A NEW WAY TO STUDY ANCIENT BEAD WORKSHOP TRADITIONS: SHAPE ANALYSIS USING ELLIPTICAL FOURIER TRANSFORMS

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A new analytical methodology using trigonometric functions of Elliptical Fourier transforms (EFTs) is presented for studying morphometric proportions of stone beads. The methodology was tested using ethnographically produced bead types from a single workshop compared to a discrete assemblage of stylistically similar archaeological beads from the Levant. The two-dimensional outlines of the shapes of both sets of beads were analyzed using the same methodology and EFTs were used to classify beads by their stylistic types and calculate their average morphometric values. These data defined the variation present within a techno-stylistic workshop tradition. EFT data from the modern bead groups were compared to the archaeological samples and both shared the quantitative characteristic of a single workshop tradition. The archaeological samples can be interpreted as reflecting a distinctive workshop tradition. This pilot study suggests that EFT analysis provides meaningful, empirical demonstrations of shared group membership, in terms of style and metrics.

INTRODUCTION

One of the most basic objectives of archaeological research is to identify discrete groups of artifacts (beads, in the context of this article) that share a common origin. The demonstration that certain beads closely share styles, materials, and technical procedures has long been taken as plausible evidence for their origin in the same or similar cultural traditions and their production during a specific chronological time period (Beck 1928; Xia 2014). With the emergence of early complex societies throughout the world, some communities began to specialize in the production of specific types of stone beads, first as a part of household production for personal use and eventually as a specialized craft that catered to consumers outside the household (Bar-Yosef Mayer and Porat 2008; Kenoyer 2005). Studies of bead production in South and West Asia have demonstrated that distinctive aspects of bead production, such as drilling (Kenoyer and Vidale 1992) or combinations of drilling and bead shape (Kenoyer 2008; Ludvik, Kenoyer, and Pieniążek 2014; Ludvik et al. 2015), can be used to link beads to a specific region or cultural tradition and time period. These arguments rest on the assumption that groups of similar beads were produced according to similar idiosyncratic, learned processes shared by artisans operating in the same workshops, trained by the same master artisans, and using the same or similar toolkits (Kenoyer, Vidale, and Bhan 1994). Beads that might have similar shapes, but different proportions of length-to-width measurements, drill hole diameters, or were produced using different chipping, grinding, polishing, or drilling technologies, could have been made by differently trained artisans, possibly in different workshops and during different time periods (Kenoyer 2017a).

A considerable body of research has been published on different aspects of early bead technology, production, and trade in South and West Asia, and summarized by various scholars (Kenoyer 2003; Ludvik 2018; Roux 2000). In this literature, applications of multiple archaeometric and quantitative methods have provided concrete data for defining specific suites of attributes that can identify the products of distinct workshops, which in turn can be associated with different cultural traditions (Kenoyer 2017a-c; Law 2011; Ludvik 2018). An example that is particularly relevant to this study is the identification of long carnelian beads at sites such as Ur (Woolley 1934; Zettler 1998) and Kish (Mackay 1929) in Mesopotamia that appear to have been made using raw materials and technologies that are distinctive of the Indus Valley region of what is now Pakistan and western India (Kenoyer 2014). These beads date to around 2500-1900 BCE and their presence in Mesopotamia has long been thought to reflect the trade of beads made in workshops within the Indus Valley region (Chakrabarti 1990; Ratnagar 1981). Some scholars, however, have proposed that it is possible that Mesopotamian artisans were also making similar beads (Reade 1979, 2008). A study by Kenoyer (1997:272, 2008:21-26) confirms that some of the beads from the royal cemetery at Ur appear to have been made in non-Indus shapes, but using Indus drilling

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technology and possibly even Indus carnelian raw materials. This suggests that Indus artisans, or local artisans trained in the use of Indus technology, were producing the beads locally using Indus raw materials as well as Indus shaping and drilling technology. It is also possible that these artisans were making beads of Indus shapes for local use, but it has not been possible to distinguish them from beads made in the Indus workshops since the raw materials, shapes, and technologies are identical. As will be discussed below, we do now have a methodology for potentially addressing this issue and refining the ways in which to distinguish actual Indus workshops in the Indus Valley itself, and workshops outside the Indus Valley that are using Indus raw materials and technology to produce similar or almost identical objects.

In his recent study of beads from the Levant dating to the mid-3rd millennium BC and later, Ludvik (2018) was able to identify a large number of Indus-style stone beads that were made from carnelian as well as some other types of agate.[1] By comparing these beads with those found in the Indus, he has developed a more precise concept of the "workshop tradition" to aid in defining and tracking artifacts with common origins, particularly in the context of stone beads. The term "workshop tradition" refers to "a community of similarly trained artisans using the same methods of production, or *chaîne opératoire*, to produce a single coherent group of artifacts sharing stylistic, metric, and technological characteristics" (Ludvik 2018:23). Workshop traditions can thus be identified by using multiple attributes, including stylistic, morphometric, technological, and elemental characteristics. Together, beads empirically shown to share specific quantifiable aspects of these key traits are proposed to represent the idiosyncratic products of a group of similarly trained and equipped artisans operating in a specific region and cultural milieu, with their technical knowledge and the associated artifact forms and sizes passed down from master to apprentice.

