ARCHAEOLOGY AND MATERIALS SCIENCE: The Red, Etched Stones from Ancient Caesarea: Copies or Trade?

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ABSTRACT

Etched carnelian beads are among the rarest ornamental artifacts of the ancient world, widely regarded as products of specialized South Asian bead-making traditions. While these beads have been recovered from various archaeological sites throughout Asia, Northern Africa, and the Middle East, there is no published archaeological record of these artifacts being found in Caesarea Maritima, a major Mediterranean Roman port city. This study integrates archaeometry, experimental archaeology, and geochemical analysis techniques to investigate eight carnelian beads from Caesarea Maritima, including two etched artifacts. ATR-FT-IR was used to verify mineral composition. From there, microscopic examination of drill-holes and their impressions along with quantitative Drill Hole Taper Value analysis were used to compare drilling techniques. Stylistic comparisons with published etching patterns were then conducted alongside experimental attempts to recreate the etching process. ATR-FT-IR confirmed that the artifacts were genuine carnelian. Morphological analyses revealed substantial differences in all but three of the beads, indicating that most beads were likely produced in various workshops as opposed to a single production center; the three (non-etched) beads with closely related manufacturing characteristics were likely products of the same workshop. Stylistic evidence further suggests that one etched artifact displayed characteristics of Indus-related production while the other etched artifact exhibited features related to Near Eastern or Anatolian tradition. Drill hole analyses corroborate these conclusions based on chronological and geographical specific techniques. This study's findings support that these artifacts represent an ancient trade network connection between Caesarea Maritima, Indus peoples, and Anatolian peoples, respectively. This study provides insight into technological diffusion and long-distance exchange routes in the ancient Mediterranean.

INTRODUCTION

Carnelian, a red-orange variety of chalcedony, was among the most valued ornamental stones of the ancient world (Kenoyer et al., 2025). Across South Asia and the broader Near East, carnelian beads were associated with wealth and prestige, with the Indus River Valley Civilization emerging as one of the earliest and most influential centers of carnelian bead production (Mohanan, 2025). Among the rarest examples of these artifacts are "etched" carnelian beads that display white geometric designs produced via traditional artisanal methods rather than engraving (Mackay, 1933). Carnelian beads with white designs are often referred to in one of two ways. In the majority of publications, the beads are called "etched," referring to their geometric designs; certain publications, however, have begun calling these beads "bleached" as it matches more precisely with the chemical reaction that gives the bead its patterns (Kenoyer, 2003). For the sake of consistency, this paper will use the term "etched."

Two examples of etched carnelian beads were recently uncovered among artifacts excavated by Dr. Robert Bull of Drew University between 1971 and 1986 from the Mediterranean port city Caesarea Maritima (Bull et al., 1986; Wiemken & Holum, 1981; Bull et al., 1982; Levine et al., 1986). Despite Caesarea Maritima's prominence as one of the Eastern Mediterranean's most notable Roman trade ports, no previous study has examined etched carnelian beads recovered from the site. The discovery of two etched beads among the Caesarea excavations, therefore, provides a critical opportunity to determine whether these artifacts are imported products of workshops in the Indus Valley region, locally produced mimetics, or perhaps evidence of formerly undocumented trade. Determining the provenance and authenticity of these artifacts could provide insight into patterns of trade, technological diffusion, trans-regional cultural interaction, and the circulation of luxury goods across ancient societies.

Due to the fact that no single line of evidence can conclusively determine the origin of these artifacts, establishing their provenance is an inherently multidisciplinary endeavor. Chemical analyses via attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FT-IR) can verify if the artifacts are genuine carnelian and assess consistency with reference materials. Morphological characteristics, particularly drill-hole composition, preserve evidence of production techniques that can be compared with known chronological and regional drilling traditions. Furthermore, stylistic analysis of the etched motifs can reveal relationships between documented bead collections from other archaeological sites worldwide. By combining complementary analytical approaches, this research seeks to clarify whether the beads represent products of a common manufacturing tradition or multiple production centers and, in doing so, contribute new evidence toward understanding ancient Mediterranean trade.

