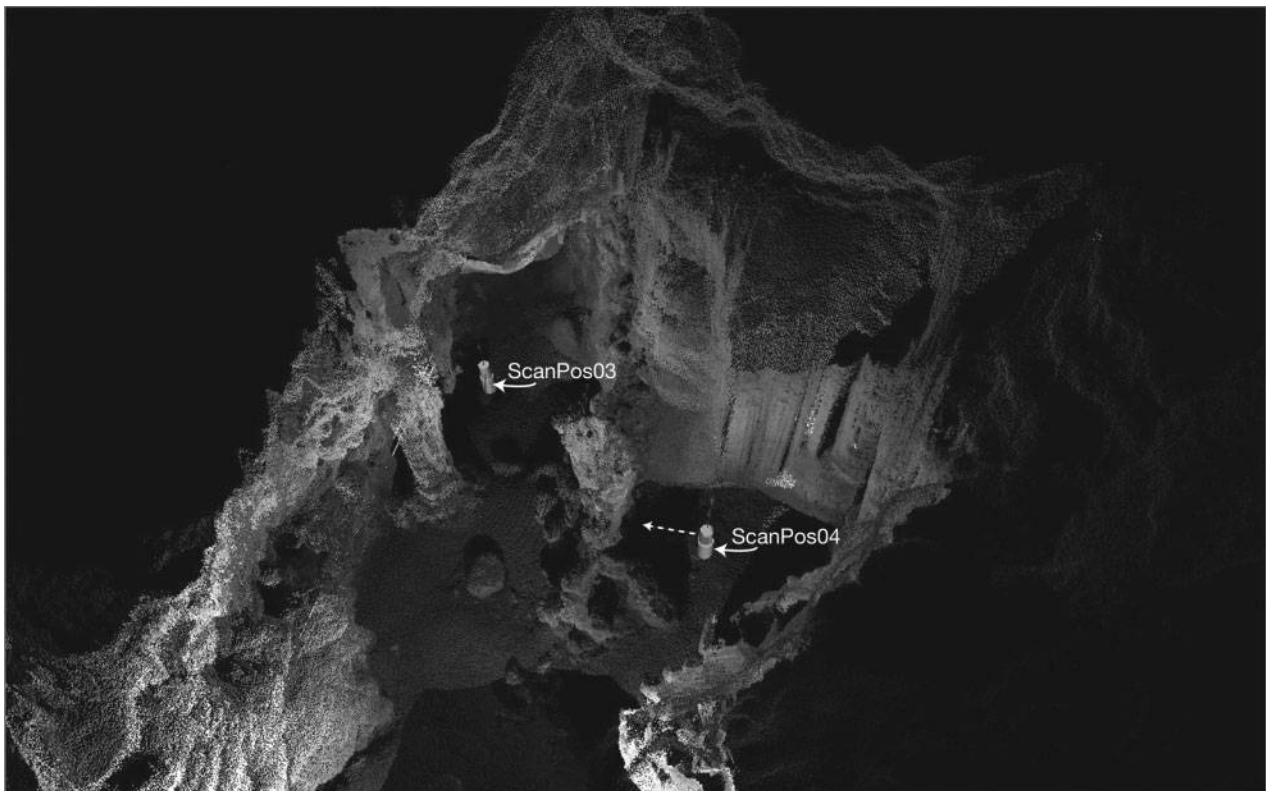


Figure 8 Color image obtained by the point cloud laser scanning technique reproduced here in black and white. Shown here is the southwestern end of Level II, an area excavated by Davaras (1969: 621–622). The area of the image is noted in Figure 3. The image was generated by J. Frey using RiScan Pro and Pointools View 1.7 P. Image reproduced by permission of the Greek Speleological Society (Δελτίον της Ε.Σ.Ε.).

This technique offers three advantages over standard electronic distance measuring devices such as total stations. First, rather than requiring the use of a handheld prism, it uses non-transparent surfaces to reflect the laser beam back to the instrument for measuring distances. The intensity of the returned signal can be quantified to scale surface roughness, a proxy for rock type or modification by man. Thus, measurements and characterization of even the most inaccessible features are possible without endangering members of the survey team or the unique natural features of the cave.