In order to develop a methodology to try and distinguish Indus-style beads made in Mesopotamia, it is necessary to go beyond the study of drilling and raw material and carefully assess the entire *chaîne opératoire*. This includes the raw material, and the shaping, drilling, and polishing processes. In this article we focus on the methodology to assess the specific shapes of the beads produced in a well-established workshop tradition. Specifically, we propose a method to quantitatively assess whether or not artisans trained in what we call a single workshop tradition actually did produce beads of a certain shape (i.e., elliptical barrel) within a definable range of morphometric variation. This method can also be used to examine whether or not the proportions associated with one techno-stylistic group can be differentiated from those of beads made in other styles and thus theoretically coming from other workshops traditions. In order to do so, Elliptical Fourier transforms (EFTs) were used to quantify morphological, metric, and stylistic difference/similarity between and among three groups of modern beads from Khambhat, India, known to have been made in what we consider a paradigmatic single workshop tradition. One group of ancient beads and one group of archaeological beads were also analyzed and compared to the modern beads. Based on the close correlation between the modern and ancient samples, it is clear that EFT analysis can be used to identify ancient workshops that were intentionally producing specific styles of stone beads for specific groups of consumers.

THE BEAD COLLECTIONS

To examine the range of variation in the products of a proposed single workshop tradition, the authors first studied three groups of modern beads that were intended to replicate ancient beads found at the site of Harappa and dating to the Harappa Phase of the Indus Civilization, ca. 2600-1900 BCE (Kenoyer 1987) (Figure 1, a-c). All of the modern replica beads were produced by bead master craftsman Inayat Hussain and his assistants in Khambhat, India, commissioned by Kenoyer as part of his ethnoarchaeological study of traditional beadmaking in Pakistan and India (Kenoyer, Vidale, and Bhan 1994:281; Vidale, Kenoyer,

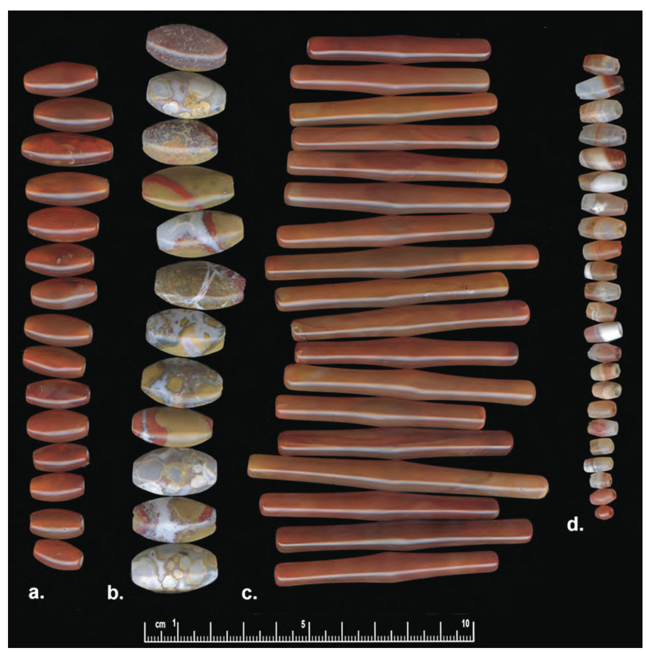

Figure 1. Modern and ancient beads utilized in the study: a) carnelian, long barrels; b) jasper, elliptical long barrels; c) carnelian, very long bicones; d) banded carnelian, long barrels and long bicones (Afghanistan) (photo: J. Mark Kenoyer).

and Bhan 1992:1). The same types of tools were used in all stages of chipping, grinding, and polishing. Each bead was also hand drilled with a bow drill and double diamond drills by master bead driller Pratap Bhai. These beads were not made specifically for this study but were being produced in order to develop replicas of ancient Indus style ornaments. Hussain was requested to produce three different types: very long biconical carnelian, long elliptical barrel agate, and long barrel carnelian.

Although hundreds of beads were made of each type, Kenoyer selected just 88 beads for analysis: two handfuls of the very long biconical beads (n=29) taken from a large bag of finished beads, and one strand each of the long elliptical barrel beads (n=34) and the long barrel carnelian beads (n=25) that had been prepared by the beadmakers. The strands were part of larger bunches intended for shipment. Each strand reflects choices the beadmakers made in selecting beads that they considered to be typical of the same style as requested by the customer.

In the production process for the very long carnelian beads, Inayat Hussain was asked to optimize raw material length to produce the longest beads possible given the natural size of the carnelian nodules. For the other two bead types, the artisans focused on the production of a certain size and shape (i.e., long elliptical barrel and long barrel). Hussain chipped all of the bead blanks and both he and his assistants were involved in the grinding and polishing of the beads. This way he could oversee all stages of bead production. If at any point a bead did not meet Hussain's expectations, he made sure that it was modified to ensure both quality and conformity with the type being produced. The beads were all produced by one individual master bead maker and his assistants according to three formal techno-stylistic templates. Each type was defined by the practice of what the authors term Hussain's own workshop tradition of manufacture. This collection of ethnographically produced beads provides an excellent sample with which to empirically test the workshop tradition model, since each group of beads from Hussain's workshop matched the proposed criteria of a single bead workshop tradition. These beads provide three examples of types made by the same group of craftsmen trained by the same master, using the same tools, and producing products within a strictly defined morphometric and stylistic template. Using these artifacts of known provenance, it is possible to test the model to determine if single-workshop tradition types do share quantifiable characteristics that can be used to identify and differentiate them.

In addition to the modern beads, two groups of ancient beads were selected for comparative purposes. One set of beads (n=37) came from a necklace of banded carnelian long barrel and long biconical beads (Figure 1, d) purchased from an Afghan bead dealer in Istanbul. These had been restrung by the seller and grouped together on a single string because of their similar shapes and raw material, but it is not known if they all came from the same region or time period. Examination of the drill holes indicates that they all were drilled with tapered cylindrical or constricted cylindrical stone drills (probably 3rd millennium to 2nd millennium BCE) and all were made of relatively similar types of banded carnelian. Overall the beads appear to have been made in similar but not identical ways and may not have come from a single workshop, but would serve as a test to determine if they fit within what we would call a single workshop tradition.

