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Original article

Detection of geometric changes for an historic theatre by comparing surveying data of different chronological periods

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ABSTRACT

This paper presents results from a study where identification and documentation of geometric changes are examined from a weathered ancient theatre using map regression methods. Specifically, a comparison is made between a topographic map created in the 1960s by the German Archaeological Institute and a new map of the same area using state-of-the-art geodetic and terrestrial laser scanning (TLS) techniques. The work scale of the maps is 1:100 and can reveal changes and deformations of relevant size to the scale of the map (over 1.5 cm). The process, described in detail, entails georeferencing, planimetric and vertical comparison and assessment of the changes. The study demonstrates the importance of detecting topographic changes in cultural heritage sites and can be applicable to similar analyses over a range of time periods.

1. Introduction

The conservation, preservation, and documentation of cultural heritage landscapes and sites have concerned conservationists, historians, and scientists for many years. The conservation of a cultural heritage site depends on the materials of which it is composed and on complex processes such as ageing and environmental effects. Therefore, detecting and quantifying even small-scaled changes in cultural heritage sites helps further understanding the deterioration process, particularly in relation to the underlying mechanisms which drive their evolution. Considering the large number of cultural heritage sites, the monitoring methods must be reliable and accurate and capable of detecting and documenting changes on various scales.

Historic changes in cultural heritage sites can be quantified with geospatial data from a number of techniques depending on the application. These techniques vary from field topographic surveys to advanced technologies of dense data collection by satellite, airborne imagery, laser detection ranging or terrestrial laser scanning (TLS). TLS is a favourable technique allowing complex sites to be rapidly surveyed at previously unattainable point densities. It also provides the resolution and accuracy for cultural heritage applications requiring detection, characterization, and analysis of changes, as well as large-scale deformations.

Often, it is possible to use data from historical maps to examine differences in heritage sites. In maps where accurate historical topographic data are available, map regression techniques can be implemented between recent and earlier maps of the same area to determine changes or to locate past features [1]. Using modern maps to transcribe or reproject earlier maps can help to locate these features with contemporary survey controls and techniques. Map regression is performed either by comparing individual features between maps, or by reprojecting an entire map so as to fit another onto which it can then be superimposed. The process can include resolving any differences in map scale, projection, datum, or format; and the interpretation of each map in its meaning and accuracy.

In map regression, the comparison is made planimetrically and vertically. The most common approach refers to the vertical component and such comparisons are performed using digital surface or elevation models (DEMs). The comparison is performed using the DEM reconstruction from the historic map with subsequent DEMs from recent maps, which produce DEMs of difference. Examples include change detection in archaeological sites using satellite imagery data or for predictive archaeological research [2–4]. The use of DEMS derived from TLS for the detection of changes has

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been reported for landscape archaeology [5], as well as comparisons with other historic data in order to extract information about archaeological resources and landscape change [6–7].

This paper aims to present a methodology used for detecting topographic changes for the archaeological site of the Kabeiroi in Thebes, Greece using map regression by comparing an early topographic map of the late 1960s created by the German Archaeological Institute [8] with a recent map created using TLS data. Emphasis is given on the ancient theatre of the sanctuary. Ancient theatres have always appealed more in the preservation and restoration of historic monuments, due to the increased interest of countries to enhance the cultural activity of a region. Often, an ancient theatre can be used for performances but the usage of an ancient theatre for such purposes needs to be approached with particular attention [9]. The work presented in the paper is linked to the restoration of the ancient theatre of the Kabireion sanctuary and involved surveying measurements for the structural documentation of the theatre to plan and optimize maintenance of the theatre. Over the years, researchers have monitored and studied changes in ancient theatres and their surrounding sites using either classical surveying techniques for small scale phenomena, or aerial photogrammetry for larger ones [10–12]. Related TLS research has expanded substantially, delivering high-resolution elevation models and significantly improving the monitoring of degradation processes in ancient theatres [13–15].

In this work high accuracy geometric documentation techniques are used (TLS and geodetic techniques) to create a 3D model and a topographic map of the ancient theatre. The comparison to identify geometric changes is performed planimetrically and vertically. The georeferencing and integration of the data is performed within a geographic information system (GIS) environment. Planimetrically, the comparison is made through polygons and vertically, through selected sections of the theatre. Finally, a statistical analysis is given to identify whether the positional differences of well-identified objects in both maps represent real differences and not considered artefacts of the old map. The remainder of the paper is structured as follows. Some historic notes of the study area are given in section 2. Section 3 provides a description of the 1960s topographic maps and the present data acquisition using TLS and geodetic techniques for the documentation of the theatre. The methodological framework is outlined in section 4, followed by the data processing and the results for the planimetric and vertical comparison between the two maps. Also, a statistical analysis is given to assess the differences within a specified uncertainty. Finally, section 5 gives a discussion regarding the obtained results along with concluding remarks.

2. Historical notes on study site

The archaeological site of Kabeirion of Thebes in Greece has been the target of a number of previous archaeological studies [16]. In 1887 the Kabeirion was discovered due to a chance find of bronze statuettes. It was exclusively excavated in 1888-9 by the German Archaeological Institute [17] and the excavation was continued by Bruns between 1956 and 1966. A supplementary excavation took place in 1971 [8].