Second, a laser's scanning grid relies on an internally-generated geometry of points in which adjacent scans are used to triangulate not only the location of the 3D point, but to also merge two or more scans together to create a 3-dimensional image. As such, there is no need to register the instrument's location with respect to permanent benchmarks. Instead, point cloud scanning utilizes small reflectors that are temporarily placed in the cave, imaged during scanning, then removed at the end of the laser survey. It is these less destructive tie points and impermanent benchmarks that are later used to aid in "stitching" the various scans together during data processing. Third, due to its impressive rate of data capture, this laser scanner is by far the fastest technique.

A digital camera (in our case, a Nikon D-100 camera with a Nikor 14 mm lens), can also be mounted on top of the laser scanner in order to capture registered digital images during each scan. Data from these photographs may then be used to assign color values to the spatial locations of the points produced by the laser scanner. As illustrated here, the results of scans with integrated color provide incredibly accurate digital models of cave physiography (FIGS. 8, 9).

The overall survey results were impressive. In 2009, with the use of a Riegl LMS-Z420i laser scanner, the survey team was able to map an area equivalent to that surveyed over the entire two weeks of the 2005 season in less than four days. Scans were taken from 52 instrument stations to produce contour data with centimeter accuracy (± 1 cm/50 m). Moreover, the survey was able to include all of the cave's features from floor to ceiling at a level of detail that was not previously possible using a traditional total station. As stated above, combined with images from the high resolution digital camera, the resulting point cloud data were capable of realistically representing the various colors of the cave's features.

To be sure, our survey was not the first use of this technology for mapping archaeological contexts. The advent of 3D laser scanning in the early 1960s generated a growing number of uses over the intervening decades



Figure 9 Color image obtained by the point cloud laser scanning technique. Shown here is Level I of Skoteino Cave looking from the back toward the entrance of the cave (south to north); stratigraphy within the limestone bedrock is clearly denoted in the cave walls. The image was generated by J. Frey using RiScan Pro and Pointools View 1.7 P. Image reproduced by permission of the Greek Speleological Society (Δελτίον της Ε.Σ.Ε.).

(Cannataci *et al.* 2003). In particular, its use was expanded to include heritage management documentation, preservation, and conservation (Cannataci *et al.* 2003). It is presently being used, for example, for the documentation and conservation of historical buildings (e.g., churches), ancient sites, monumental sculpture, museum objects, and other ancient artifacts including the remains of an unearthed Roman boat (Wehr and Wiedemann 1999; Boehler *et al.* 2001; Cannataci *et al.* 2003; Kuzminsky and Gardiner 2012). In Greece, laser scanning has been used to map monuments of historical significance, including the architectural features near the Stoa of Eumenes on the Athenian Acropolis (Lefantzis 2006; Lefantzis and Pagounis 2006) and the Archaic limestone predecessor of the later marble Temple of Poseidon at Sounion (Paga *et al.* 2012: 10).

The use of laser scanning for caves is a more recent application, beginning at least by the late 1980s at Spain's Altamira Cave. Additional examples include: the Nottingham Caves in the United Kingdom (Nottingham Cave Survey 2010); several caves in Italy (Caprioli *et al.* 2003), including the Grotta dei Cervi (Patias *et al.* 2008: 109); the Dunhuang caves in China (Lutz and Weintke 1999); the Cingle de la Mola Remigia cave in Spain containing prehistoric rock art (Domingo *et al.* 2013); Les Fraux Cave in Perigord, France, a Bronze Age cave containing extensive cave art (Grussenmeyer *et al.* 2010); the deep chamber in Balankanche Cave in the Yucatán, Mexico where Maya artifacts were discovered in 1959 (CyArk Heritage Sites 2007); and Preacher's Cave on

Eleuthera Island in the Bahamas, a 17th century A.D. refuge site (Doering *et al.* 2006).

