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Extracting Linear Features in Archaeological Contexts

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The detection and recording of tens to hundreds of centimeter-scale features in archaeological sites represent a challenge in data collection during field work. Traditionally, archaeological field documentation relies on sketches and line drawings made by hand. Sensors facilitate the characterization, mapping, and quantification of millimetre-scale features, which are otherwise difficult to detect with the naked eyes. High-resolution terrestrial laser scanning is an optimal method for documenting cultural heritage sites due to its transportability and efficient collection time, while processed 3D models facilitate detailed analysis. To demonstrate this approach, a Late Bronze Age Mycenaean cemetery in Greece was selected as a study site due to its size and active excavation status despite ongoing looting activities. The cemetery consists of several chamber tombs, which were hewn from a soft marl hillside using sharp tools. Chisel marks were observed in one of the chamber tombs. The cemetery was surveyed, resulting in point clouds with 0.7 mm spacing. The resulting 3D point cloud model was analyzed as a proof of concept to test the semi-automatic detection of the observed chisel marks. Two separate, but complementary methods, were applied to one surveyed tomb, resulting in the identification of 39 chisel marks divided into four linear feature families. Future work can improve the efficiency of detection as well as further classification of features, especially in sites where natural and anthropogenic features need differentiation or to reconstruct the sequence in which features were created.

CCS Concepts: • **Applied computing** → **Architecture (buildings)**; • **General and reference** → **Measurement**; • **Human-centered computing** → **Visualization**;

Additional Key Words and Phrases: Tomb, Mycenaean, Terrestrial Laser Scanning, Linear Feature Extraction, Digital Documentation

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1 Introduction

Late Bronze Age (LBA) (*ca.* 1650–1065 BCE) Mycenaean settlements are documented throughout present-day Greece and western Turkey, and are notable for a variety of tomb types, among which the chamber tomb is the most common [5, 6, 8, 34]. The LBA Mycenaean cemetery of Aidonia, Greece [19, 20] (Figure 1), exemplifies the architecture of the chamber tomb. The hillsides are excavated to form a three-part architectural style (Figure 1(c)) with a *dromos* (pl. *dromoi*; a passageway) leading to a *stomion* (pl. *stomia*; a doorway) into a *thalamos* (pl. *thalamoi*; the burial chamber) [17]. With growing digitalization trends, the demand for more digital archaeological catalogs is growing, with a focus on photogrammetry and **terrestrial laser scanning (TLS)** [21, 25]. Gutierrez et al. [14] presented a digital catalog from processed terrestrial laser scans as part of documenting the vulnerable LBA Mycenaean cemetery of Aidonia. The chamber tombs in the cemetery were hewn into soft layers of marl [15, 27] using sharp LBA tools. LBA Mycenaean metal hoards contain “narrow” and “wide” chisels, where the cutting edge is less than or greater than 3 cm, respectively; these chisels are associated with masons [3]. However, exact quarrying methods are unknown.

As part of the broader context to digitally document and record the architectural details within LBA Mycenaean chamber tombs, a TLS campaign took place in the Aidonia cemetery in August 2019. A concentration of linear features exhibiting similar geometry but different colors was observed in a small section of the *thalamos* in tomb 9 (Figures 1(a) and 2) during a visual inspection of the structure before performing the scans. The origin of the linear features is likely anthropogenic, corresponding to marks generated by chisels as described by Blackwell [3], preserved on the walls of the tomb chamber, providing evidence of systematic chiseling techniques. Archaeological interpretation of these marks is ongoing.

This article is a proof of concept intended to analyze the processed point clouds to identify anthropogenic linear features observed in the walls of the *thalamoi*. Two well-known multivariate statistical and geometric methods, i.e., **principal component analysis (PCA)**-based local distance [26] and omnivariance mapping [7] applied to characterize 3D point clouds, are used to extract the observed linear features (i.e., chisel marks in this context) from the high-resolution point clouds. This application is a showcase for demonstrating the potential benefit of having high-resolution point cloud data in the digital documentation of cultural heritage.