The most important monuments of the Kabireion sanctuary are [18]:

- the temple: devoted to the gods called Kabeiroi. It is a rectangular building the oldest remains of which are dated at the 6th century B.C. onwards. The preserved foundations are from the end of the 4th century B.C. The temple was supplied with pronaos, cella and a courtyard with two rectangular sacrificial pits and was enclosed by a circuit wall;
- the theatre: built during the hellenistic period (3rd–1st centuries B.C.) on the same axis as the temple. It had no front scene, but had 10 sectors in the cavea and an altar in the middle of the orchestra. It was used for the attendance of religious ceremonies concerning the initiation of the pilgrims;
- the Stoa: built in the 1st century B.C. and is a long-narrow building of 40 m length, on the south-east of the theatre;
- circular and elliptical buildings: found everywhere in the sanctuary. They contained sacrificial pits and benches along the walls for the practices of initiation. The largest one from the end of the 5th century B.C., between the temple and the stoa, was probably a plain unroofed enclosure wall;
- the circuit wall: before 300 B.C. enclosed the temple and an open-air area in front of it. In the 2nd century B.C. it extended to the east in order to include the cavea of the theatre.

Over the years, wild vegetation and the shutdown of the ancient drainage systems have caused damage while a large part of the ancient buildings and constructions have been filled in by soil embankments. To date, following excavation of the area several visible remains can be seen with the most important being the theatre and the temple (Fig. 1a).

3. Data

In the following subsections, a presentation of the data (old topographic data and up-to-date TLS data) collected for the Kabireion theatre is given.

3.1. Topographic Maps of 1960s

The German cartographic presence in modern Greece started in the 19th century with its origin in matters of archaeological and historical interest. Its contribution to the topographic mapping of several parts of Greece is extremely important [19]. The historic material that was used in this work involves three maps:

- paper copy of a map at a scale of 1:1000, created in 1966 by von W. Zick and revised in 1969 by W. Heyder, showing the Kabeiroi sanctuary and its environs (Fig. 1b);
- paper copy of a map at a scale of 1:100, created in 1969 by W. Heyder, showing the Kabeiroi theatre prior any excavations (Fig. 1c);
- paper copy of a map at a scale of 1:65, created in 1969 by W. Heyder, providing height levels of the Kabeiroi theatre prior any excavations (Fig. 1d).

There is no firm information regarding the field surveying techniques that were employed in the creation of the above maps. Based on the surveying techniques employed at the time, it is certain that angle observations were acquired using theodolites. The accurate measurement of long distances is achieved using electronic distance measurement (EDM). However, it is certain that EDMs were not used in the specific archaeological expedition, besides tape measuring. The first EDM equipment by the early 1960s was large and cumbersome and it was not until the 1970s that EDMs came into everyday topographical use. Towards the end of the 1950s, photogrammetry was introduced for the topographical mapping of some German states but it is almost certain, from the above three maps, that photogrammetric type data were not acquired for the Kabireion sanctuary. Regarding height information, it is considered that geodetic levelling was used to estimate height differences, this being a mature technique in the 1960s.

Clearly, the challenge of using historic data from topographic maps is dependent on the quality of source materials and processing methods for their construction. For example, contour