The second archaeological sample of long barrel carnelian beads (n=16) comes from three different sites located in modern Israel/Palestine, the ancient Southern Levant: Bet Dagan, Tell el-Ajjul, and Holon (Figure 2). All 16 are technically Indus-style beads, displaying the use of constricted cylindrical stone drills and other characteristics consistent with Indus-associated beads. These artifacts are part of a collection documented by Ludvik for his doctoral dissertation and come from secure burial contexts dated to the late 3rd millennium BCE (Ludvik 2018). They were selected because their close similarities in shape, raw material, drilling technology, and overall production processes highly suggest an origin in a common workshop tradition. Elliptical fourier analysis would serve to test this hypothesis.

PRELIMINARY ANALYSES

Each bead was first measured using a digital caliper to record overall morphology and drill hole diameters, following the measurement protocol used to document stone beads (Kenoyer 2017; Ludvik 2018; Ludvik et al. 2015). The measurements taken from each modern bead confirmed that Hussain's craftsmen did in fact produce beads of a given type within a set range of variation; the measurements of their products were very tightly clustered in terms of metric proportions, especially a relatively narrow range of length-to-width ratios (Figure 3). Based on these initial measurement studies, it was concluded that the best metrics for illustrating the differences between the three bead groups were the length-to-width ratios compared with average drill hole diameters. The spread of values for these two parameters was therefore preliminarily taken to indicate the expected signatures for beads made in the same style by the same workshop tradition (indeed, by the same individuals) and for the signatures of beads made optimizing the length of raw material.

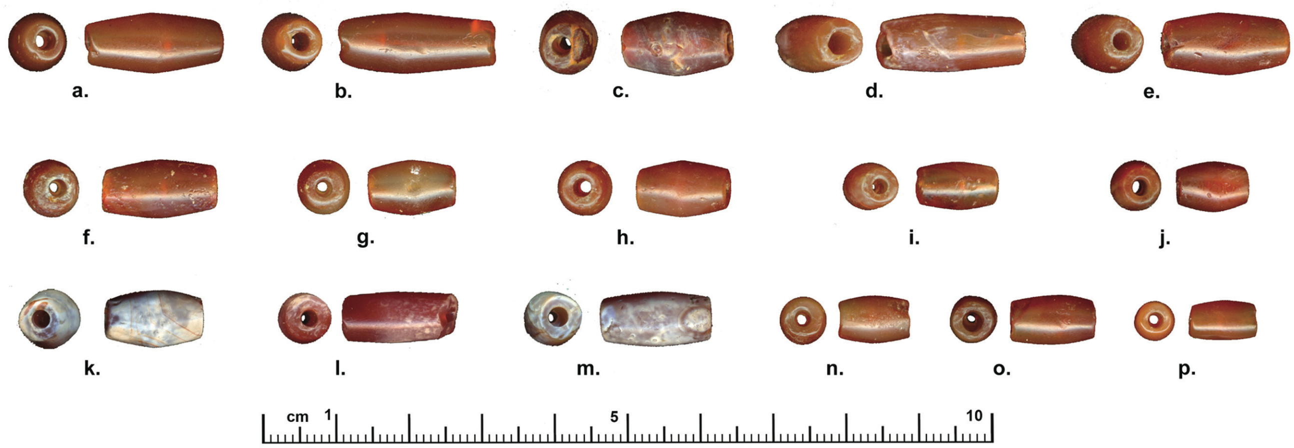

Figure 2. Ancient beads from the Levant: a-j) Bet Dagan; k-m) Tell el-Ajjul; n-p) Holon (photo: Geoffrey Ludvik and J. Mark Kenoyer).

In order to test the statistical significance of these differences, one-way analysis of variance (ANOVA) tests were performed, alongside post hoc pairwise t-tests. The three assumptions for ANOVA (normality, homogeneity of variance, and independence of observations) were first tested to see if this statistical method was appropriate. The bead groups met the third assumption of independence based on study design (i.e., groups were assigned in such a way that no one bead was counted in two groups). The other two assumptions required formal testing for normalcy and homogeneity of variance in each group, both in terms of length-to-width ratio and average drill hole diameter metrics. A standard normalcy test (Shapiro-Wilks) was employed in the statistical program R first. To test the homogeneity of differences at an inter-group level, a Levenes test in R was also employed (Ludvik 2018: chapter 6). All three modern bead groups as well as the two ancient groups (Afghan and Southern Levantine) were determined to be suitable for ANOVA testing. The results of ANOVA, followed by pairwise t-tests with Bonferroni corrections in R, indicate that the differences observed between the groups of beads are significant in some but not all cases, even for the three groups of beads known to have been produced in different styles. This suggests that, while the use of length-to-width ratios and average drill hole diameters functioned well to demonstrate coarse distinctions between bead types, a more refined method was necessary to conclusively and significantly identify the products of distinct workshop tradition types; the two metrics alone were insufficient to demonstrate statistically significant differences.

After being introduced to the use of Elliptical Fourier transforms in the study of animal tooth morphology during a lecture by Dr. Juliet Brophy of Louisiana State University and in collaboration with co-author Dr. T. Dobbins, a new way of studying bead shapes was pursued. In order to more clearly differentiate the modern bead groups and assess the range of variation within single workshop tradition types, Elliptical Fourier transforms were utilized to describe bead shapes as trigonometric functions (ellipses of known sine/cosine functions). The following section outlines Elliptical Fourier transform analysis and describes how it demonstrates that the workshop tradition model does accurately reflect an archaeological reality: beads made by similarly trained artisans in similar styles with similar tools are indeed similar in metric proportions and can be differentiated in practice.

ELLIPTICAL FOURIER TRANSFORMS METHODOLOGY

As a first step in EFT analysis, flatbed digital scans are made of the beads on a group-by-group basis, with each bead labeled sequentially and identified by sample name. The scans are then examined to obtain solely bead outlines by means of the edge-finding program in MATLAB®, a commonly utilized programming language and numerical computation system in engineering. The outline coordinates are then determined and analyzed using Elliptical Fourier transforms, also in MATLAB®. The resulting information is ultimately used to find the range of morphometric variation of a type of bead and employed to group the beads by type. After using this methodology to test the three groups of modern beads, the two groups of ancient beads were analyzed for comparison.