BACKGROUND

Cultural Significance and Trade Networks

Carnelian has persisted as a symbol of wealth and strength since ancient times. The stone was rare and had profound religious and cultural significance. Its color represented life, fertility, and purity in ancient South Asian cultures (Beck, 1969). The Indus River Valley civilization revered carnelian, often incorporating it into jewelry and regalia to showcase prosperity (Mohanan, 2025). Carnelian was so coveted that even a single bead was cherished, making it a significant presence in trade networks (Mohanan, 2025).

Caesarea Maritima was a city in Roman Judea under the Roman Empire circa 100 CE; today, it is located on the coast of ancient Palestine, or modern day Israel (Britannica Editors, 2024). The site of Caesarea Maritima was first built by King Herod, the ruler of Roman Judea, who constructed a port city that was challenging to navigate to by land, in turn ensuring the protection of his people and kingdom. The main harbor of Caesarea Maritima was one of the most prominent trade ports in the Mediterranean Sea due to its central location, often intercepting trade from across the known world (Bull, 1982). Many items, including those from the Indus River Valley region, may have been brought across oceans to the port of Caesarea Maritima because of their rare or lucrative nature (Blakely, 1988). Although the Indus River Valley civilization existed years prior to Caesarea Maritima, etched carnelian beads from the region could have reached Mediterranean societies due to the revival of etching practices that occurred after the collapse of Harappan society (Simpson, 2020).

The geographical diffusion of authentic Indus Valley carnelian beads relied heavily on an expansive trade network of land-based and maritime routes, including through both the Indian Ocean and Silk Road (Kenoyer et al., 2025). Over land, merchant caravans transported luxury commodities along routes such as the Uttarapatha, which connected to the Khyber Pass, linking the Indus Valley region directly to markets in Central Asia. Simultaneously, maritime trade routes along the Indian Ocean connected Indus Valley lapidary workshops to the ancient world at large. Continuing on this route, merchants departing from major port centers such as Barygaza, which is located in modern-day West India, navigated vessels across the Arabian Sea, trading carnelian beads in early Mesopotamian cities and with trade routes spanning the Persian Gulf region (Tripathi, 2025). From this point forward, cargo ships transported carnelian beads through the Red Sea, where they were then carried directly towards principal Mediterranean trading hubs, which targeted the consumer markets of the elites (Netchev, 2026).

Time Periods

The site of Caesarea Maritima, where the two etched beads were found, played a role in several consecutive empires. The first empire of significance was the Roman Empire, which spanned from circa 0 CE to 500 CE and stretched across Europe, Asia, and North Africa (Beebe, 1983). Roman Judea, the greater area of Caesarea Maritima, was a client kingdom–semi-autonomous and run by local leaders. The people in Ancient Caesarea were free to practice their own religions and traditions, and they expressed this through carnelian engravings on rings (Hall, 1997; Rosenfeld et al., 2003).

After the fall of the Western Roman Empire, Caesarea Maritima was part of what was known as the Byzantine Empire. This state existed from circa 500 to 700 CE and was the advent of the Eastern Orthodox Christian Church (Vasiliev, 1958). Additionally, following the Byzantine Empire were the Islamic Caliphates from circa 700 to 1100 CE (Schick, 2021). These Caliphates marked a period of religious unity and flourishing trade in the Middle East (Elshaikh, 2024). A few centuries after the beginning of the Arab Period marked the rise of the Crusaders–groups that traversed the Middle East for geopolitical motivations–who possibly brought rare items from across continents (Blaydes & Paik, 2016).

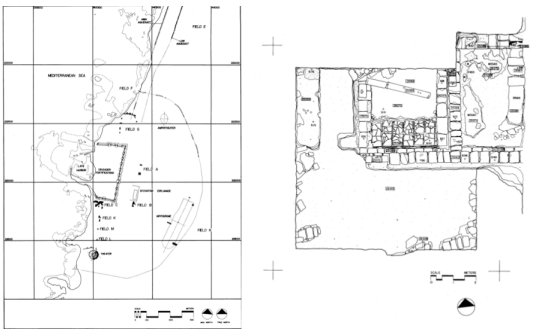


Figure 1: Map of Caesarea Excavation Site. (R) Caesarea broken into excavation fields, defines the primary classification of the site; (L) Field C broken into its Loci, the secondary classification of the site. Bull, R. J., Krentz, E., & Storvick, O. J. (1986). The Joint Expedition to Caesarea Maritima: Ninth Season, 1980. *Bulletin of the American Schools of Oriental Research. Supplementary Studies*, (24), 31–55. https://doi.org/10.2307/20066658.