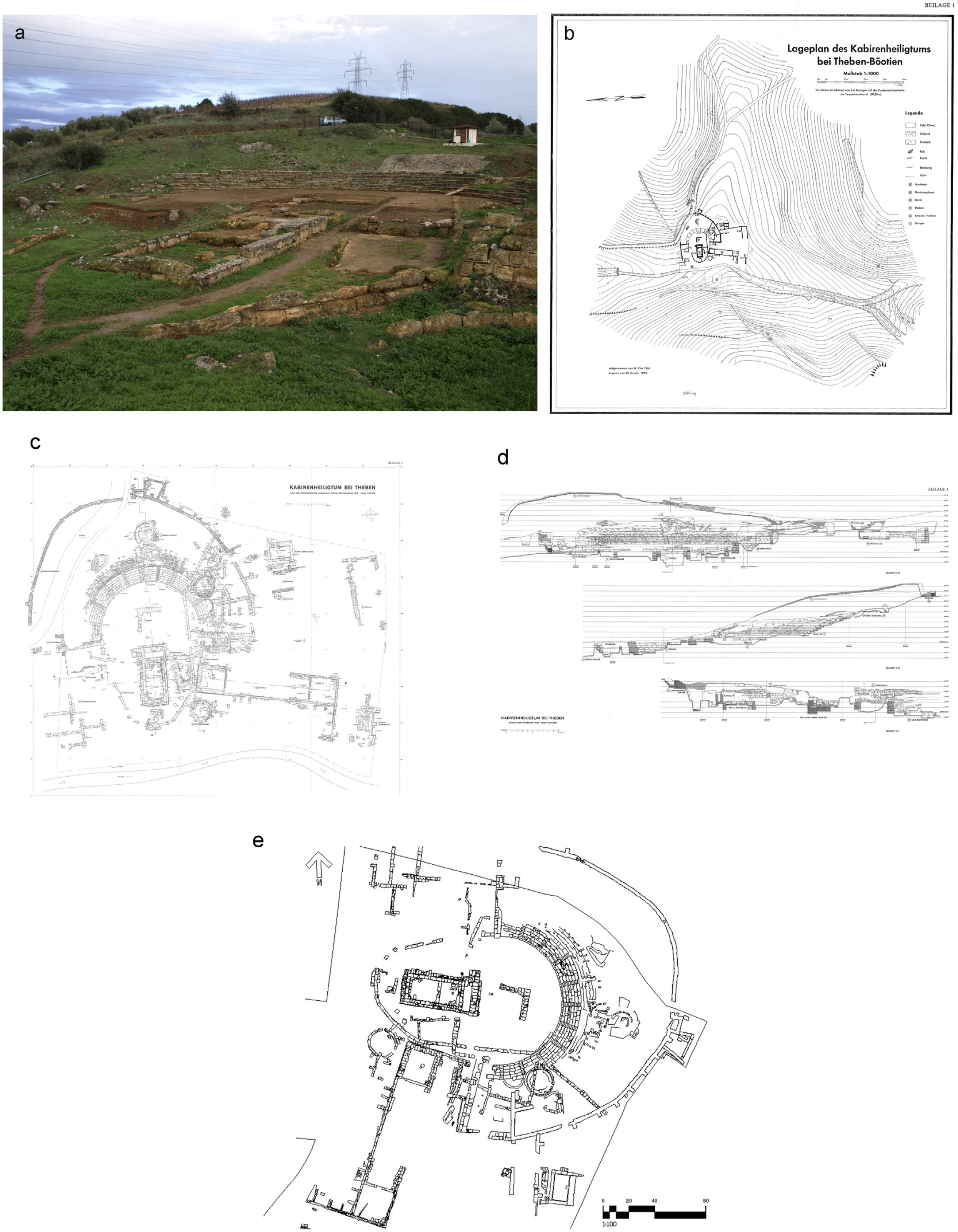

Fig. 1. a: the Kabireion theatre; b: topographic map of the Kabireion site by the German Archaeological Institute dated 1969 (scale 1:1000); c: topographic map of the Kabireion theatre by the German Archaeological Institute dated 1969 (scale 1:100); d: height elevation map of the Kabireion theatre by the German Archaeological Institute dated 1969; e: selected vectorlines in the 1969 topographic map.

lines on many early (i.e. pre 1940s) topographic maps were “artistically” drawn with little intervening field observations between field measurements. However, it noted that the archaeological drawings of the specific period, which is the 1960s map, were using simple and minimal lines without too many artistic elements following a trend originated by the Danish architect Erik Hansen [20]. The quality and confidence in the historical topographic data available are usually the limiting factors in the accuracy of the resulting differences between the maps and the subsequent analysis. Before using the information contained in old maps for map regression purposes, its quality must be assessed. According to [21], three different aspects should be assessed. The first is the topographic accuracy that denotes the quantity and quality of information about landscape objects, i.e., whether the map depicts all features of a certain class. The second aspect is the chronometric accuracy, i.e. the dating of the information contained in the map. Dating the age of map information (i.e. when the data were acquired) is often difficult, as the production or the revision of a map commonly took several years. The third aspect is the planimetric completeness (or geometric accuracy). The geodetic accuracy describes the accuracy of the positioning of the map in a global coordinate system (i.e. reference system, map projection) and the planimetric accuracy refers to the extent to which distances and bearings between identifiable objects coincide with their true values. This can be achieved by comparing the positions, distances, areas, and angles of features on the map and in reality.

Regarding the 1960s maps, topographic correspondence with reality was checked in situ (see section 4.2). It became evident

