Prehistoric bedrock features: recent advances in 3D characterization and geometrical analyses

Dani Nadel a, *, Sagi Filin b, Danny Rosenberg a, Vera Miller b

a Zinman Institute of Archaeology, University of Haifa, Mount Carmel, Haifa 3498838, Israel
b Department of Transportation and Geo-Information Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

Abstract

Bedrock features such as hewn mortars, cupmarks and cupules are known around the world. In the Levant they first appear in Natufian sites (ca. 15,500–11,500 Cal BP), in large numbers and a wide variety. Traditional archaeological documentation was commonly limited to hand drawing and general photography. In order to better document these features and provide a high-resolution analysis platform, we hereby introduce a protocol based on photogrammetry, 3D modeling and geometrical characterization even of the deepest features. As case studies, we analyze a deep narrow mortar and a bowl-like mortar from the Natufian site of Raqefet Cave, Mt. Carmel, Israel. Using 20 images per feature was sufficient to create a 3D model for each, with a millimeter level of accuracy. We then characterized each by measurements of volume, shape, vertical and horizontal reflective symmetries. The method offers quick and affordable in-field archaeological recording apparatus, facilitating the derivation of high-resolution 3D models. Using the method provides new avenues for bedrock features documentation and analyses, both on intra- and inter-site levels.

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1. Introduction

Bedrock features such as hewn mortars and cupmarks are known in the archaeological record of the southern Levant at least from the late 1920’s, when several such features were documented during Garrod’s excavations at el-Wad terrace (Garrod and Bate, 1937: 11, plate V). Since these seminal excavations, hundreds of bedrock features were reported from sites in the southern Levant. Most of these were dated to the Natufian culture (ca. 15,500–11,500 Cal BP) and to the Pre-Pottery Neolithic A (ca. 11,500–10,500 Cal BP).

These features first appear in the Natufian, and they were part of notable changes and innovations in material culture (Bar-Yosef, 1998, 2002; Bar-Yosef and Belfer-Cohen, 1989). The appearance of large and diverse ground-stone assemblages and bedrock features, reflecting a variety of functions and use contexts, must have been associated with changes in subsistence patterns and possibly with the transition from nomadic hunting and gathering to sedentarism and food producing economies (e.g. Bar-Yosef, 1998, 2002; Bar-Yosef and Belfer-Cohen, 1989; Belfer-Cohen and Bar-Yosef, 2000; Byrd, 2005; Garrod, 1957; Henry, 1989, 1995; Wright, 1991, 1992).

South Levantine bedrock features include a variety of types and sub-types that reflect chronological and functional variation. Natufian bedrock features include deep narrow types, all of which disappear by the Pre-Pottery Neolithic. Natufian bedrock features were found in sites spread from Syria in the north to the Negev in the south, and from the Coastal Plain in the west to the Azraq Basin (Jordan) in the east, in a wide range of geological and ecological settings (e.g. Goring-Morris et al., 1999; Janetski and Chazan, 2004; Johnson et al., 1999; Nadal and Rosenberg, 2010; Nadal et al., 2009; Richter and Maher, 2013; Terradas et al., 2013).

In recent years, a growing interest in these remains led to research projects focusing on their documentation, analysis and publication (e.g. Eitam, 2008, 2009; Nadal and Lengyel, 2009; Nadal and Rosenberg, 2010; Nadal et al., 2009; Rosenberg and Nadal, 2011; Terradas et al., 2013; Weinstein-Evron et al., 2013). However, their past use is not easily reconstructed, and even the details regarding production technology, spatial distribution and preservation patterns are still obscure in many cases.

An important factor that frequently hampers a detailed and efficient documentation is the difficulty to accurately record these features in the field. So far, bedrock features were commonly...
documented by hand-drawings supplemented by photography. These resulted in a general graphic description of the feature, usually not very accurate. This was especially true for specimens with deep shafts. Such work in the field was time consuming and thus expensive. The acquired level of accuracy prevented consistent, high-resolution characterizations and comparisons between specimens.