2 Feature Extraction and Digital Mapping

Data Description

The TLS survey was completed using a Leica ScanStation C10. According to the specifications of the Leica ScanStation C10 [9], the so-called modelled surface precision equals 2 mm, with the note that this value is subject to the applied modeling methodology. Fifty-one scan positions were used to collect 3D point cloud data of the slope and 16 chamber tombs of the Mycenaean cemetery of Aidonia. Each point of the clouds stores three spatial coordinates (x , y , z) and intensity. Intensity is the amount of light returned to the scanner. The scanner control software of the Leica C10 scanner does not allow exporting raw intensity values; therefore, intensity values are relative values without a fixed unit of measurement, cf. [16], on a normalized range from 0 to 1 [32]. The acquired dataset is available at: <https://doi.org/10.4121/df349dfc-9668-4169-a7d6-9852d68b4adf.v2> [23]. Following the collection and processing of point clouds, linear features observed in the western wall of chamber tomb 9 were extracted and mapped from the chamber tomb point cloud 3D model as a proof of concept. Data acquisition and processing of the cemetery point cloud comprises four main steps: (i) acquisition of TLS data (scanning and registration); (ii) pre-processing of point clouds (outlier filtering, cloud thinning, and georeferencing); (iii) unwanted object removal; and (iv) tomb segmentation. See more details on the collection and processing of the data in Gutierrez et al. [14].

Two scan positions (scan position file sequence: Aidonia_s1_s5.e57 in Lindenbergh et al. [23]), one inside the *thalamos* and one within the *dromos*, were required to fully scan all the architectural elements of chamber tomb 9, notably the walls. The resulting TLS 3D model of the chamber tomb (*dromos*, *stomion*, and *thalamos*) contains ~247 million points, while the *thalamos* alone contains ~143 million points (Figure 2).