In Spain, scanned data from the Altamira Cave were used to create a replica cave for tourist access. This was in response to the alteration of the cave atmosphere resulting from elevated temperature and carbon dioxide concentrations from increased tourist traffic. These changes caused serious degradation of its famous Late Neolithic cave paintings (Patias *et al.* 2008: 109; Donelan 2002). In Greece, the only cave where 3D laser scanning technology has been used, in addition to Skoteino Cave, is the Polyphemos Cave of Maronia, Rodopi, in northern Greece (Patias *et al.* 2008). The Polyphemos Cave is traditionally considered the location where Odysseus blinded the Cyclops Polyphemos; excavations indicate human use from prehistory through Byzantine periods (Patias *et al.* 2008: 110). Here the cave mapping also included measurements of subterranean atmospheric conditions because of concern that increased tourist traffic could lead to deterioration of the cave environment. Because of the length of the Polyphemos Cave (350 m), 3D scanning was done only in the first two chambers (Patias *et al.* 2008: 109, fig. 1).

Discussion

The repeated survey of Skoteino Cave using different techniques placed the present survey team in the unique position of being able to comment on the relative advantages of each approach in overcoming the challenging mapping conditions encountered in subterranean environments. In terms of cost and

portability, the traditional measuring tape and compass are small and easily carried, with measurements taken relatively fast and simply, yet they produce inaccurate data. These data provide rapidly obtained reconnaissance information, with inaccuracies unsuitable for scientific work. Total stations used with reflectors, coupled with digital data collectors, record spatial data points that can be easily converted into drawings in computer mapping programs. Using a total station has a number of disadvantages in a cave environment, however. It is difficult to collect data in extreme low light situations, and multiple datum points are required for good collation of data points into accurate depictions and maps. While a total station is able to collect a far greater number of data points as compared to the tape and compass method, the amount of spatial information that can be collected in a reasonable amount of time still results in rudimentary digital models.

A terrestrial laser scanner has many advantages. The technique provides data depicting the entire cave from floor to roof and as with a reflectorless total station, a terrestrial laser scanner does not require a handheld reflector prism to conduct a survey. Both the reflectorless total station and the 3D laser scanner are effective for surveying complex interior shapes in a dark cave environment; with the use of light and a camera, the laser scanner has an advantage in that it is capable of capturing digital images in order to add color information onto the point cloud data. Perhaps most significantly, a terrestrial laser scanner is capable of producing an amazingly accurate virtual model of whatever has been scanned. As a result, the historian, archaeologist, or geologist can explore and share with others many aspects of a unique subterranean environment without having to be physically present in the cave. More importantly still, because the point cloud data can be used to generate models that test different lighting conditions and the visibility of parts of the cave from numerous points of view, researchers are able to test hypotheses concerning perceptions of the cave environment (Pujol 2004: 7).

There are, however, numerous disadvantages to the laser scanner technique, that range from simple practical considerations to far more abstract ideas concerning the function and goals of reproducing an ancient monument or environment. Simply in terms of the physical limitations of a terrestrial laser scanner survey, several points should be noted. Transportation of a 20 kilo laser scanner (40 kilos together with its box; although newer designs are lighter) and camera was cumbersome and difficult on the slippery, irregular cave floor. A scanner requires additional equipment (laptop computer, generator, and power/data cables) to operate correctly. While the scanner itself functioned flawlessly in the low light

of the cave, the digital camera was not able to accurately gather color data at either low light levels or at long distances. As a result, artificial lighting (a 500 watt halogen lamp) was required to supplement the camera's flash. The entire imaging area must be evacuated to ensure a clean scan; this is not always an easy option at locations with a large number of visitors. While large and very heavy 12V lead batteries are capable of powering the scanner, the number of additional instruments requiring power made the use of a generator a far more efficient option. Batteries had to be constantly replaced and recharged, and carrying these into and out of the cave for recharging was both physically taxing and a hindrance to the steady progress of the scanning project. All of these problems became more complex as the survey moved deeper into the cave. Even though the newest terrestrial scanner models are much more portable, consume less power, and feature improvements such as wireless connectivity and onboard data storage, we expect that many of these problems will still affect the survey process, albeit to a lesser degree.

With respect to the survey process itself, terrestrial laser scanners may be simpler to use, but surveyors still need to observe many of the same traditional survey practices that govern the use of a total station. One must carefully decide where to place both the laser scanner and the reflectors in order to observe complex spatial relationships and to minimize shadow zones behind prominent physiographic features. In addition, while the use of temporary reflectors as anchors between survey sessions is both simpler and less destructive than the creation of permanent benchmarks, once those markers have been removed, it can be difficult to add new point clouds to a preexisting model.