Artifacts

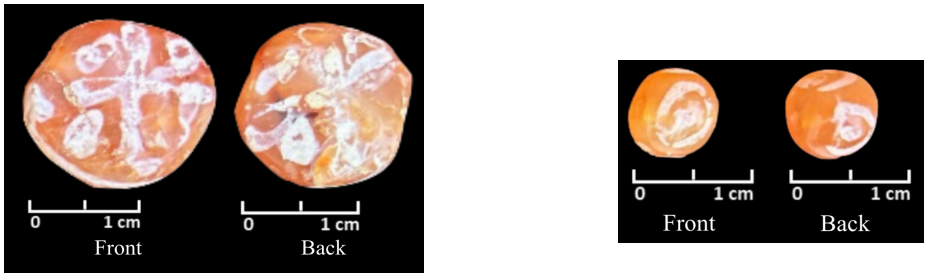


Figure 2: Etched Artifacts from Caesarea. The only two etched carnelian beads found in the Drew Archives from Caesarea Maritima. These beads were historically very valuable. (L) Sample 6000. (R) Sample 1003.

In Caesarea Maritima, carnelian beads were first excavated by Dr. Robert Bull during a joint expedition from 1971 to 1986 (Figure 1). Only recently were eight of the carnelian beads rediscovered when a class of Drew University students in the spring of 2026 were reexamining material from Caesarea (Figure 2; Pfeiffer, 1982). Two beads were identified to have distinct etchings with varying designs. The larger etched bead was excavated in 1976 in Field A, Area 6.1, Locus 00; the organization of the Caesarea excavation site is mapped in Figure 1. This bead was found in a mixed context with Roman, Byzantine, and Arab pottery and was in the first levels of the excavation of this field. The smaller etched bead was excavated in 1979 in Field L, Area 1.7, Locus 3. This context was loose fill, including glass and human bone fragments lying above unsealed Crusader-period burials, placing the bead's burial point around 1200 to 1300 CE (Bull et al., 1991). It is important to note that there could be pronounced differences in time periods between the two etched beads' production and use as the beads were not found directly together, and beads were often kept and traded for long periods of time.

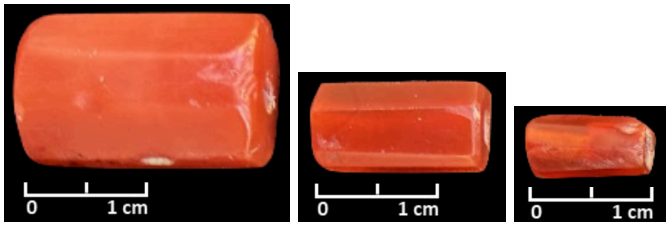


Figure 3: Octagonal Artifacts from Caesera. Three octagonal carnelian beads are all found in field C. In order left to right, Samples 7015 Field C.1, 7015 Field C.2, 7015 Field C.3.

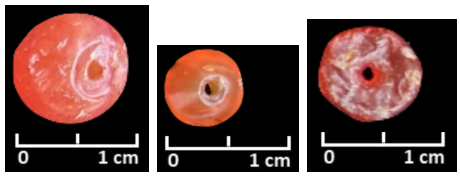


Figure 4: Round Artifacts from Caesera. These round beads were found in field C. In order from left to right, Samples No Provenience (NP), 21025, 21026. Samples NP and 21025 are spherical while Sample 21026 is flat.

Correspondingly, non-etched carnelian beads, seen in Figures 3 and 4, were found in Field C and were included in this study to help further understand the use and presence of carnelian at the site and the possible trade of these beads. Investigating the continuity of certain manufacturing practices in the beads themselves will aid the study of the origin of the beads and whether they were from the same workshops or regions.

Bead Etching Practices

Historically, carnelian beads with etchings have been admired due to the expert craftsmanship necessary to produce such intricate designs. Though their etchings may seem carved into the stones, they are actually formed through an alkaline bleaching process combined with heat treatments. To begin the process, a thick, sticky paste is created by mixing a solution of sodium carbonate (Na_2CO_3) with plant juice, most commonly derived from the desert shrub *Capparis aphylla* (Mackay, 1933; Beck, 1933). After polishing, this paste is applied onto the surface of the stones, which are then heated over a fire to trigger a chemical reaction. The intense temperatures separate the sodium from the carbonate to chemically bond with the silica (SiO_2) structure. It is also important to note that a precise duration and temperature was vital to obtain an effective result (Holé, 2022). This intricate thermal-alkali reaction alters the properties of the carnelian fundamentally, changing its refractive index and thus causing the treated areas to transform into an opaque, white color (Glover & Bellina, 2003). The pattern is fused into the stone, which ensures that the intricate design is preserved for millennia.