More generally, this method of employing MATLAB® computation enables the study of an artifact's size and shape in a thorough, multidimensional manner. This allows the entire shape of the artifact to be studied and statistically analyzed. The technique is well suited to the study of

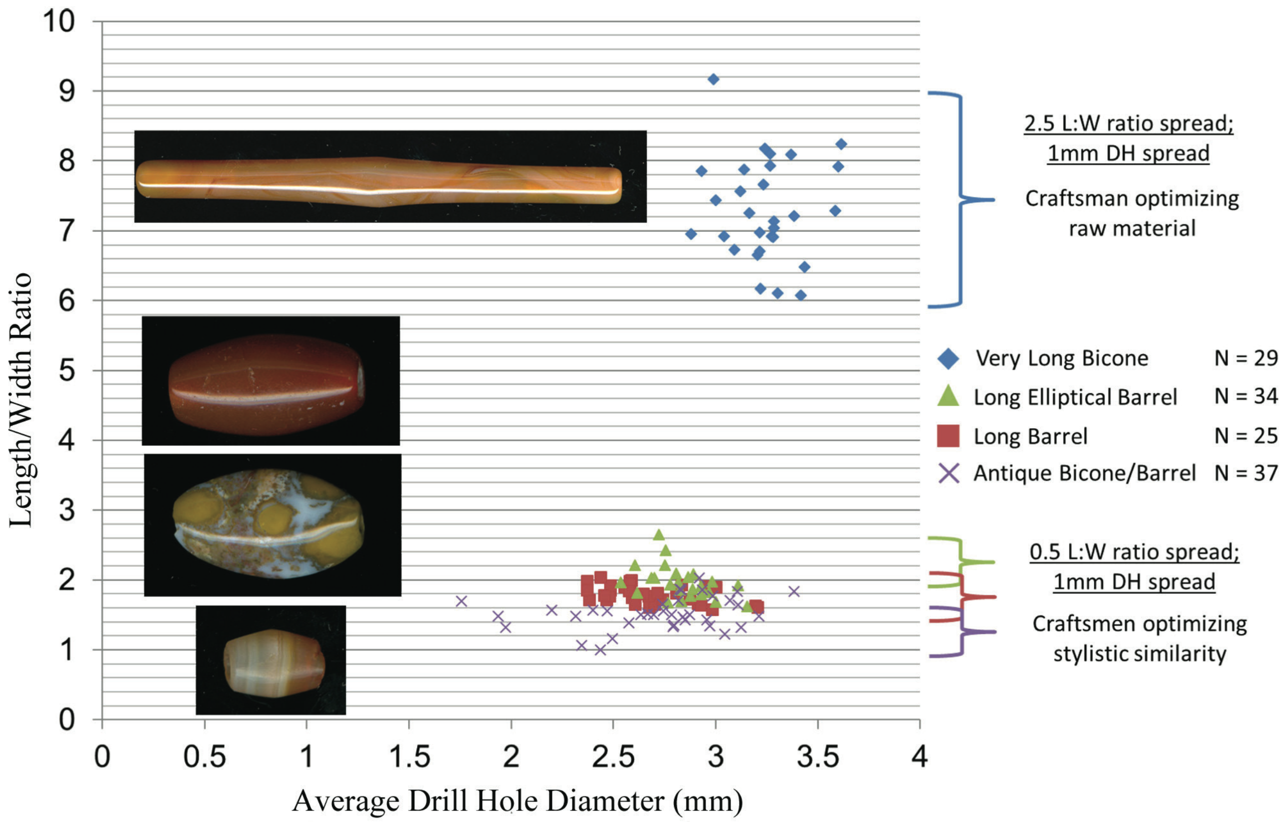

Figure 3. Length-to-width ratio vs. average drill hole diameter (mm) (graphic: Geoffrey Ludvik).

symmetrical bead shapes and can also be used to study other kinds of artifacts that can be classified and seriated by shape. Therefore the approach we outline here has the potential for wide methodological application. A researcher would simply need to take high-quality scans or pictures of the artifacts in question and upload them into the program for analysis in consultation with a colleague familiar with the system. Care should be taken to ensure that these images show the profile of interest (side, top view, etc.) and not a skewed angle that would artificially warp the image. In addition, if the absolute size of the artifact is going to be analyzed for this work, some reference will be needed to scale the pixel sizes in the image to real space coordinates (centimeters, inches, etc.). After the images are acquired, someone familiar with MATLAB® analytical procedures can employ software to find the edges of the artifact. The position of the edge of the artifact can then be used to find the Elliptical Fourier coefficients of the outline of the artifact, quantitative values that can be statistically analyzed in a variety of ways. We employed MATLAB®, but similar studies could easily be replicated in other programming languages like Python™, which are free to use. Both MATLAB® and Python™ have publically available packages to automatically find the edges of an image and calculate the elliptical coefficients.

Bead Shape Analysis

All beads involved in this study were scanned against the same black background by an HP Scanjet G4050 digital photo scanner with a resolution of 600 dpi. Each image was cataloged and an outlined bead shape was found using a series of analysis routines written in MATLAB® and using MATLAB®'s Image Processing Toolbox. The contrast between the bead brightness and the background was used to determine the bead edges. The images were converted to black and white by defining any brightness above a certain level as "white" in code and everything else as "black;" the pixels where the black to white transition occurred identified the edge of each bead. The results of this process can be seen in Figure 4. The output of this analysis was x and y coordinates describing each point along the edge of a given bead and controlled for bead size with a millimeter scale. This method allowed for a very precise outline of each bead to be created in a matter of minutes for all 141 beads considered here along with a list of x/y coordinates that were later used to assess morphometric similarities and differences (*see below*).