The aim of the current paper is to present a protocol for high resolution recording, documentation and characterization of bedrock features, incorporating photogrammetry, 3D model generating and geometrical analyses. We describe the analytical procedure and results for two typologically distinct Natufian case studies from Raqefet Cave. Within a broader perspective, the documentation and analyses provide the platform for a wide range of synchronic and diachronic studies regarding changes in dimensions, shapes and context. In this regard, the study of Levantine bedrock features should follow one of the most basic protocols in the study of archaeological material remains, namely, the foundation of an accurate data set. More than anything, it is the lack of a reliable data set that we are addressing in our current work. As types, densities and contexts of bedrock features changed during the shift from nomadic hunting-gathering to settled villages, their documentation and ensuing analysis are of paramount importance. Once accomplished for a variety of both Natufian and Pre-Pottery Neolithic sites, insights regarding their role in mundane, economic and spiritual life will be reached.

2. Materials and methods

2.1. Raqefet Cave

Raqefet Cave is located in Wadi Raqefet, Mt. Carmel (Fig. 1). The cave has five chambers and was first excavated by Noy and Higgs (1971). The renewed project at the site focused on exposing the dense graveyard and adjacent bedrock features, all ascribed to the Natufian culture, dated here to ca. 14,000–11,700 Cal BP (Nadel and Lengyel, 2009; Nadel et al., 2013). There are ca. 100 bedrock features in the cave and its adjacent terrace, and some were found with Natufian remains buried in them. The two case study features discussed hereby are of distinct types, a deep narrow mortar (C-XVIII, Fig. 2) and a bowl-like mortar (C-XXII, Fig. 3).

2.2. Photography and 3D modeling

The use of photogrammetry in archaeology is common today for archaeological and historical sites and large features (e.g., Al-kheder et al., 2009; De Reu et al., 2013; Ducke et al., 2011; Lerma et al., 2010; McCarthy, 2014; Olson et al., 2013) as well as for small objects, although for the latter scanning and other means are more common (e.g., Grosman et al., 2008; Lin et al., 2010); thus, some aspects of photogrammetric technology and implementation are redundant here. In our case, as traditional archaeological surveying and documentation techniques are unsuitable for high resolution documentation of bedrock features (especially the deep ones), thus we utilize photogrammetry as a means for their characterization. Close-range images are acquired from short distances (0.5–1 m above bedrock) to allow for detailed mapping of deep and shallow...
bedrock features. A set of images from different positions and vantage points are acquired for complete coverage.

We used a Nikon D70s camera with a 24 mm f/2.8 lens for field photography. The camera was calibrated (to recover its intrinsic parameters — focal length, principal point, and lens distortions) before and after each imaging sequence. Point cloud extraction was performed using the Photomodeler Scanner software (www.photomodeler.com), while the evaluation of the mortar’s metrics were implemented using Matlab software (www.mathworks.com). Both point cloud extraction and metrics computation were run on a standard desktop computer.

The application of photogrammetry to bedrock features documentation in general, and deep narrow mortars in particular requires certain adjustments, especially as the studied object here is a hollow, while in most archaeological cases it is not. An additional challenging aspect was facilitating sufficient illumination conditions into deep shafts so that the form and texture of the specimen will be revealed and photographically recorded. This was accomplished by placing mirrors directing light into by the mortars. The number of images per bedrock feature discussed here was ca. 20 and sets of scale bars were used during photography to ensure proper scaling. The derived model consists of both the bedrock feature (mortar) and the adjacent bedrock surface. The image orientation phase (estimation of the cameras pose parameters – position and orientation) was followed by a 3D point cloud creation of both the feature and the surrounding bedrock (cf. Furukawa et al., 2010; Snavely et al., 2008). Density and spatial distribution of the point cloud were analyzed via triangulation of the pointset and assessment of the average arc-length and trapped area per triangle. For documentation of the rock surface and for positioning of the mortars within it, images were also acquired in smaller scale to facilitate an overall coverage of the cave or rock exposure (open-air site) with bedrock features, and in medium scale images to facilitate the measurement of 3D points in the cave or on the rock exposure and 3D rendering.

In our protocol, the first step in processing the derived point cloud was to separate the feature from its surrounding bedrock. The approach used here considers the feature’s points as ‘anomalous’ entities which are topographically lower than the otherwise continuous bedrock surface’s points. This ‘anomalous’ behavior is modeled by an assessment of the relative height between each point to its nearby neighbors where a height difference bigger than a permissible value leads to discussion of that point from the set (online support A). Once a scaled 3D model of each feature was established, it served as the basis for a variety of measurements and analyses. These begin with the rim and then focus on the geometry of the cavity itself.