The practice of etching carnelian first began in the Indus River Valley (Frenez & Lischi, 2026). This civilization was known for having products of the highest quality, and the etched carnelian beads they produced were known for being smoothly polished, having cleanly drawn lines, and lacking breaks or scars from production (Ludvik et al., 2020). Besides their esteemed quality, it was also speculated that these beads were so valuable due to limited inventory. This was demonstrated by the number of replicas created from terracotta and steatite in workshops around the African and Asian continent (Simpson, 2020).

Chronology of Ancient Drilling Techniques

A substantial archaeological connection has been drawn between an ancient bead's perforation and method of production. Carnelian is classified as a hard stone, approximately 7.0 on the Mohs' Scale, so turning the raw stone into beads required sophisticated drilling techniques (Ludvik et al., 2022). Over centuries and across cultures, such techniques became specialized and evolved, often independently. A drill hole's characteristics serve as a significant link from the bead to its era of production (Ludvik et al., 2022).

Pecking

Pecking was one of the first and most rudimentary methods of drilling holes into hard stone beads such as carnelian. This manufacturing method has been reported from sites in locations such as Mesopotamia, Arabia, Egypt, and the Indus Valley. The technique involved pecking the bead from one side using a percussor until a single, large, cone-shaped piece popped out of the other end. Occasionally, pecking was done from both sides of a bead until the perforations met in the center. Due to the brute-force nature of the pecking method, the drill holes of pecked beads tend to have rough openings (Ludvik et al., 2022).

Stone Drilling

For hard stones, stone drilling involved mounting a tapered green jasper or chert drill bit into a bow drill and applying downward pressure. This technique resulted in long, tapered perforations that varied between cylindrical and conical. For carnelian specifically, the stone drilling technique corresponds to highly-polished internal drill holes (Ludvik et al., 2022).

There is a specific type of stone drilling directly tied to the Indus Valley called constricted cylindrical drilling, or Ernestite drilling. This method employed a cylindrical bit made from Ernestite rock, drilling the bead from both sides until the bored holes converged in the center. For longer beads, it required the use of a progressively smaller bit size as the drilling approached the centerpoint, resulting in a distinctive tiered cylindrical drill hole. Beads using this technique have been found worldwide (Ludvik et al., 2022).

Diamond Drilling

Diamond drilling was done in two main techniques: single and double diamond drilling. In single diamond drilling, a jagged diamond chip was inserted into an iron drill shaft, producing an irregular, cylinder-shaped hole. This technique was associated with Afghani styles starting from the Achaemenid Period (Ludvik et al., 2022). Double diamond drilling was developed earlier, utilizing an iron drill shaft with two diamond bits; this technique was commonly used in South Asia but was also found in North Africa (Kenoyer, 2003; Kenoyer et al., 2025). Diamond drilling sometimes included the use of a single bit followed by a double diamond drill. Diamond drills introduced a new level of precision to bead making, revolutionizing the craft (Kenoyer et al., 2025).

METHODOLOGY

The artifacts found from Caesarea Maritima were analyzed in three ways: chemically, morphologically, and stylistically. Each method was selected to determine whether the beads excavated at Caesarea Maritima were the product of trade, local-production, or duplicates.

ATR-FT-IR

Attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FT-IR) is an instrument that utilizes infrared radiation to determine the bonds present in a substance. This study uses a Thermo-Scientific Nicolet iS10 FT-IR with a Smart iTR™ Attenuated Total Reflectance Sampling accessory. Infrared radiation causes bonds within a molecule to vibrate, generating a quantitative measure to analyze the elemental composition of an unknown material. ATR-FT-IR was chosen since it was not destructive. Wavelengths from 600 to 4000 cm^{-1} were passed through all samples and store-bought carnelian as a reference. Non-bead samples were prepared using a gem saw. Multiple scans were executed per sample to avoid error. Each sample's most representative spectrum was selected for statistical analysis.