An example of each bead type is plotted in Figure 5 for visual comparison of types, both in their true shape/

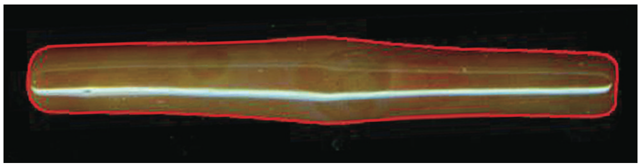

Figure 4. Very long biconical carnelian bead with outline from analysis code (photo: Thomas Dobbins and Geoffrey Ludvik).

size and when normalized to the overall bead size. The very long bicone beads are quite distinct in size and shape, but the elliptical long barrel, and historical beads from the Afghanistan group are more similar in shape, accounting for the difficulties in assessing statistically significant differences. Nevertheless, using the EFT method, these types are still readily distinguishable. The variation in the shape of the very long bicone beads is plotted in Figure 6. Note that while there is great variation in bead lengths, widths are quite consistent.

Elliptical Fourier Transforms

In order to analyze and compare the shapes of the beads in a more complete way, Elliptical Fourier transforms were used. The idea of a Fourier transform is to describe a set of data in x space as a summation of sines and cosines. Elliptical Fourier transforms allow one to apply this analysis technique to a closed contour (a shape that loops back on itself) by performing a Fourier transform on the x and y coordinates of the pixels found by the image analysis routine mentioned earlier. This essentially generates a mathematical description of a given closed-contour shape in terms of a series of concentric ellipses that fit together to define its border coordinates. The formulation is:

$$x_N(t) = A_0 + \sum_{n=1}^{N} a_n cos(2n\pi t/T) + b_n sin(2n\pi t/T)$$

$$y_N(t) = C_0 + \sum_{n=1}^{N} c_n cos(2n\pi t/T) + d_n sin(2n\pi t/T)$$

where t is the parameterization in which the unit is the amount of time to move one pixel, T is the basic period of the data (the amount of time to make it all the way around the contour), N is the number of harmonics used in the expansion, and an, bn, cn, and dn are the coefficients of the expansion of order n. In order to find the values of the EFT coefficients for use in subsequent analyses, we used the following equations where tp is the number of steps required to reach the point p:

$$a_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta x_p}{\Delta t_p} [cos(2n\pi t_p/T) - cos(2n\pi t_{p-1}/T)]$$

$$a_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta x_p}{\Delta t_p} [sin(2n\pi t_p/T) - sin(2n\pi t_{p-1}/T)]$$

$$a_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta y_p}{\Delta t_p} [cos(2n\pi t_p/T) - cos(2n\pi t_{p-1}/T)]$$

$$a_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta y_p}{\Delta t_p} [sin(2n\pi t_p/T) - sin(2n\pi t_{p-1}/T)]$$

There are several features of these transforms that are significant for this analysis. First, by increasing the number of harmonics used in the fitting, the accuracy of the fit improves (up to a point related to the number of points in the

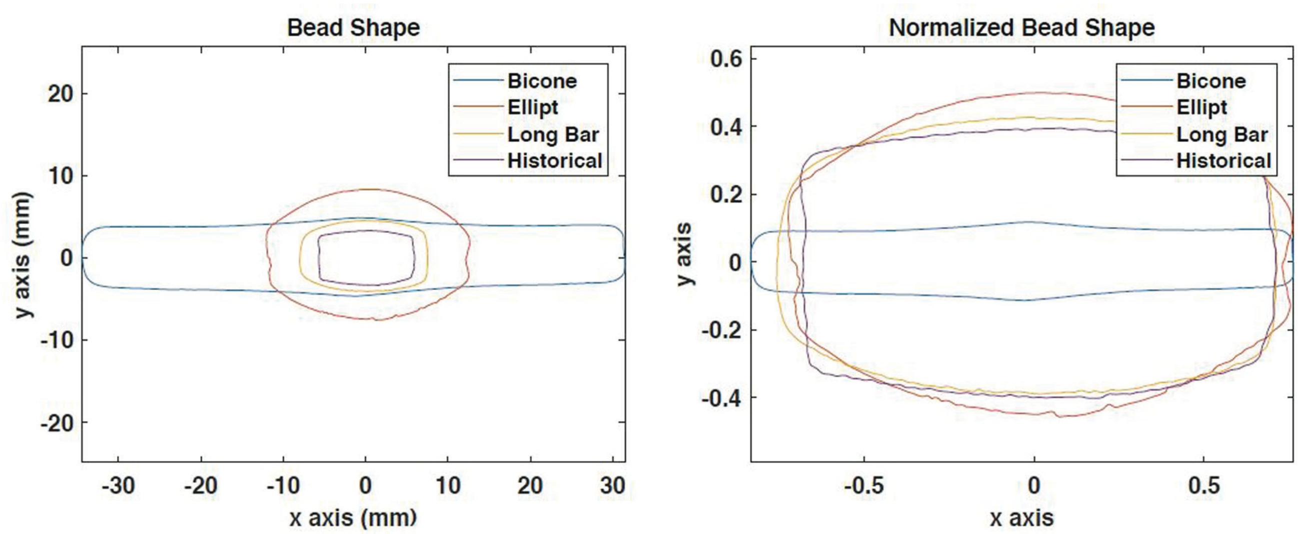

Figure 5. Example beads compared. Actual size (left) and normalized (right) (this and all subsequent graphs by Thomas Dobbins and Geoffrey Ludvik).