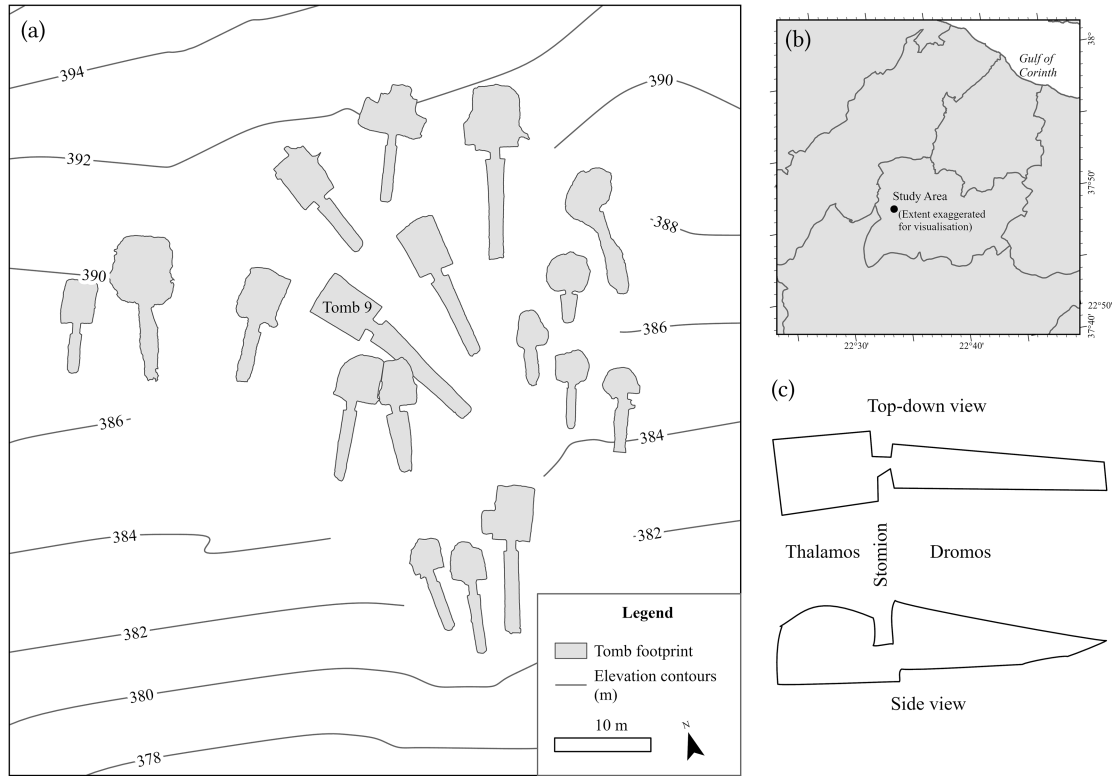


Fig. 1. Schematic of the cemetery. (a) Aidonia cemetery with tomb outlines and elevation contours. (b) Inset map showing the location of the study area in northeastern Peloponnese, Greece. (c) Sketch of the main architectural components (*thamos*, *stomion*, *dromos*) of a chamber tomb. Top-down view of Tomb 9 (labeled in a) and a side view based on processed lidar data.

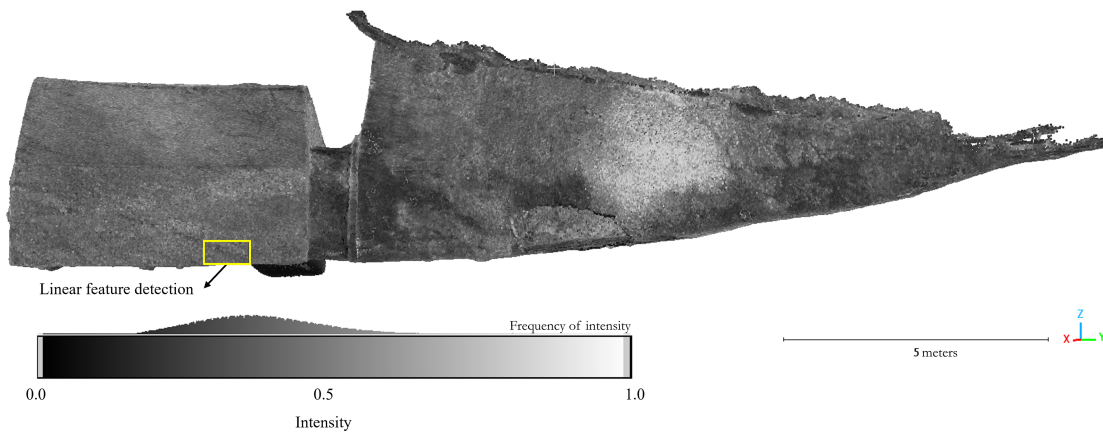


Fig. 2. Side view from the west of chamber tomb 9 illustrating the three major architectural elements (*thamos*, *stomion*, and *dromos*). Raw point cloud with point spacing of ca. 0.7 mm displayed using the intensity attribute. The outlined yellow rectangle shows where linear features were detected on the western wall of the *thamos*, which is shown in Figure 3(b).

Methods for detecting and mapping linear features were applied to a pre-selected section from the western wall of the *thalamos* point cloud. The exposed section contains numerous linear features observed during the TLS survey campaign. The studied section measures 50 cm high and 100 cm wide and contains a point cloud of ~719k points (outlined in Figure 2).

Methods for Linear Feature Mapping

Given the high resolution of the collected point clouds (7 mm laser beam footprint; 0.7 mm point spacing), linear mesoscopic features can be detected and mapped on the surfaces of the chamber tombs. These features are interpreted as anthropogenic activities, namely chisel marks [18]. To visualize and potentially extract the chisel marks from the scan data, two different methods (1 and 2) were used on the area of interest. Method 1 is based on PCA, and Method 2 computes the *omnivariance*. Both are well-known and robust methods used to visualize geometrical features and characterize local structures in point clouds via eigenvalues. Both methods are complementary and relatively easy to apply [7, 12, 26].

Method 1, based on PCA, consists of finding the best-fit plane of the area of interest, determining distances of individual points to that plane, and visualizing the distances using color scales adapted to quantiles. Rather than using the actual value of the distances, the quantile-based histogram equalization uses the rank of the ordered distances to define the color scale [13].