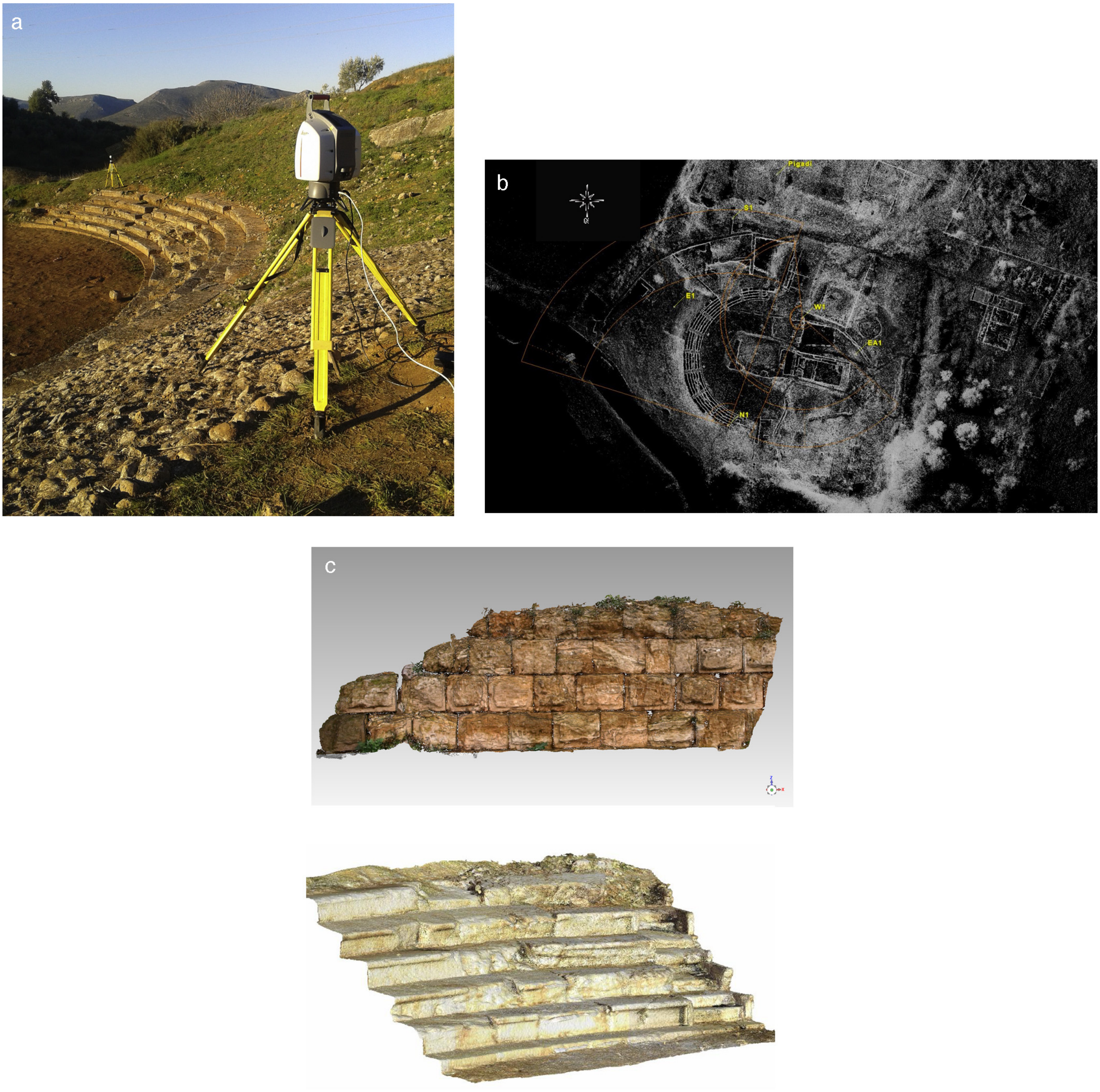

Fig. 2. a: TLS data acquisition; b: point cloud of the Kabireion site; c: details of the rendered model of the theatre stairs and the wall.

that the 1960s theatre map of scale 1:100 presents only the largest erosions of the theatre which was constructed from soft-porous stones. Many Greek theatres were constructed using marble where cracks due to flaking or other capillary cracks would be evident. With regards the second aspect, the data collection was performed between the late 1950s and early 1960s [8] with the revised map dated in 1969. There is no information regarding the reference system and the map projection. It is assumed that a local coordinate system and a planar projection have been used. Various methods exist for analyzing and visualizing the third aspect, planimetric accuracy in historical maps [22]. Almost all methods derive from two sets of corresponding points which define a vectorline, i.e. one set in a modern reference map and one in the old map. Each vectorline starts and ends at the points that are identified in both the old map and the modern reference map. The distance and orientation of the vectors between the two maps are compared to indicate outliers that are due to gross positional errors in the old map. In this work, a total of 30 vectors were examined which are indicated in Fig. 1e. The same vectors were measured in both the field and the TLS derived map. The maximum difference was at the ± 5 cm level and the RMS of differences was equal to 2.3 cm. Whist it is recognised that early maps may present different levels of point and relational accuracy in topography, the 20th century maps were constructed according to cartographic standards and therefore it has been assumed that the planimetric accuracy of the map is in the order of 5 cm.

3.2. TLS maps

A topographic map of the Kabireion sanctuary using state-of-the-art surveying techniques was created. Specifically, a combination, of techniques utilising total station surveying, GNSS surveying and TLS were implemented. Initially, a control network of four points was established outside the site to be used for documentation and monitoring purposes. The network was measured by static GNSS surveying (Javad Triumph-1 geodetic receivers) and was connected to the national survey network (realised in the Greek