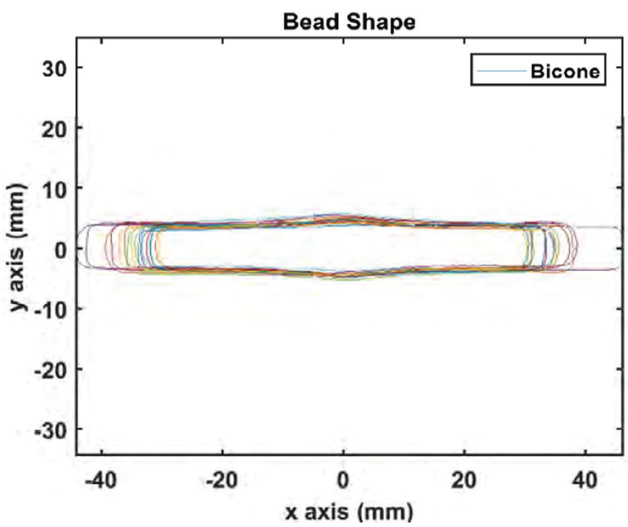

Figure 6. Very long biconical beads group morphometric variation.

contour). That being said, the first few terms tend to be the most important in order to find the overall shape of the bead, while the higher order modes "fill in" the outline (Figure 7). As such, this work will focus primarily on the lower order modes in EFT analysis.

Additionally, a procedure was undertaken for rotation and normalization of the EFT coefficients to ensure proper comparisons between beads. This is important for several reasons. For example, the rotation is necessary so that all the beads are aligned in the same direction (e.g., the bead in Figure 7 has a slight axis tilt prior to rotation based on its position on the flatbed scanner during initial imaging). In this case, the semi-major axis (the longer dimension of the bead) is rotated such that it falls in the x direction (*see* equation below). This allows comparison of bead shape despite the fact that the images were not initially aligned in precisely the same direction.

$$\theta_1 = \frac{1}{2}\arctan[\frac{2(a_1b_1 + c_1d_1)}{a_1^2 + b_1^2 + c_1^2 + d_1^2}]$$

The second step after rotation is to normalize each bead by its size for one round of testing. This can be useful in that it allows comparison of solely the stylistic shape of the beads of varying size while ignoring the overall size of the beads in question; absolute differences in size are an important feature in techno-stylistic type to be sure, but also considering morphology independently of length and width provides an additional test of bead similarity/difference. Normalization can be done in one of two ways: 1) by normalizing the beads by the length of the first harmonic (roughly the length of the bead) or 2) by normalizing them by the average radius of the first harmonic (roughly the average of the length and height of the bead). In this study, normalization by length was used, though the conclusions drawn were not dependent on the choice of normalization. Non-normalized beads were then analyzed in a second round of testing, since bead size is an important element of their classification. The rotated reconstructions of the beads used in this analysis were plotted in Figure 5 to show the different shapes of the three modern bead types and the ancient Afghan beads, while Figure 6 shows the spread of the very long biconical bead by way of example.

SPREAD IN BEAD SHAPE

In order to classify the variation within a single bead type and between bead types, two calculations were made using the EFT coefficients. The two calculations were the sum of absolute differences and mean squared methods for calculating error:

$$\sigma^2 = \sum_{n=1}^{N}(x_n - \bar{x})^2$$

$$E = \sum_{n=1}^{N}|x_n - \bar{x}|$$

The two methods for calculating error have differing dependence on deviations from the mean. Sum of squares more heavily weighs large outliers than the sum of the absolute values. As such, they give different information on the spread of the beads from the average and therefore both will be examined in this work. The spread of each type of bead from its mean EFT coefficient value is plotted in Figure 8. The degree of spread of the beads from their mean bead shape is comparable in all cases, but the largest morphometric deviation is seen in the very long bicone beads due to a few exceptional outliers.

It is significant that the ancient beads, both those from the Afghan bead group and the distinctive long barrel group found in the Southern Levant, have a consistent spread in deviation from their mean EFT coefficient values, comparable to the behavior of the three modern bead types in this same test. Thus, these two ancient groups seem to match the expected variability in morphometric proportions of groups known to have been produced in single workshop tradition types, suggesting that they may also have each been products of single traditions of manufacture.