Omnivariance (O_λ), Method 2, is a geometric feature that describes the 3D distribution of each point within a local neighborhood [24]. In this study, circular neighborhoods of 5 mm radius were used to compute O_λ . The width of chisel marks randomly measured on tens of marks in the wall ranges between 2 and 8 mm. By performing trial and error tests with values within the width range of the marks, the chosen neighborhood radius allows one to visualize both narrower and wider chisel marks. O_λ is the geometric mean of the eigenvalues, $\lambda_1, \lambda_2, \lambda_3$, of the covariance matrix of the 3D coordinates of the points c in the local neighborhood, expressed as:

$$O_\lambda = \sqrt[3]{\lambda_1 \cdot \lambda_2 \cdot \lambda_3}. \quad (1)$$

In this study context, although PCA may be more suitable for detecting linear features compared to *omnivariance*, PCA may rely upon the roughness of the surface studied. A more detailed comparison of the advantages and limitations of both methods is given in Section 4. When each method is applied, the point cloud is colorized with a ramp of colors ranging from blue (cooler) to red (warmer) tonalities, to visualize the contrast of the anomalies (linear features). Once linear features were visualized, these were manually digitized onto the cloud by systematically picking points representing either highly deviated distances (residuals; locally contrasting warm/cold colors) from the best-fit plane or high values of omnivariance (warm color). The linear features were digitized using the Compass 2.0 tool [33] in CloudCompare [10]. The purpose of the digitization process is to generate 3D lines. Measuring the length and attitude of the lines enables the geometric characterization and statistical analysis of the linear features observed in the tombs. The attitude is expressed in trend and plunge (Figure 3(a)). The trend, specified by the azimuth (0° – 360°), is the horizontal angle of the line measured clockwise from the north; the plunge is the inclination or vertical angle (0° – 90°) of an inclined line measured downward from a horizontal plane [30]. For the statistical analysis, the trend and plunge of the linear features were plotted in a lower-hemisphere, equatorial equal-area (Schmidt or Lambert net) stereonet [11]. The tool used in this study is Stereonet v.11 [1, 4].

3 Results

Chisel marks with different orientations, inclinations, and lengths are observed in the west wall of the *thalamos* in chamber tomb 9 (location and observed marks shown in Figures 1 and 2, and Figure 3(b) and (c), respectively). The marks are not uniformly distributed; a cluster of marks is observed on the right side of the analysed section (red outlined rectangle; Figure 3(b) and (c)). As a result of exposure, the marks have been filled with green (left