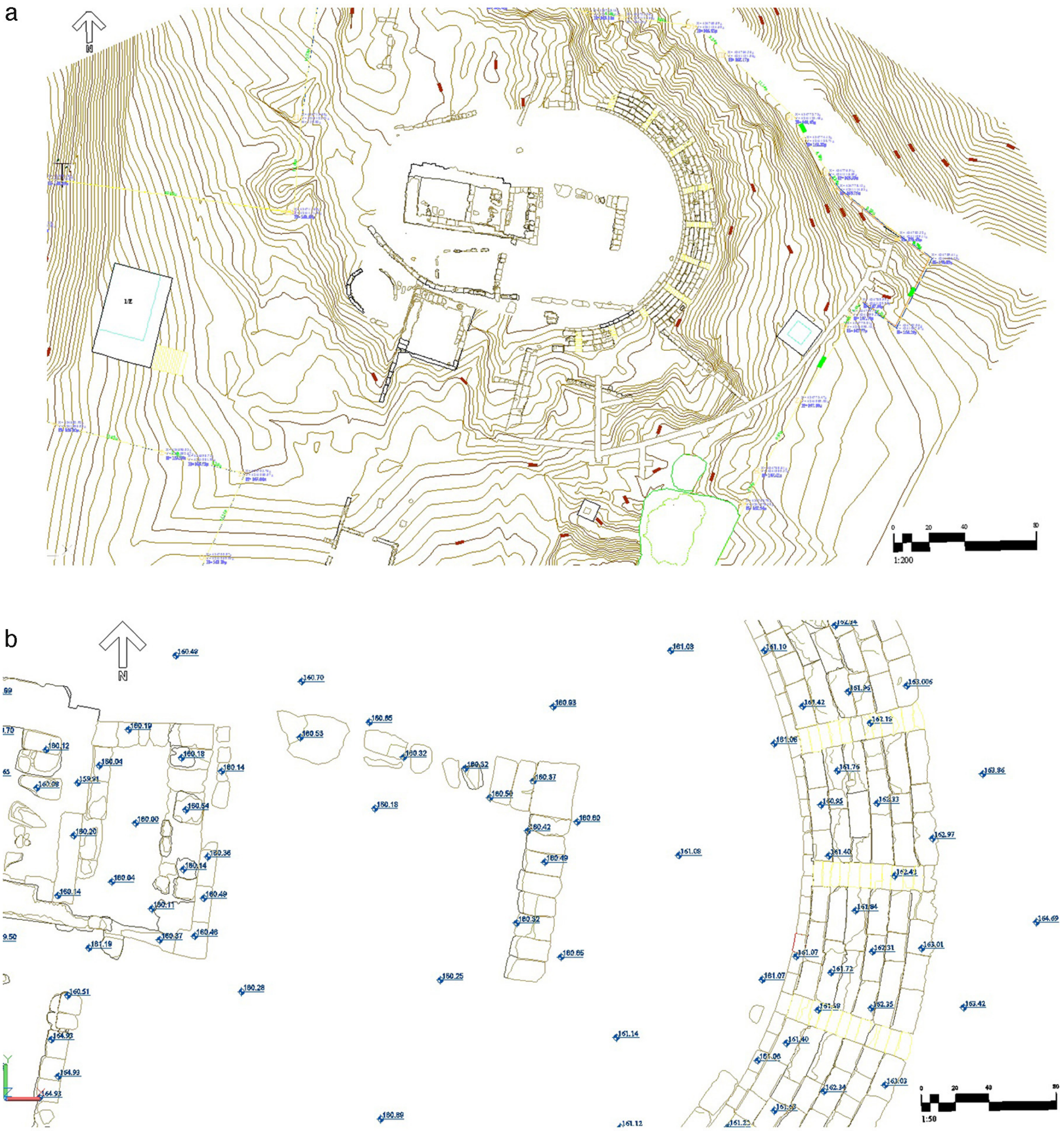

Fig. 3. a: view of the TLS topographic map; b: detail of the TLS map showing part of the theatre.

Geodetic Reference System 1987, GGRS87) with an accuracy of 0.007 m in the horizontal and 0.011 m in the vertical. The collection of horizontal point coordinates for the surroundings of the theatre was performed easily using network RTK surveying at an accuracy of 2–5 cm.

The TLS data acquisition was performed using the Leica Scanstation2 laser scanner (www.leicageosystems.com) from 37 different positions with known coordinates in order to fully capture the site and avoid occlusions (Fig. 2a). The positions of the 37 points were prior estimated by static GNSS measurements at the precision of the manufacturer (Javad Triumph-1 receivers with horizontal precision of 0.3 cm ±0.1 ppm × baseline length, www.javad.com). This means that direct georeferencing was used. In this way the scanner was set up over a known point (and its height over the point measured), was centred, levelled and oriented towards another known target where a spherical reflective target was set up (backsight), like a total station. The acquired scans taken from multiple scanner stations were already in the same reference system (GGRS87) and then were easily merged into one dataset. The spherical reflective targets were scanned with an accuracy of 1–2 mm and the RMS error of the direct georeferencing was 0.9 cm (in the horizontal) and 10 cm (in the vertical). An effort was made to maintain short distances (up to 100 m) between the scanner and the scanning objects and the scan point density was 3 × 3 mm and in some cases 6 × 6 mm. The data processing was performed using the commercial software packages Cyclone and Geomagic. Prior to registration, suitable filtering was applied to remove noise, redundant points and outliers.

Fig. 2b gives a typical example of the registered point cloud, which in turn becomes a 3D model using appropriate software. The 3D model was also rendered using texture mapping techniques. Fig. 2c and d give examples of the texture mapped 3D model of the theatre. Texture mapping is intended as a method for adding colour information to a 3D model derived from TLS data. This is usually been accomplished by photogrammetry or using control points or marks placed at the building or terrain [23]. In this model, a number of digital colour images acquired from an external camera were mapped onto the 3D TLS model. Thus, full resolution colour texture is mapped inside every triangle of the reconstructed 3D model and not only at the vertex points. Therefore, a true orthophoto is created. However, the aim of this work was not only to create a 3D model of the theatre but also 2D topographic maps and sections for the structural documentation of the monuments. The 2D derived map in the national grid (of the GGRS87) was used for a direct comparison with the old topographic map (Fig. 3a).

This was performed through the Cyclone CloudWorx for AutoCad (hds.leica-geosystems.com) software package. Within this environment a number of cutplanes can be defined, representing slices of elevations from different sides of the structure as well as a horizontal slice resulting in a footprint of the structure. The thickness of a slice can be changed based on the type of the geometry that is applicable. In this work, a "semi-automatic" line generation process was used. Once the operator creates a "slice" a least squares best-fit line on the points is generated based on the defined geometry (i.e. line, circle, etc.). Depending on the number of points in the "slice", the RMS of the residuals for the least squares best fit varied from 0.2–2 cm. Line fitting for points of free geometry, like edges and corners, was performed manually. The 2D plan was then made by using the standard CAD drafting tools.

4. Topographic comparison

The general procedure prior to any comparison between the two maps is to perform a georeferencing transformation in order to have a unique reference system, i.e. the same geometric framework. For this task, two sets of corresponding points are used, one originating from the modern map and assumed accurate while the second is from the old map and is considered inaccurate. A sequence of geometric transformations is applied between the sets of points so that to register the old map with the coordinate system of the new map. In this work, the map of 1969 (Fig. 1c) after being manually digitised, was registered to the coordinate system of the GGRS87 in order to coincide with the system of the TLS map (Fig. 3a). An affine transformation was used to establish the one-to-one correspondence between the old and the new map. This is coincident with a linear transformation that includes a translation (shifting), a global rotation and a scale change. The affine transformation gave an a posteriori sigma of 0.106 m for about 20 control points with a regular distribution. The resultant sigma of 10 cm for this number of points corroborates with relevant literature [24].