Perhaps the most difficult challenge has come from this method's greatest strength—the immense amount of data acquired during a simple survey. The preliminary model of the upper half of Skoteino Cave produced by terrestrial laser scanning contained 117,681,417 points (1909 MB of data), making the production of a digital model of the cave with the type of processors that were available to the project a complicated and time consuming process. As we have begun to discover, the time and effort that we assumed was saved in the data collection phase was merely transferred to a later stage in the project, when each of the 52 individual scans had to be cleaned, colored from the associated photographs, and stitched together to form a properly registered point cloud. While we accept that advances in processor speed and storage will inevitably alleviate some of these issues, for the present time, simply visualizing the amount of data generated by this technique remains a challenge. In

essence, one is forced to reduce the amount of data in order to manipulate the point cloud so that the resulting model is potentially a less accurate reflection of the original surfaces than a simpler plan accompanied by photographs.

What is more, it is only in the last few years that many different software and hardware manufacturers have begun to move away from exclusive and proprietary solutions to a common set of standards. In many ways still today the models that can be produced from these prohibitively complex point clouds cannot be easily converted into formats that are traditionally recognized by the academic and publishing communities. Nor, at present, do we know of a way to integrate the spatial evidence of artifacts and features that were previously excavated and were therefore not present in the cave at the time the terrestrial laser scanning was carried out. Voxel-based models represent a promising approach to integrating archaeological stratigraphy within a 3D GIS, but have yet to accommodate complex 3D structures like point clouds generated by laser scanners (Bezzi *et al.* 2006; Lieberwirth 2008). Ideally, 3D laser scanning should “go beyond visualization” (Koller *et al.* 2009: 7.13) but, at present, there does not seem to be any easy-to-use or standard software for artifact integration (P. Sapirstein, personal communication 2012).

As methods of digitally recording and storing spatial information about sites and monuments grow ever more complex, archaeologists must begin to critically evaluate whether the traditional printed journal and its illustrations are the most appropriate formats for displaying these data to the wider scholarly community. As the accompanying illustrations show, the images produced by a laser scanner are now beginning to rival that of the more traditional photograph. While it is possible to create classic plans and elevations by cutting sections and profiles through a point cloud model (Maletic *et al.* 2003: 4), graphic presentation is restricted to a 2D format. Clearly, a different means of reproducing a 3D model—one that can be manipulated and viewed from different angles—is now needed if the goal is to recreate the experience of witnessing firsthand an archaeological site or monument. Online journals or links to stable URLs featuring more interactive models would appear to be the best solution to this growing problem (cf., <http://nottinghamcavessurvey.org.uk/>).

Yet, at an even more basic level, the growing popularity of terrestrial laser scanning as a means of recording and representing monuments and environments raises significant questions about the role of the archaeologist and cartographer in interpreting the ancient world. Until the advent of 3D scanning technology, the creation of a plan or elevation drawing

remained an act of onsite interpretation. This essential characteristic of traditional cartographic survey is most apparent to us in the case of the earliest drawings of Skoteino Cave, where the roughly sketched plan of the cave floor is as much a product of the archaeologists’ impression of the subterranean environment as are their actual measurements. Even with the use of the most sophisticated total stations, the collection of spatial information continues to require one or more surveyors to determine which points are most worthy of recording.

This was apparent to us throughout the second phase of mapping the cave interior, when the decision as to how many and which points were needed to represent the shape of a stalagmite or the point of transition from the floor of the cave to its sloping walls resulted in an ongoing conversation among members of the team. Furthermore, when these points were connected with vectors in a CAD program—often the evening after they were collected—the resulting features were still very much an act of interpretation, much more akin to the traditional use of ink and vellum. On the other hand, the automated process of collecting spatial data by means of a terrestrial laser scanner requires little to no onsite discussion of the cave’s features and environment. Instead, terrestrial laser scanners simply produce a near exact digital copy of whatever they scan in a remarkably short amount of time. The resulting dataset must then be integrated to produce an overall model, typically some time after the end of the laser scanning campaign. While the overall detail of the model should rightly be considered a positive development in terms of the historical preservation of cultural heritage monuments and sites, it is worth considering the ways in which the transfer of the critical stage of interpretation to a less immediate time and place may affect our understanding of the archaeological past.