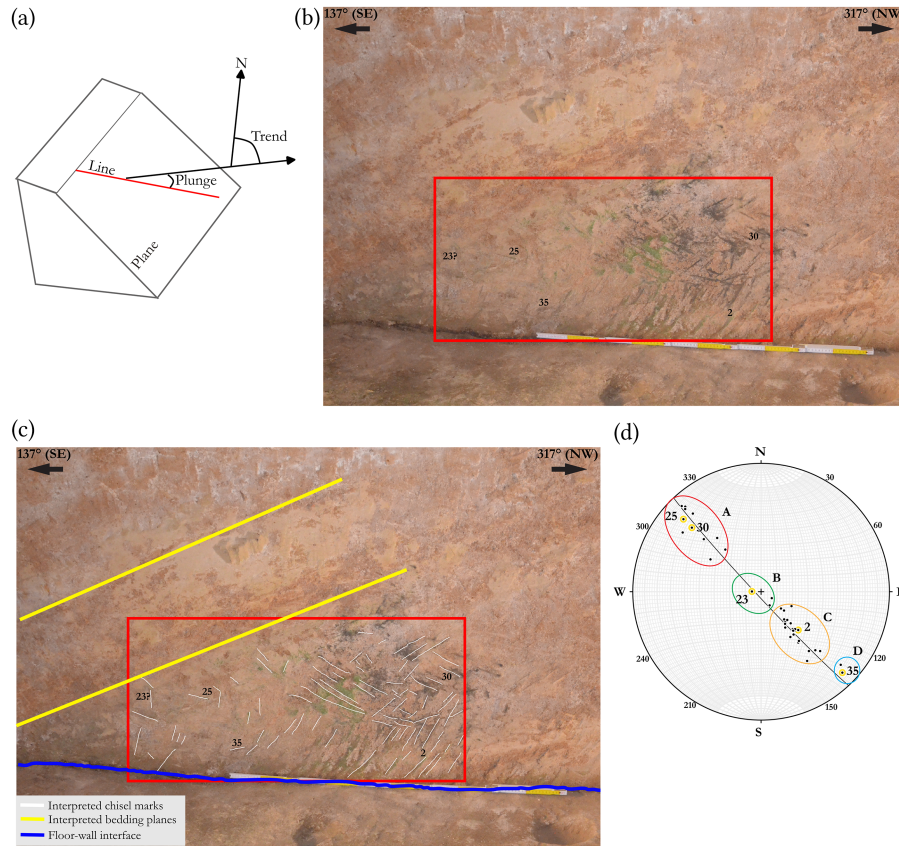


Fig. 3. Chisel mark results. (a) Illustration to explain the trend and plunge, after [28]. (b) Photo showing the west *thamos* wall of tomb 9. Black arrows on the top corners show tomb orientation expressed in azimuth angle. Chisel marks of different lengths and orientations are observed. The tape is 1 m long. Numeric labels are used as correlation guidance between the figures. Hard to identify marks have question marks beside them. (c) Interpretation of the *thamos* wall. White lines are chisel marks, yellow lines are bedding planes, and the blue line is the floor-wall interface. (d) Trend and plunge of the 39 mapped chisel marks are plotted in the lower-hemisphere stereonet along with the orientation of the wall plane (solid black line). Color circles outline chisel mark families on the *thamos* wall of tomb 9 (marked A, B, C, D).

and dark gray (right) mould. The two applied methods, introduced in Section 2, used for detecting linear features in the point cloud, delivered point distances to a best-fit plane and omivariance results, which are shown in Figure 4(a) and (b), respectively. Linear anomalies highlighted in warmer colors in both plots (e.g., values greater than 0.005 m in Figure 4(a) and values greater than 4×10^{-6} m in Figure 4(b)) represent the chisel marks in the point cloud. Thirty-nine chisel marks were detected and mapped directly on the cloud. For spatial reference and comparison, 5 chisel marks (23, 25, 30, 35, and 2) showing different characteristics are labeled across Figure 3.

The best-fit plane of the wall and the chisel marks were plotted together in a lower-hemisphere stereonet (Figure 3(d)). The great circle (solid black line) corresponds to the wall plane, which is oriented northwest-southeast (317° azimuth) with a dip angle of ca. 87° towards the southwest. Trend and plunge are used to plot each vector line (i.e., chisel marks) in the stereonet. Black points are projections of the chisel marks onto a 2D stereographic plane. Although points follow the wall plane in general, the observed misfit may confirm the non-planarity of the wall. Based on their orientation, the mapped linear marks, which average 0.04 m in length, can be grouped