4.1. Methodology

The comparison between the maps is concerned with topographic changes in both the horizontal and vertical. For the horizontal comparison, the use of polygons was implemented rather than comparing single point data [25,26]. The advantage of

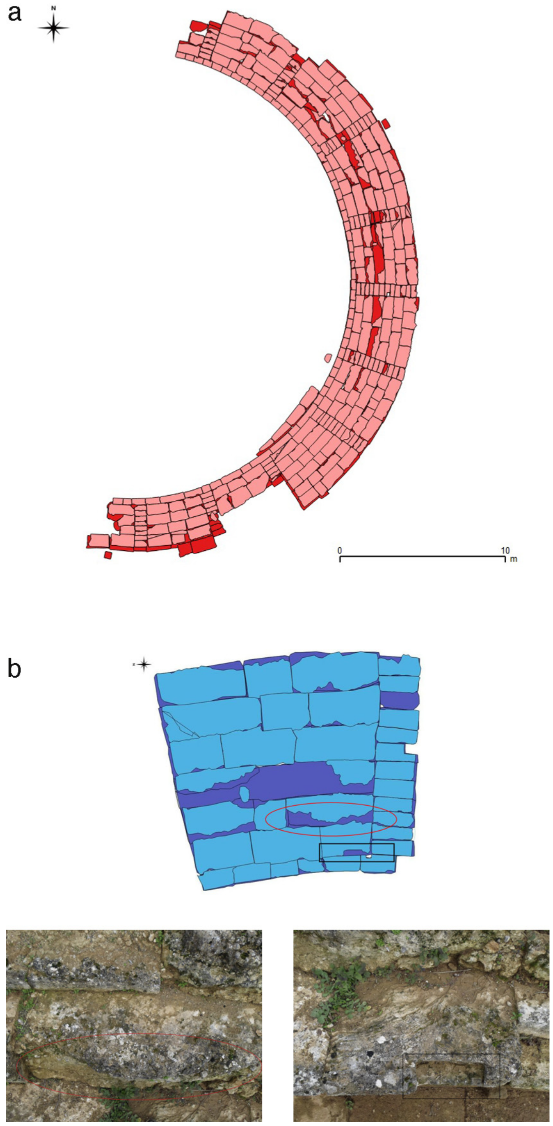

Fig. 4. a: differences between the 1969 and the TLS maps for the theatre; b: example of geometric differences.

polygon data over point data is that the former provide a more accurate representation of the size and shape of structures. In archaeology the use of polygons is often employed giving a more comprehensive spatial distribution of archaeological resources within a study area.

As discussed in section 3.2, the TLS map was created using polylines which define polygons in the same way as in the 1969 vectorised map. The polygons referred to each structural element of the seats which in this case are the stones. The comparison between the two maps involved polygon site boundary locations, shapes and areas by calculating the percentage of the polygon non-overlap. Comparing the same polygon derived from each map, a difference $\delta_i = \text{polygon}_{TLS} - \text{polygon}_{map1969}$ is calculated. Regarding the difference, the use of a critical threshold t (i.e., a null hypothesis) is implemented for screening the change, based on the ratio of observed changes to error. A significance level at 95% is used for *t* values to filter out changes that are not significantly different than the errors. Assuming a Gaussian distribution, the Student's *t*-test is used to standardise the differences by:

$$t_i = \delta_i - \bar{\delta}/\sigma_\delta, \quad i = 1, \ldots n \tag{1}$$

where, *n* is the total number of polygons and $\delta_i - \bar{\delta}$ is the differences from the mean $\bar{\delta}$ with associated standard deviation of the difference σ_δ. The *t*-value reflects the confidence that the change is an actual change or difference (*e*):

$$e_i \rightarrow [\left|t_i\right| \geq t_{\alpha/2,\,\text{n-2}}] \tag{2}$$

4.2. Planimetric comparison

The comparison of the two different topographic maps was performed within a GIS environment (open access software QGIS). The theatre was divided into a number of components following the crunei. Each component comprises a number of polygons and for every polygon an attribute table provides specific information about the size (i.e. perimeter) and the area of each polygon along with the differenced area between the polygons derived from the two topographic maps. The GIS software creates the difference as a new feature based on the area of the input layer that is not overlapped by the clipping or compared layer.

Fig. 4a shows the comparison between the digitised map of 1969 and the TLS map. The area differences between the two maps for the cavea (or koilon) are shown in dark colour. This has been created by superimposing the TLS map onto the 1969 map. Thus, the dark areas in Fig. 4a are missing to date. Fig. 4b illustrates a zoomed part, whereby the differences of the topographic maps indicate clearly the weathered stone elements of the theatre which is also verified by the recent photographs.

The majority of the lost material is seen in the middle sections of seats (kerkides) and the retaining walls. The stone material of the theatre is soft-poros, which is found locally near Thebes. It is brittle and tends to disintegrate when weathered. Thus the damage suffered has been mainly from erosion, and the growing of plants. The orchestra area was covered by a deposit of earth and was found by the Regional Archaeological Service to have had an increasing depth. In fact, the earth deposit was washed in an easterly-westerly direction, i.e. towards the orchestra area. On the other hand, the earth deposit has preserved the theatre and this is mainly the reason that there is less damage than might be expected. In [27] the geology of the area of Thebes in historic times is described as being composed of a group of plains covered with deep top soil, unusually fertile for Greece.