2.3. The rim

One of the most difficult problems in the field was defining the rims of the features. These were sometimes on an uneven bedrock surface, and commonly suffered from erosion, breakage and post-manufacture/use incrustation. During the analysis of the 3D models, the definition of the rims also required particular attention. In order to define the feature’s rim-related points we triangulate the pointset as a means to establish neighborhood among the points. Generally, points inside the feature should link only to feature points whereas points along the rim connect also to outside bedrock points and thereby signaling the latter out of the feature’s model.

Because of the bedrock surface macro- and micro-topography, the rim’s points may not be coplanar. In order to identify the rim’s 2D shape, the points are projected onto a fitted plain which minimizes their sum-square-of-offsets. We characterize the rim’s shape by its area, barycenter, dimensions (length and width) and symmetry. The area is computed by:

$$A = \frac{1}{2} \sum_{i=1,n} x_i(y_{i+1} - y_{i-1})$$

where $x_i$, $y_i$ are the coordinates of a point along the rim.

For the barycenter computation, the rim pointset is triangulated first and then it is set by:

$$x_c = \frac{\sum_{i=1,n} x_i A_i}{\sum_{i=1,n} A_i}; \quad y_c = \frac{\sum_{i=1,n} y_i A_i}{\sum_{i=1,n} A_i}$$

where $x_c$, $y_c$ are the barycenter coordinates; $A_i$ the area of each triangle; and $x_{ci}, y_{ci}$ the barycenter of each triangle.

Dimensions of the rim are computed in reference to the barycenter. The rim pointset is first re-triangulated, so that all triangles share a common vertex at the rim’s barycenter, and then the rim’s shape covariance is computed (online support B). The rim axes are extracted from the covariance matrix and so are their dimensions.

Based on the computed axes, reflection symmetry can be analyzed by mirroring half of the rim onto the other half both along the major and minor axes and differences are quantified.

Field observations indicate that rims are usually circular or oval. To assess these observations the boundary of the form is evaluated by fitting both geometrical forms to the rim’s pointset using the Gauss-Helmert model (online support C). To decide if and which of the two potential forms best represents the rim, we use the Akaike Information Criterion (AIC) that measures the relative quality of a model for a given set of data by the goodness of fit of the model and its complexity (Akaike, 1974). AIC values, under normal distribution, are computed for each model according to:

$$AIC = 2k + n \ln \frac{\sigma}{\hat{\sigma}}$$

where $k$ is the number of parameters in the model, $n$ is the number of points and $\sigma$ is the sum of square of the offsets from the fitted model. The preferred model is the one whose AIC value is the minimal.
The root-mean-square-error (RMSE) measures the goodness of fit of the boundary points to the prescribed shape.

2.4. 3D characterization

The characterization of the feature’s 3D shape is the main focus of this work. Several parameters are addressed in this section, as described below.

Depth — computed as the distance between the height of the mortar’s rim barycenter, \( z_{bc} \), and the mean value of the lowest points in the set (to minimize the effect of potential outlying depth value of the lowest point):

\[
\text{Depth} = z_{bc} - z_{\text{min}}
\]  

(4)

Volume — computed by tetrahedralization of the pointset and summation of the individual tetrahedrons’ volumes. Triangles which are established by triangulating the pointset define the tetrahedrons’ bases and their apexes were set at a common reference point, which is the rim’s barycenter here (online support D).

Centroid of volume and dimensions — the geometric center of a body and the covariance which is a measure of distribution of the body’s volume are calculated (online support E).

Symmetry evaluation — symmetry is a measure of self-similarity. We set the reference axis, along which symmetry is evaluated, as a vertical line passing through the lowest point in the bottom of the feature. This choice is motivated by the observation that the vessels are predominantly vertical and that their bottom is clearly defined and thus present the logical reference point. In that respect, an efficient form of symmetry evaluation is mirroring the vertical profile and assessing the reflective symmetry.