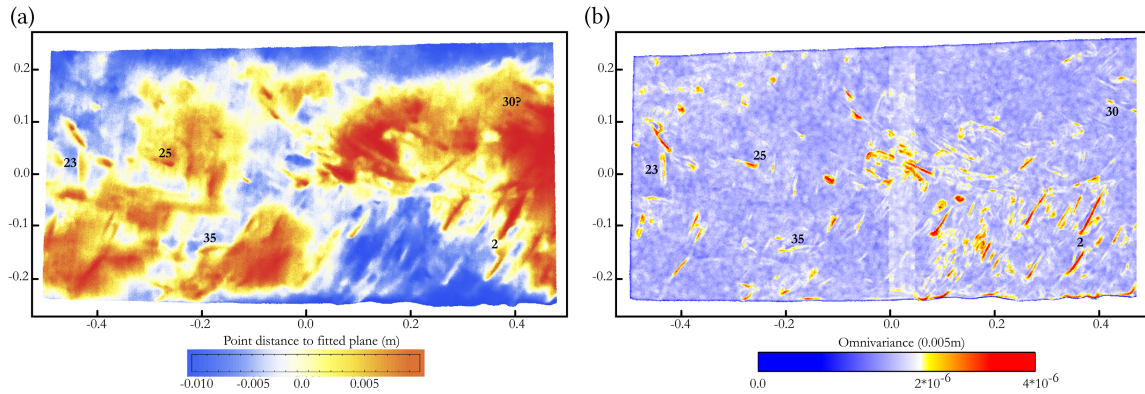


Fig. 4. Chisel mark features. (a) Point distances to best-fit plane—Method 1. Points colored with warmer colors are deviated off the plane with positive distance (away from the center of the *thalamos*), whereas points colored with cooler colors are deviated off the plane with negative distance (towards the center of the *thalamos*). Mark 30 is hardly identified in Method 1. (b) Omnivariance geometric feature—Method 2. Warmer colors representing higher values of omnivariance indicate noticeable changes in the 3D distribution of the points. Mark 30 is clearly identified in Method 2.

Table 1. Chisel Mark Families Based on Their Orientation

Family	Number of marks	Avg. length (m)	Avg. trend (°)	Avg. plunge (°)
A	11	0.039	314.6	28.8
B	3	0.035	180.2	82.1
C	23	0.04	138.9	57
D	2	0.053	133.7	14.3
OA/AVG	39	0.04		

Overall (OA) number of chisel marks and average (AVG) length of chisel mark families are shown.

into four families (Table 1 and Figure 3(d)): Family A groups the second largest population of chisel marks and predominantly trends towards the northwest (cf. features 25 and 30); family B is represented by almost vertical marks with an average plunge of 82° (feature 23); family C trends dominantly to the southeast and is the largest group (feature 2); and family D is the smallest group and contains chisel marks trending towards the southeast with the shallowest average plunge of 14° (feature 35).

4 Discussion

The two methods, Method 1 and Method 2, used to detect chisel marks on the *thalamos* wall of chamber tomb 9 are compared. Both methods assist in the identification of the chisel mark families. Method 1 required two steps: estimation of the best-fit plane of an area of interest and calculation of point-to-plane distances (Section 2). Method 2 assists in the detection of the marks in one step: computing the *omnivariance* (O_λ) geometric feature (Section 2). Fitting a plane to the point cloud using PCA, Method 1, results in a signed distance to this plane for each point. The histogram of all these signed distances is shown in Figure 5. The standard deviation of the distances equals 0.0034 m. Note that this value is a bit lower than the surface precision of 0.002 m, as reported in the Leica C10 specifications. This is expected, as the considered wall is not perfectly planar, while the expression of the chisel marks and additional surface irregularities adds to the actual standard deviation.

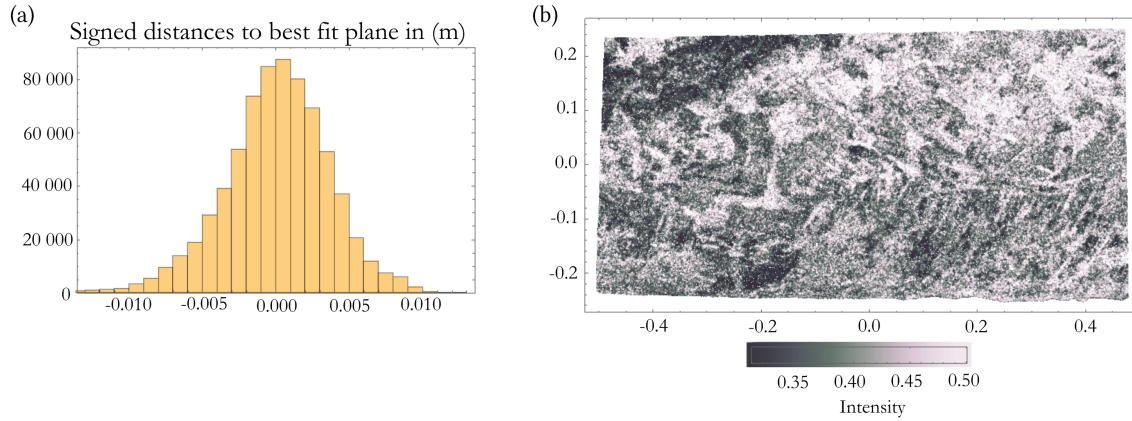


Fig. 5. (a) Histogram of the signed distances in [m] of the actual point cloud to a best-fit plane. (b) Point cloud of the study area colored by scanner recorded intensity.