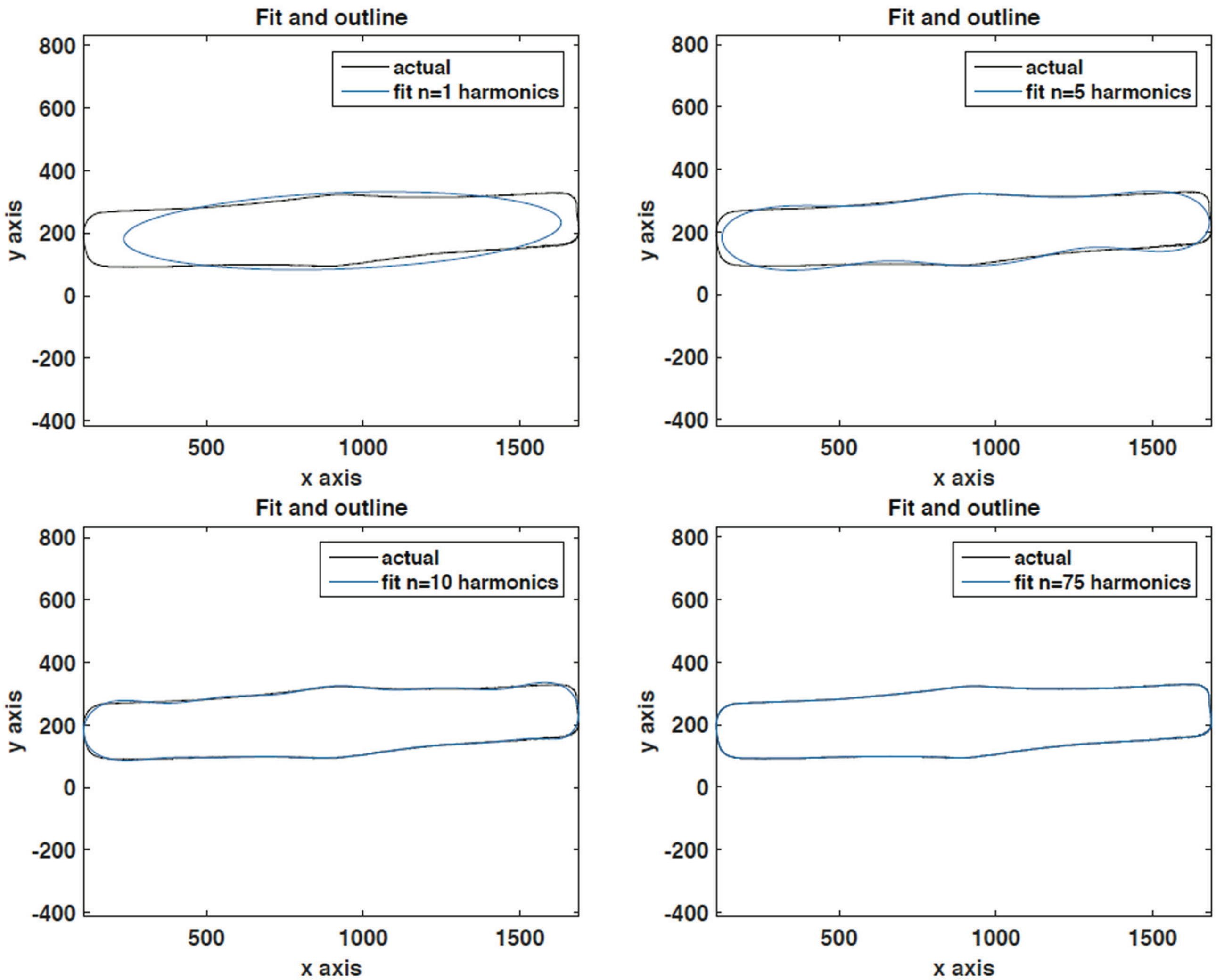

Figure 7. Bead outline plotted with fits of varying mode numbers.

DIFFERENTIATING BEAD SHAPES

With the description of the spread of morphometric proportions from their mean values complete, EFT coefficients were then used to differentiate between bead types. This is important because the ancient Afghan beads, the ancient long barrel beads from the Southern Levant, the modern long elliptical beads, and the modern long barrel beads are relatively close to each other in size and shape, but are nevertheless known to be truly distinct bead types.

As such, a method was developed to differentiate between bead types using the ETF data. A simple first step, following the methodology described above, was to calculate each bead's deviation from the average EFT coefficient values of another bead type rather than its own. If the beads are in fact different, one would expect the comparison to the means of other bead types to yield a larger deviation than when the beads are compared to their own group mean. The results of this simple analysis are shown in Figure 9. They demonstrate that the spread from mean values within each group is less than the spread of each of those beads from the mean values of other bead groups. This indicates, for these collections of known group membership, that the bead types as defined are differentiable and coherent. This method can also be used to identify which bead types are most similar to each other in shape.

There are several issues with the simple analysis, however. For example, it depends on the use of preexisting group identities, assuming the groups have been accurately defined (in this case, a good assumption given the control groups and the distinct beads from Afghanistan and the Levant). Additionally, it only takes the magnitude of deviation into account, not the direction of deviation. A bead that was shorter by a set amount from the average would

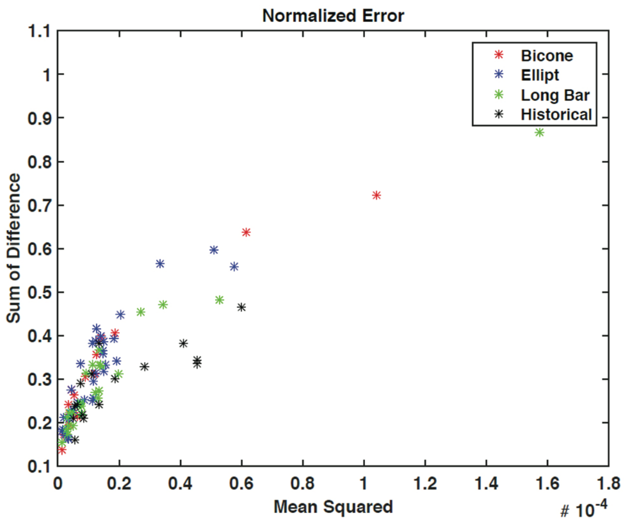

Figure 8. Normalized error of each bead from its average.

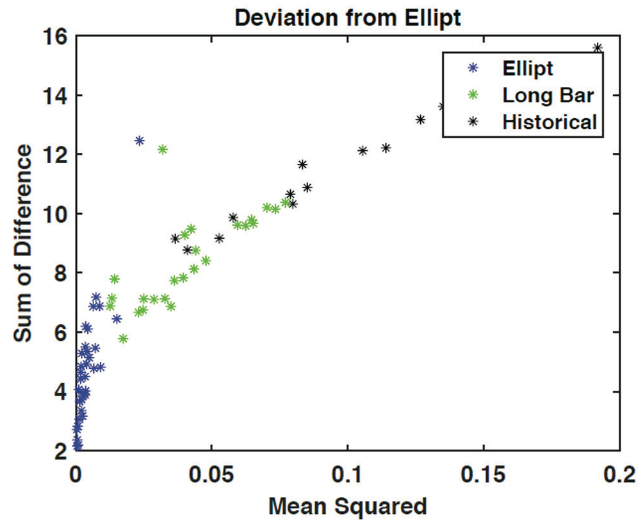

Figure 9. Deviation of each bead from the average long elliptical bead.

have the same deviation as a bead that was longer by the same amount and would be grouped together, despite having different shapes. Therefore, a better analysis technique, in this case canonical discriminant analysis, was also used.