4.3. Vertical comparison

The vertical comparison was more difficult to execute as it was not possible to register both maps in the same vertical datum. The 1969 map refers to a local height system (Fig. 1d) whereby sections were taken based on step elevations varying from 27 to 41 m. On the other hand, the height information of the discrete points of the TLS map refers to the mean sea level. Therefore, it was decided to examine height differences rather than absolute elevations. For this reason, cross sections of the point cloud at appropriate

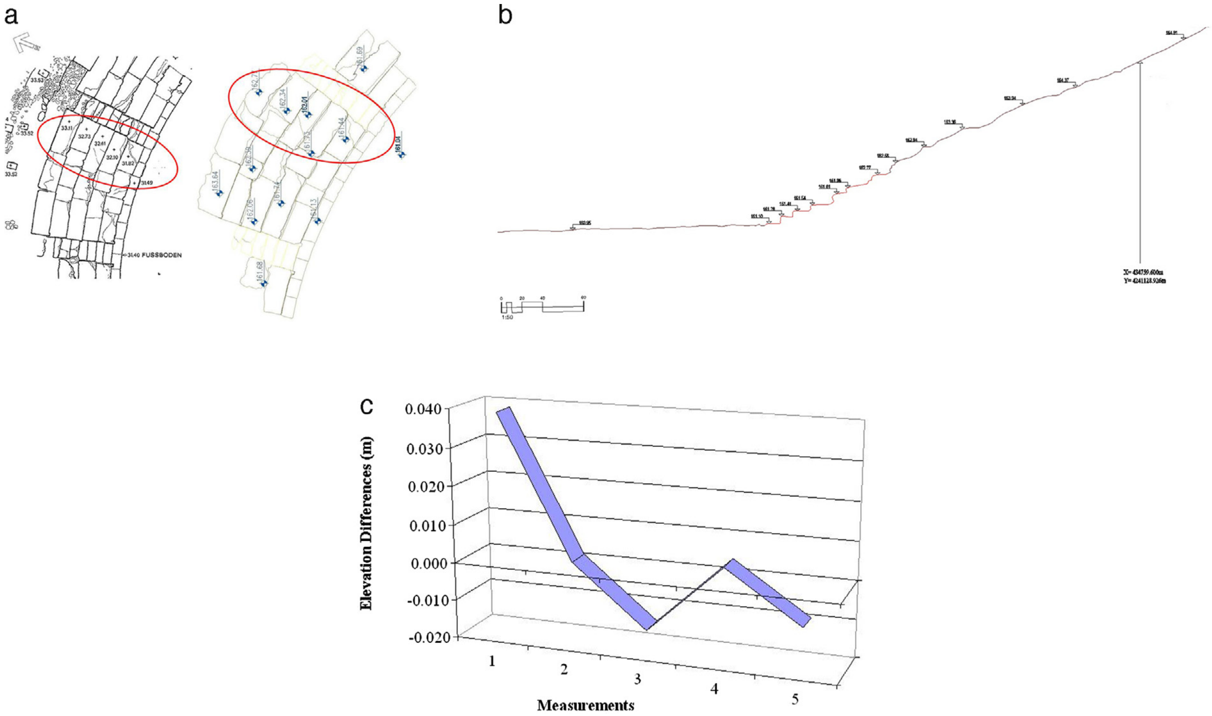

Fig. 5. a: selected area in the 1969 map and identical area in the TLS map for deriving sections (6th crunei); b: typical example of a section derived from the TLS topographic map; c: elevation differences for the steps of the 6th crunei.

levels were made, at exactly the same points shown at the 1969 map. Fig. 5a shows an example from the 1969 map depicting six points of known elevations at the local height datum and the equivalent part in the TLS map, with the height information referred to the mean sea level. Its respective section is given in Fig. 5b with the height values shown on each step. The elevation differences between the two sections are given in Fig. 5c which vary from 2–4 cm. However, this difference is not considered significant statistically as it is within the data error noise of the ground survey. The same procedure was followed for all the sections of the theatre.

4.4. Statistical analysis

The analysis for assessing the geometric changes between the two maps was based in the quantification of uncertainty in each individual polygon for the two maps, the propagation of these uncertainties into the differenced polygon, and finally the assessment of the significance of the propagated uncertainty. These steps were followed for all the produced polygons derived from each map. This is because it is important to recognize and minimize uncertainties in data that are particularly elusive with early topographic data. The uncertainty in the topographic data from which the maps and thus the polygons are derived has already been discussed in section 3 (in the order of 5.7 cm). The final step refers to how a probabilistic thresholding can be carried out with a user-defined confidence interval (Eq. (2)). A two-tail hypothesis testing (with $t = 0.71527$) was formulated to check for differences between the polygons that are significant at the 95% confidence limit (i.e. $\alpha = 0.05$). For a number of 305 polygons, 8.5% were identified to have statistically significant differences at the 95% confidence level (*P*-value = 0.475), thus rejecting the null hypothesis. Fig. 6a gives the frequency distribution of the standardised polygon differences (cf. Eq. (1)) and Fig. 6b represents the volumetric distribution of the differences. In all three graphs of Fig. 6, the x-axis represents the class frequencies with the x-values indicating the midpoints. The volumetric distributions look very similar as the area distribution towards lower magnitude changes. Generally, the volumetric distribution is often considered better for resolving signatures of change.

Similarly in the vertical comparison, for a sample of 50 elevation differences, their standardised values were checked upon a two-tailed t-test at the 95% confidence interval (i.e. $\alpha = 0.05$) and a critical value of $t = 0.720$. The frequency distribution for the elevation differences (Fig. 6c) identified 16% to have statistically significant differences at the 95% confidence level (*P*-value = 0.473), thus rejecting the null hypothesis. At a closer look, the specific differences could not be attributed to actual changes such as ground elevation or subsidence. The large differences were attributed to erroneous estimation of heights. Indeed, the remaining 94% of points follow an almost normal distribution with differences not exceeding the ± 1 cm. Therefore, it can be said that between the 1969 and 2015 topographic maps, the theatre structure does not appear to have any elevation changes.

The difference of polygons was implemented in this work to extract quantitative planimetric and vertical differences between the two maps The above results have shown that changes of 8.5% planimetrically (over ± 5 cm) and 15% vertically (over ± 4 cm) were statistically significant at the 95% confidence level. Regarding the vertical component, the elevation changes are mainly due to erroneous height determination and the difficulty in comparing the two maps because of the different height datums. Considering that the uncertainties in historical cartographic data tend to be larger the method is best suited for large magnitude topographic changes (e.g. subsidence). Creation of such datasets has a broad base of application in archaeological studies and heritage management as it provides a basis for both two and three-dimensional geometrical change through time analyses.