We compare the axis of symmetry to a formal computation, which is derived from the moment of inertia of the volume for symmetrical objects. An inertia matrix of an object is a mathematical descriptor of the dispersion of the object’s volume around its center, expressed by:

\[
\mathbf{IN} = \mathbf{I}_3 \text{tr}(\mathbf{C}) - \mathbf{C}
\]  

(5)

where \( \mathbf{IN} \) is the inertia matrix, \( \mathbf{I}_3 \) is the \( 3 \times 3 \) identity matrix, and \( \mathbf{C} \) is the mortar’s covariance matrix. Among the matrix’ eigenvectors the one closest to the \( z \) axis is chosen and evaluated against the vertical axis to assess the inclination angle and the distance between the two (online support F).

Another similarity analysis used here regards the preservation of the boundary form (shape) along the vertical axis. For this purpose horizontal cross sections are extracted, circles and ellipses are fitted and tested for their barycenter deviation from the axis of symmetry and preservation of the shape, e.g., transition from circle to ellipse, or in the case of the ellipses preservation of their eccentricity. Eccentricity values — shape-related measure for the ratio of the major and minor axes — are given by:

\[
e = \sqrt{\frac{r_{\text{major}}^2 - r_{\text{minor}}^2}{r_{\text{major}}^2}}
\]  

(6)

with \( r_{\text{major}}, r_{\text{minor}} \) — the major and minor axes dimension. Similarity in these values allude to shape preservation.

Shape characterization — this aspect is addressed using three parameters: slope and curvature along the profiles (longitudinal cross sections), and the fit to a closed analytical form. Slope is a measure of the steepness of the curve at a point, defined by the slope of the tangent line, which is given by:

\[
\text{slope} = \arctan \left( \frac{y_2 - y_1}{x_2 - x_1} \right)
\]  

(7)

Fig. 4. A point cloud (A, left) and a triangular mesh (B, right) of mortar C-XVIII.
Curvature can be defined in terms of the radius of the circle that osculates the curve in the point of interest (Larson and Edwards, 2013):

$$k(s) = \frac{1}{\rho(s)}$$

where \(k\) is the curvature value as a function of the curve length along the cross-section \(s\), and \(\rho\) the circumscribed radius. If the curve is convex at the point, the curvature is positive and otherwise negative. The curvature values are normalized in the range of \([-1, 1]\), by the largest value along the cross section, which relates to the position where the change in slope is largest (online support G). Since curvature computation exhibits sensitivity to noise, it is smoothed here using generalized cross-validation (Garcia, 2010; Shahray and Anderson, 1989).

As for the resemblance of the feature's surface to a closed analytical form, three surface types are considered:

i) a paraboloid, a three parameter surface given by:

$$f(x,y,z) = \frac{x^2}{a^2} + \frac{y^2}{b^2} - z_i$$

where \(a\) and \(b\) are the paraboloid radii;

ii) a bi-quartic surface, a 25 parameters surface:

$$f(x,y,z) = \begin{bmatrix} a_{00} & \cdots & a_{04} \\ \vdots & \ddots & \vdots \\ a_{40} & \cdots & a_{44} \end{bmatrix}_{5 \times 5} \begin{bmatrix} 1 \\ y_i \\ y_i^2 \\ y_i^3 \\ y_i^4 \end{bmatrix} - z_i$$

where \(a_{00}-a_{44}\) are the polynomial surface parameters; and

iii) a cone:

$$f(x,y,z) = \left( (x-x_0)^2 + (y-y_0)^2 \right) \cdot \cos(\theta) - (z_i-z_0)^2 \cdot \sin(\theta)$$

Fig. 5. The fitness between the extracted rim (point cloud), a circle and an ellipse (mortar C-XXII). The latter follows better the actual rim’s shape.

Fig. 6. Reflective symmetry of the rim of mortar C-XVIII, with a) reflection along the y-axis and b) along the x-axis. The rim is marked by the dotted green and black lines. The vertical line is the axis of symmetry, and the wiggling line along it represents the differences between the two sides of the rim. The small differences indicate that the rim is symmetric. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
where $\theta$ is the opening angle of the cone. Parameters are estimated using the Gauss-Helmert model and the best-suited form is chosen using the AIC test (Eq. (3)).

The first two surfaces echo the oval, parabolic-like shape that many bedrock features tend to have. The bi-quartic surface is chosen over a simpler parabolic form because of the greater ability of a 4th-degree polynomial to capture features with ‘bowl-like’ shapes. A cone form could potentially characterize some deep narrow forms.