Canonical discriminant analysis, a type of machine learning, can be used to find the linear combinations of the EFT coefficients that most effectively differentiate various types beads. This method allows one to find what terms in the ETF spectrum are the most different between the various bead types, and could, with careful analysis, allow for improved insight into the important features that differentiate beads by type. This analysis was done using SAS® software and the results are shown in Figure 10. They indicate that the three groups of modern beads produced in different styles are easily differentiable when considered using canonical discriminant analysis. Using the combination of EFT and canonical discriminant analysis it is potentially possible to classify a new bead of unknown identity into one of the types already analyzed and documented.

CONCLUSION

It has been demonstrated that EFT has great potential in the study of the archaeology of craft production, especially stone beads. With its reliance on quantitative trigonometric analysis, EFT provides a more objective mechanism for determining beads that belong to coherent stylistic, morphometric, and technological groups. The preliminary examinations of length-to-width ratios and average drill hole diameters, but especially the application of EFT analysis of bead shape, have been shown to provide empirical support for the assumption of idiosyncrasy in bead production.

Using EFT, we have been able to document and quantify the range of variation indicative of beads produced in the same workshop traditions. It has been shown that craft persons operating within the same workshop tradition do, in fact, make beads similarly. The three groups of beads from Hussain's workshop in Khambhat provide an excellent case study. Through the examination of their EFT coefficients, it is clear that each single techno-stylistic group deviates from its mean shape and size within a clustered, definable, and differentiable range.

Conversely, it has been shown that artisans operating in different workshop traditions do, in fact, make beads differently. The two archaeological groups of beads were easily differentiated by EFT coefficients from the modern products of Hussain's workers. Additionally, the three

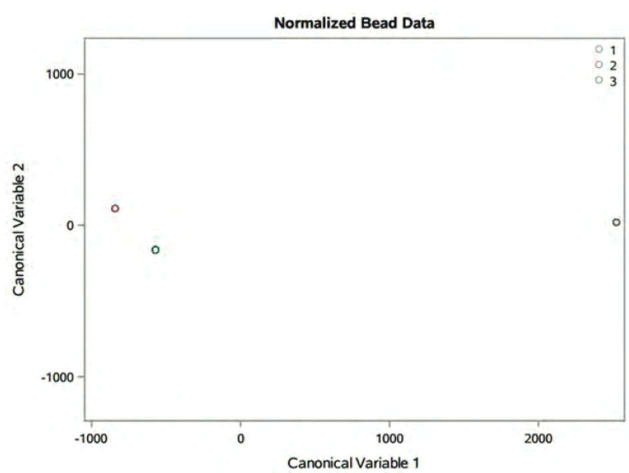

Figure 10. Results of canonical discriminant analysis on the three modern bead groups.

distinct techno-stylistic types produced in Hussain's workshop were also differentiable, suggesting that EFT coefficients provide a reliable method to examine group membership.

Lastly, we have demonstrated that, by analogy to the behavior of modern control groups, ancient beads made with similar styles, proportions, and technologies can plausibly be linked together as potential single workshop tradition types. Like the groups of modern beads produced in single workshop traditions, the two archaeological samples examined here display a similar spread from their mean EFT values. This provides support for their possible identification as groups of products made in the same workshop traditions in antiquity. For the Indus-style beads from the Southern Levant (late 3rd millennium BCE), this suggests the common origin in a single workshop tradition of manufacture for 16 beads from different necklaces buried with four different individuals. This does not mean that they were made in a single workshop but that they were made by groups of artisans who were working with similar sets of raw materials and tools, producing closely matching bead shapes.

At present Kenoyer and his colleagues are in the process of studying a larger sample of beads from sites in the Indus Valley, such as Mohenjodaro, Harappa, and Dholavira, to determine if it is possible to identify a distinctive workshop tradition that reflects the entire Indus region or perhaps regional varieties based on major sites. Similar studies need to be carried out in other regions, specifically at the sites of Ur and Kish. Once these data have been collected it will be possible to compare what has been identified in the Levant with the workshop traditions of the Indus and Mesopotamia to determine if the beads from the Levant derive from actual Indus workshops or workshops of Indus-style bead production in Mesopotamia.

It is possible that there is a single, relatively homogenous tradition of Indus-style bead production in the 3rd millennium BCE in the Near Eastern world, likely associated with a small number of workshops of similarly trained artisans but dispersed to many regional sites. As discussed earlier, this has already been proposed based on technical and qualitative stylistic considerations, but with EFT analysis, a quantitative demonstration of group similarity can now be tested. In all, EFT has the potential to greatly assist archaeologists and other researchers in documenting the workshop traditions of origin for stone beads. This method has demonstrated great quantitative accuracy in defining the range of variation between and within single workshop tradition types. This, in turn, has produced an expected range of EFT coefficient values indicative of single workshop tradition styles that can now be used as a starting point to empirically identify new beads that share key morphometric similarities and plausibly common origin in a coherent group. The application of EFT is poised to advance the study of the idiosyncratic, learned processes responsible for the production of different groups of artifacts in the archaeological record. This pilot study has shown that it is indeed possible.

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ENDNOTE

1. Such beads were identified as "Indus-style" primarily because they were perforated with constricted cylindrical stone drills, a diagnostic technology developed and used by artisans of the Indus Valley Civilization. Additional features corresponding to Indus-associated manufacture include: 1) they exhibit highly polished surfaces and fine shaping, evidencing skilled craftsmanship, 2) there is a variety of barrel/biconical forms reminiscent of documented Indus types, marking them as distinct from other beads in the regional archaeological record, 3) they have morphometric proportions consistent with other beads known to have derived from the Indus craft repertoire, and 4) they are often made from similar varieties of high-quality raw material, i.e., slightly translucent, deep-red orange carnelian.

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