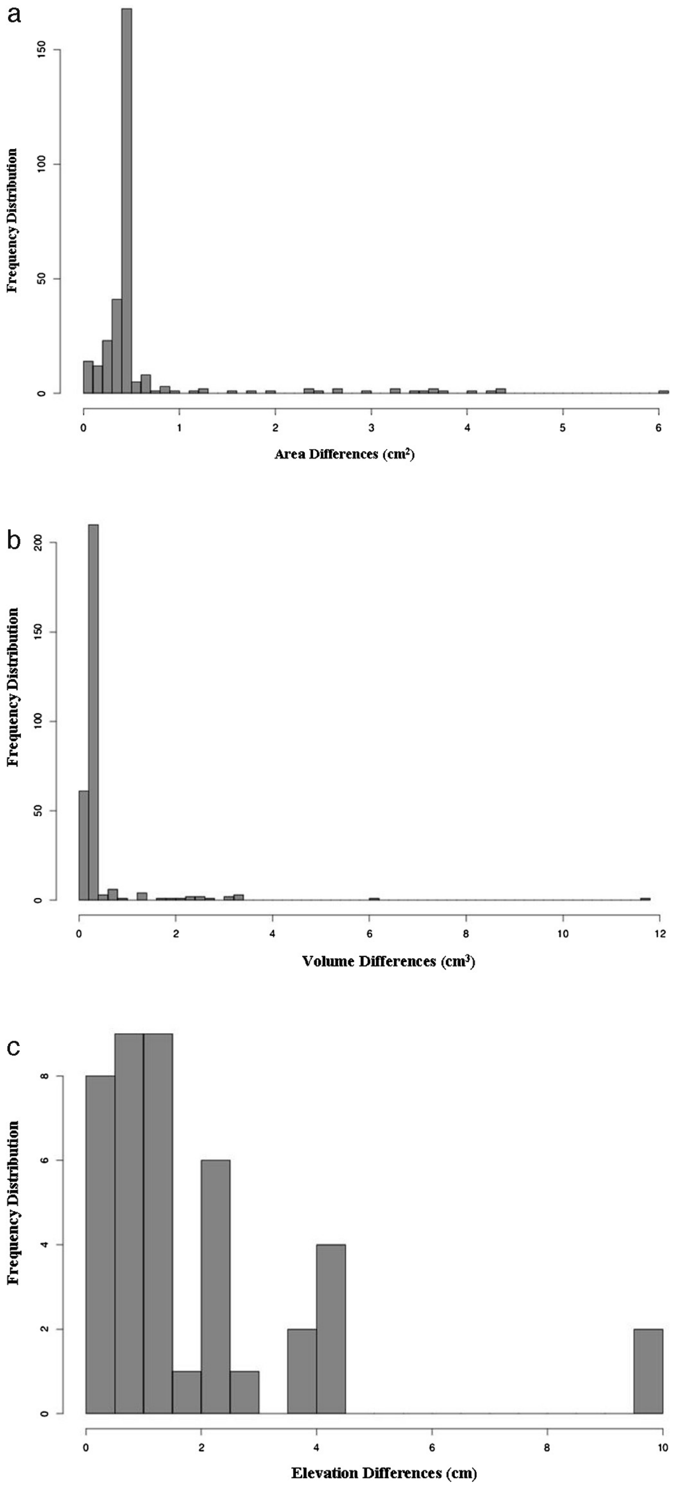

Fig. 6. Frequency distribution of the standardised (a) area differences, (b) volumetric differences, (c) elevation differences.

5. Concluding remarks

The continuous development of new sensors, data capture methodologies, multi-resolution 3D representations and the improvement of existing 3D recording methods significantly contribute to the documentation, conservation and presentation of heritage information and to the growth of research in the heritage field. It has been shown in this paper that topographic change detection using TLS techniques, coupled with surveying methods provides much of the necessary information needed to identify geometric changes at the scale presented herein, in order to help for management decisions.

The principles of detecting topographic changes as shown above for cultural heritage monuments documented by repeat topographic surveys can be applicable to similar analyses over a wide range of time periods. It is emphasised that the topographic changes detected in this work refer to scales in the order of 1:100. The same maps cannot be used to highlight erosion changes at a detailed scale (e.g. 1:25 and below). This is because first, the 1960s map defines the reference scale of the comparison and second, it may have potential errors of omission as well as accuracy limitations of the data.

The planimetric differences in the theatre found between the two maps refer to structural changes over time. Although the same data collection principles used in this work to create the new survey plan of the theatre apply to create a map for comprehensive conservation documentation, the comparison performed in this work is not valid for this type of task because of the limitations of the old map.

Whereas the topographic change results presented herein provide the highest available level of geometric change detection, additional work in combining these results with site-specific data on geomorphology, hydrology, etc. will provide a more thorough understanding of the causes of the documented topographic changes on these time scales. This information should provide archaeologists with an improved basis for making management decisions regarding the archaeological resources in the Kabireion sanctuary.

Finally, this work represents one of the many examples seen for the digital documentation of archaeological sites. Despite some notable exceptions in a few countries, many archaeological data records are still not accessible because the traditional approach of protecting the intellectual property rights of researchers often leaves the primary data from excavations unpublished for decades. Access to data and data sharing is important for a sustainable documentation in archaeology and for the successful application of the techniques described in this paper.

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