Besides detecting most of the chisel marks, Method 1 also outputs local roughness values for the non-planar wall, with deviations of 5–10 mm (0.005–0.01 m) (Figure 4(a)) from the estimated best-fit plane that represents the wall. Figure 4(a) notably shows that the wall is not flat but undulating. Positive deviations may be related to areas where the rock is softer. The area with the highest positive deviations concentrates most of the chisel marks. Paradoxically, in this area, some marks (e.g., mark 30) cannot be easily detected when applying Method 1 since the marks are hidden by the local high deviation caused by the roughness of the wall. The efficiency of Method 1 on the detection of linear features is heavily dependent on the planarity of the studied surface; here is where Method 2 becomes important. The omnivariance is not dependent on the wall roughness and evaluates very small neighborhoods. High values of omnivariance indicate drastic changes in the 3D distribution of each point within a neighborhood of 5 mm (0.005 m) (Figure 4(b)).

Both methods can complement each other. While surface roughness obtained through Method 1 can provide hints about softer areas of the material, where clusters of chisel marks are expected, Method 2 confirms the presence of these clusters of chisel marks by providing a clearer discretization of each chisel mark. Both methods succeeded in detecting chisel marks (e.g., mark 23) that were not captured by the photograph due to poor lighting conditions. In addition, Figure 5(b) shows the signal intensity as recorded by the scanner. This visualization shows several local features, but these seem not directly related to the geometric visualizations in Figure 3. Scanner intensity has a well-known dependency on distance and incidence angle [16], as well as material, local moisture conditions, and roughness [29]. As the chisel marks affect the micro-relief of the wall, they affect in consequence the local incidence angles, which in turn may result in local intensity variations.

Only anthropogenic-derived linear features (i.e., chisel marks) were detected in the studied section; detected marks were interpreted as being too erratic to be created by geologic processes. However, the methods applied in this study can also be applied to the characterization of naturally derived linear features such as stratigraphic bedding and micro-fractures. Given the questionable stability of *thalamos* roof integrity, micro-fractures or other larger fractures may be detected and mapped on any of the architectural elements, including *stomion* and *dromos*. This information may contribute to understanding the underlying geologic characteristics in the hillside.

5 Conclusions and Recommendations

Using a high-resolution TLS-derived model of chamber tombs, anthropogenic linear features can be detected, mapped, and analyzed in an automated and therefore objective way at centimeter scale. The applied methods for linear feature detection enabled the identification and mapping of 39 chisel marks in a pre-selected section of

chamber tomb 9. A disadvantage of both the PCA-based and the omnivariance methods is that they both require a specific type of spatial support. PCA is used to define a plane on a set of input points with a certain spatial extent, while omnivariance is computed using surrounding points within a certain spatial neighborhood. A possible extension would be to first model the surface of the wall using, e.g., a B-spline method [2], which would highlight micro-relief and therefore chisel marks. The chisel marks have an average length of 0.04 m and were grouped into 4 families based on their spatial orientation. Future work is needed to expand the linear feature mapping to the remaining surveyed chamber tombs in the cemetery. This might include the application of machine learning or other artificial intelligence tools in the automatic detection and mapping of linear mesoscopic features associated with geological processes. An example would be to adapt the applied method here with that from Li et al. [22], where PCA was used to create archaeological line drawings of a statue. Other work applies DEM and GIS-based methods to line detection in engraved artifacts [31]. Other future work could focus on the quantitative analysis of the efficiency in chisel mark identification, for example, by evaluating the performance of each method using performance metrics (e.g., accuracy and precision) that compare the chisel mark detection made in the field (ground truth) with the automatic detection made by both methods.

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