At the present moment, the research team at Skoteino Cave has engaged in a much more modest use of the data generated through its terrestrial laser scanning survey. The creation of a highly detailed color point cloud has allowed investigators to document the natural features of the Bronze Age ritual area. These include its entranceway (which is framed by grand, tall stalagmites), the natural “altar” (the broad stalagmite mentioned above that is either naturally occurring or cut to give the appearance of a table), the entranceway into the innermost ritual area (which is framed by a natural column and a stalagmite), and more (see Tyree *et al.* 2005–2006: 56, figs. 6, 7). It has further allowed documentation of additional manmade features that are probably not ancient but nevertheless of interest for the more recent history of the cave, such as rows of benches

forming a theater of some sort; catch basins for collecting water (still used today in festivals); and vertical scorch marks that are evidence of candles and/or torches that were originally placed in slots chiseled into the cave walls (Tyree *et al.* 2005–2006: 53, 55–57, fig. 2). Because the point cloud can be manipulated in a virtual space, investigators are able to produce images illustrating any part inside the cave that rival photographs in detail and clarity.

Other elements of an experiential approach to cave studies include subterranean visibility and atmospheric conditions: light intensity levels, temperature variability, relative humidity values, carbon dioxide concentrations, air circulation, smell, etc.—are all better sensed within the context of our proposed virtual models (Tyree *et al.* 2005–2006: 58–61). Thus, for example, cool air and darkness upon entering a cave creates a suspense that is intensified by the smell of dense, earthy moisture (Tyree 2001: 41). While it is the case that the third phase of mapping the cave required the use of intense artificial lighting to color the point cloud, it is still possible to build a model that recreates the much darker conditions of the cave in antiquity. Thus, we will come to a better understanding of the ancient experience as one progresses farther into the darkness, and these sensory aspects of the cave environment can be coupled with the virtual models and thus, “an archaeology of the senses” can be explored at Skoteino Cave.

Conclusion

In summary, all three mapping methods presented here have distinct advantages and disadvantages. Each method has a different purpose, a different cost, and provides a distinct difference in mapping accuracy. Our experience at Skoteino has shown that one should not assume that the most recent or technologically advanced technique represents the best approach. Thus, the first two techniques, tape with compass and the EDM total station (with or without a reflector), are much easier and simpler to use and process than the third, the point cloud laser scanning technique. Mapping accuracy improves with the EDM total station and point cloud system. Traditional 2D documentation has the benefit (or often, the limitation) of including a level of selection, simplification, and interpretation of the subject, which is valuable within the realities of its accuracy as well as the historical context in which it was created. And, as noted above, the first two methods are more conducive to presentation in traditional print journals. The third method, 3D laser scanning, provides the larger amount of data using state-of-the-art technology, but with large costs in terms of money, hardware requirements, and processing time. While the acquired data are vastly improved both in

depicting the spatial setting and in quantitative accuracy, if they cannot be readily disseminated, then there has been limited gain.

Yet, as they become more affordable, technological advancements, including laser scanning, are benefiting the archaeological community in its attempts to find better methods of interpreting and representing archaeological sites. Moreover, the use of high tech equipment such as terrestrial laser scanners is particularly beneficial for some monuments and sites, such as caves, that would benefit from having 3D models. This new technique is economical in the sense that it eliminates paying for hours and hours of surveys that provide limited and often inaccurate data. Furthermore, point cloud projects can be useful in depicting different viewpoints and increasing accessibility for interpretive purposes. At the same time, one should not underestimate the time and expense of the necessary post processing of the data generated by this technique. As such, not all sites will benefit from having a 3D model and, in most cases, it is not even needed or wanted. Site plans will still be necessary, especially in traditional forms of publications. Point cloud technology represents a significant and important advancement in mapping and portraying spatial information that will continue to significantly benefit the archaeological world.

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