3. Results and discussion

The two case studies discussed here (C-XVIII and C-XXII, Figs. 2 and 3) were chosen in order to demonstrate the applicability of the method for documenting and analyzing two distinct morpho-types that reflect the range of Natufian typological variability. Moreover, as the specimens represent two of the more complex types in terms of their geometry and dimensions, the implementation of the protocol described in this paper to the characterization and analysis

Fig. 7. The location (left) and the details of six horizontal cross sections (I–VI) in mortar C-XVIII. The vertical axis extending from the mortar’s bottom (red line) and the one linking the cross-section centers (black line) are almost identical, an indication of high-level symmetry and consistency in shape along the shaft. The dimensions of the six ellipses are given below. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
of smaller and simpler types (e.g. small mortars, cupmarks) should be feasible as well.

3.1. Mortar C-XVIII

Mortar C-XVIII is deep and narrow, with a smooth inner surface (Fig. 2). The mortar’s face is documented by 4935 points which are equivalent to an average density of 2 points per sq. cm (Fig. 4). As a test case this density was found sufficient for the analyses conducted hereby, focusing on the characterization of shape and symmetry of the features. However, current fieldwork and analyses involve much higher resolutions (<1 mm), as additional parameters such as use-wear and breakage patterns are investigated. The depth of the mortar is 51.5 cm, the mean diameter is 13.0 cm and the volume is 6226.1 cm³. Fig. 4 demonstrates the separation of the bedrock surface from the mortar’s related points. The rim dimensions are 15.6 cm and 13.0 cm along the major and minor axes, respectively; its area is 619.7 cm².

Testing the conformity of the rim’s shape to a close mathematical form yields a circle fitting with a radius of 13.9 cm and ±1.2 cm accuracy, and an ellipse with 15.4 and 12.8 cm semi-axes,
with ±0.3 cm accuracy (Fig. 5). The AIC test shows that the ellipse is the more suitable shape. The ellipse center and the centroid of the rim coincide (less than 1 mm offset), and the average deviation of the ellipse from the actual rim related points is 3 mm; these indicate the goodness of fit between the rim and an oval shape. The reflective symmetry of the rim is good, with 3 mm deviations on average, which is 1.5% of its dimensions. Considering several irregularities and cracks along it, the symmetry must have been even higher (Fig. 6).

Evaluating the mortar’s symmetry is carried out by comparison of the center of volume and axis of symmetry to the vertical axis that passes through the mortar’s bottom. The distance of the center of volume from the axis is 7 mm and the angle between the axes is 0.9° (Fig. 7), both indicating a tendency to maintain symmetry. The depth of the feature was divided into six regularly-spaced intervals (as an example), and six horizontal cross sections along the shaft show their similarity in shape and orientation (Fig. 7). The eccentricity values range between 0.58 and 0.70, indicating shape preservation. The centers of all the horizontal sections are approximately 1 cm from the vertical axis; the offsets range between 5 mm and 11 mm, indicating a certain 'twist' along the mortar (Fig. 7). Fig. 8 shows the reflective symmetry of the shaft, with three longitudinal sections as examples. The overlap in two cases is very high, while in the third the bottom of the mortar shows differences of up to 2 cm, where the shaft has a ‘twist’.

Next we evaluate the mortar conformity to a simple shaped surface. Because of the elongated and relatively linear form (Fig. 4) we tested both the bi-quartic and cone surfaces. The fitting accuracies were ±3 mm and ±5 mm for the bi-quartic and cone surfaces, respectively; and AIC values of –8415 and –3693 for the bi-quartic and cone surfaces, leading to the selection of the bi-quartic form. The slope and curvature were also measured; we provide numerical computations with different spacing (1, 3, 5 cm here as examples) and compute the analytical forms as derived from the

![Curvature Values](Fig. 10). Curvature analyses along four vertical cross sections of mortar C-XVIII; 0 being the bottom and 1 and −1 are the normalized distances to the opposite ends of the rim. The insets on the left show the vertical profile analyzed on the right. The analytical computation is marked by a red line and the numerical results by black lines at different spacings. The near zero curvature values indicate that the object is relatively flat until reaching it bottom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
surface fitting procedure. The spacing size enables to control the type of analysis, with larger ones reflecting the overall form of the object, and smaller ones the deviations from a smooth form. In this regard, large spacings are useful for mortar classification, whereas the smaller ones are adequate for analysis of small irregularities and imperfections (millimetric in size). The slope analysis shows how the mortar’s faces are nearly flat (slope values are relatively uniform) all along the shaft (Fig. 9). The similarity of the slope values on both sides (with respect to the bottom) is another indication to the high symmetry of the mortar’s form. One can also see the agreement between the analytical computation (red line) and that of the numerical ones (black lines), which suggests that for further characterizations, the analytical form can serve as a very good reference. Local deviations between the numerical values and the analytical ones may indicate anomalies from the general form. The similarity between the numerical slope computations for the different spacings provides an indication to the smoothness of the faces. The curvature analysis parameters are very close to 0, alluding to the flatness of the object’s face (Fig. 10). Noteworthy is the similarity between the analytical and numerical forms, which means that the inner surface of the shaft is smooth, with only little variations.

3.2. Mortar C-XXII

Mortar C-XXII has a bowl-like morphology, and it is much wider and more open compared to mortar C-XVIII (Fig. 3). Despite the fact that this mortar is smaller than the previous, the reconstructed mortar face is documented by 1989 points, which are equivalent to an average density of 1 point per sq. cm (Fig. 11). The mortar’s depth is 17.0 cm and the volume is 5358.4 cm³. The rim semi-axes are 15.6 cm and 13.9 cm; its area is 725.0 cm².

The fitting results of the rim to a circle with a radius of 14.9 cm provide ±0.8 cm accuracy, and to an ellipse with 15.8 and 14.1 cm axes ±0.6 cm accuracy (Fig. 12). The AIC test shows that the ellipse is the more suitable shape. The offset between the ellipse center and the centroid of the mortar is only 1 mm, and an average deviation of 6 mm from the ellipse indicates the goodness of fit of the shape. The rim preserves general symmetry with an average deviation of 6 mm, which is 2% of its dimensions (Fig. 13). The reflective symmetry is low, as a stone embedded in breccia distorts the contour.

In terms of the mortar’s symmetry, the distance of the center of volume from the axis is 3 mm, while the angle between the vertical axis and the computed axis of symmetry is 22.2°; an indication to the mortar’s asymmetric shape. As for the previous mortar, the depth was divided into six, and horizontal cross-sections were generated in these regular intervals. The distance of the six centers of the horizontal sections from the vertical axis increases from bottom to top of the mortar, another indication to its asymmetric form (Fig. 14). The six sections also show variation in form and
orientation. The reflective symmetry was calculated for four vertical cross sections. These show the low level of symmetry, as in all cases the profiles do not coincide (Fig. 15). In three of them the distance between the profiles ranges between 1 and 3 cm, and only in one do they partially coincide.

To evaluate the mortar’s conformity to a simple shaped surface, we tested the parabolic and bi-quartic surfaces. The fitting accuracies are ±4 mm and ±1 mm, and the AIC values are −3307 and −15483, for the parabolic and bi-quartic surfaces, respectively. The bi-quartic surface fits the archaeological feature very well.

In terms of slope and curvature values, we tested computation with different spacing and computed the analytical forms, as derived from the surface fitting procedure (Figs. 16 and 17). The slope values on both sides are somewhat different, an indication to the asymmetric form of the object. Good agreement between the analytical and numerical forms can be noticed particularly in reference to the numerical analysis using large spacings (Fig. 16). In contrast with the slope analysis, the curvature parameters exhibit a rougher behavior, which is due to the uneven mortar face, the outcome of erosion (Fig. 17). The analytical form captures the general curvature behavior, and allows highlighting the deviation from the general, smooth-like, mortar’s face. Similar to the previous observations, here again, larger spacing in the numerical computation captures the general curvature, whereas the smaller spacing emphasizes the surface roughness and enables tracing anomalies and imperfections (cracks, holes and exfoliation).

As shown above, the method we applied in the field and later during the generating of the 3D models and ensuing data analysis, can serve archaeologists seeking high-resolution documentation of bedrock features. The characterization of each studied feature (here two case studies) in high resolution provides a range of details not available by using hand drawings or a few general photographs.

To the best of our knowledge, this is the first time that such features are described in detail, providing measurements, shapes and symmetry that are quantified and reliable and thus amenable for intra- and inter-site comparisons. Such comparisons are beyond the scope of this paper, but are under way for several sites. We specifically aim at providing the analytical tools for working on a level higher than “the site contains cupmarks/deep mortars/cupules”. Rather, specimens will be compared and analyzed using mathematical and geometrical parameters.

We see specific importance in the shape and symmetry studies hereby conducted. The horizontal and vertical cross-sections and symmetries of a feature reflect upon its manufacture and especially its use, regarding the direction and power applied to the mortar during vertical (pounding, crushing), horizontal (grinding) and rotational (pulverizing) motions (Adams, 2002). Thus, information regarding the shape and symmetry provide a new level of analysis that should be explored not only on the level of the individual feature, but rather for assemblages where several types are present. The potential for intra- and inter-site research is high, and our work (and that of other research groups) is now focused on these new possibilities.

4. Conclusions

Prehistoric bedrock features raise many questions concerning their chronology, the technology of production, the correlation of form and function, spatial distribution within sites as well as their cultural and social contexts. The combination of photogrammetry, 3D characterization and geometrical analysis provides an affordable, handy and quick high-resolution method for the documentation of isolated examples as well as large complexes of bedrock features in their archaeological settings.

The characterization of dimensions and volume provide significant data of each feature and coupled with analyses of shape and symmetry they add valuable information that enables intra- and inter-site comparisons and enhance better understanding of past functions of these features. Using the methods discussed above, we
are now advancing in the direction of achieving a clear geometric and volumetric characterization of Natufian and Pre-Pottery Neolithic A bedrock features and understanding the different attributes pertaining to each of these cultures. Thus, the combination of photogrammetry, 3D characterization and geometrical analysis of these features is a powerful tool for answering questions relating to the difference/similarities between bedrock features across cultures, ecological zones and bedrock types. The results should be incorporated in wider syntheses of cultural continuity and change.

On another level, the derived 3D models should serve as a high resolution archive regarding conservation and preservation of cultural heritage. The method is highly applicable and handy in remote, not easily accessible locations. This is specifically important for sites that commonly suffer from weathering and human-induced destruction, even if other kinds of archaeological research were not conducted at the place.

After years of neglecting bedrock features documentation and related research, especially when compared to advances in other
Fig. 15. Reflective symmetry of four vertical cross-sections along the shaft of mortar XXII. The blue and black lines are the reflective sections. The dotted line shows the distance between the two sections at each vertical point; note that in three cases the profiles deviate from one another by 2–3 cm within a 17 cm deep shaft. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 16. Slope analysis of mortar C-XVIII; 0 being the bottom and 1 and –1 are the normalized distances to the opposite ends of the rim. The insets on the left show the vertical profile analyzed on the right. The analytical computation is marked by a red line and the numerical results by black lines at different spacings. The varying slope values reflect the bowl-like shape of the object and their dissimilarity reflects the asymmetry of the shape. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
fields, the above-described protocol should facilitate easier and better documentation and analysis. As the importance of these features in past mundane, social and spiritual contexts is recently the focus of some research projects (e.g. Buonasera, 2007; Duwe, 2011; Eitam, 2008, 2009; Fowles, 2009; Nadel and Lengyel, 2009; Nadel and Rosenberg, 2010, 2011; Nadel et al., 2013; Rosenberg and Nadel, 2011, 2014), and in the Levant comprehended within the framework of other types of stone mortars (Rosenberg and Nadel, 2014), their new level of study will no doubt provide important insights into their place in ancient and recent cultures.

Acknowledgments

Fieldwork at Raqefet Cave was supported by funds from the National Geographic Society (Grant #8915-11), the Wenner-Gren Foundation (Grant #7481) and the Irene Levi-Sala CARE Archaeological Foundation. We thank the anonymous reviewers for their comments and advice. Digital Figs. 1 and 3 prepared by A. Regev, all the rest by V. Miller. Field photographs by D. Nadel. We appreciate the support of the Israel Antiquities Authority and the Israel Nature and Parks Authority.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.10.029.

Fig. 17. Curvature analyses along four vertical cross sections of mortar C-XVIII; 0 being the bottom and 1 and –1 are the normalized distances to the opposite ends of the rim. The insets on the left show the vertical profile analyzed on the right. The analytical computation is marked by a red line and the numerical results by black lines at different spacings. The undulating curves reflect the unevenness of the object’s surface (compare with Fig. 10). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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