Statistical analysis was utilized in effort to determine the similarity of ATR-FT-IR spectra to the rough-cut carnelian reference, in order to accurately identify the composition of all samples. Data were organized on Google Sheets and analyzed using the embedded RANK and CORREL functions. To standardize data across all sets, the wavelengths were trimmed from 642.207 to 1824.407 cm^{-1} to match the reference sample.

A combination of Pearson's and Spearman's rank correlation coefficients were utilized to determine the statistical significance of our results (Schwarte et al., 2018). The reflectance data of the sample and the reference were used to generate the Pearson's correlation coefficients. Then, all of the reflectance values were ranked in descending order and correlated to produce the Spearman's rank correlation coefficient. Additionally, a t-statistic was calculated for each coefficient.

Drill Hole Analyses

Primary and Secondary Back-Light Test

Due to a lack of a scanning electron microscope (SEM), there was no way to replicate the methodology which provides magnified images of drill hole impressions that have previously been used for qualitative analyses (Kenoyer & Frenez, 2020). Instead, we developed the "Back-Light Test" to circumvent this issue. This method analyzed drill hole orientation in two ways: the Primary Back-Light Test, which discerned whether an angled drill hole existed, and the Secondary Back-Light Test, which aimed to observe the inner structure of the sample. The Secondary Back-Light Test could only be applied to translucent carnelian beads. The tests are in no way as conclusive or definitive as using SEM or X-ray imaging; nonetheless, the Primary Back-Light Test should be viewed as a litmus test, while the Secondary Back-Light Test is much more conclusive.

For the Primary Back-Light Test, the selected bead was placed under a microscope such that its drill hole is perpendicular to the plane of the lens. Only the bottom light of the microscope was turned on. The orientation in which the light passed through was recorded. For the Secondary Back-Light Test, the bead was laid down with its drill hole parallel to the microscope lens and analyzed in the same way.

Drill Hole Impressions

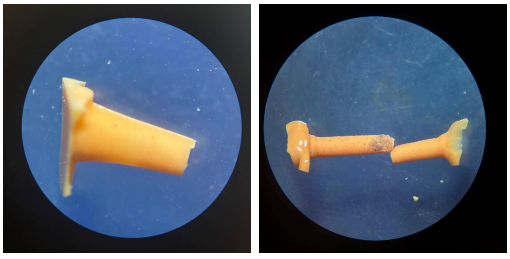


Figure 5: Drill hole impressions under a microscope at 10.5x magnification. (L) Sample 21025, mold in one piece; (R) Sample Field C.3 mold in two pieces due to sharp angle

Impressions were taken of the bead perforations. As conducted in Ludvik et al.'s (2020) study, beads were cleaned using distilled water, dried, and then impressions were made using vinyl polysiloxane. After the impressions were cured and removed, they were examined under a microscope. For longer or extremely angled beads, the impression often came in two parts, divided at the drill hole's intersection point. The two halves were then reassembled after removal for analysis (Figure 5).

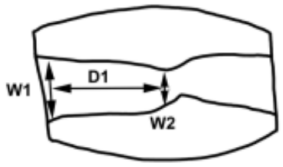


Figure 6: Visualization of DHTV. Ludvik, G. E., Kenoyer, J. M., Klonymus, H. C., Barkay, G., & Dvira, Z. (2022). Stone beads from the temple mount, Jerusalem: a relative chronology through high-resolution studies of bead technology. *Archaeological and Anthropological Sciences*, *14*(6), 115.

This method was selected for its ability to provide context into the manufacturing of the beads. The impressions also allowed for a drill hole taper value (DHTV) calculation, which quantifies the degree of a drill hole's taper. Measurements were taken in millimeters with calipers. If DHTVs across beads are not similar, it could indicate that the beads did not share a common workshop. For beads that feature double sided drilling, two DHTVs were calculated for each side's bore holes as depicted in Figure 6 (Ludvik et al., 2022).

Experimental Recreation

Despite the long history of etched bead production, the exact methods of manufacturing are still relatively unknown. (Mackay, 1933). In an effort to better understand these processes, we attempted to recreate the etching process in our lab. Through experimentation, we investigated the thermal-alkali reaction that creates the distinct "etch" on carnelian beads.

Similar attempts to recreate the bead etching process have been made, notably at the Department of Scientific Research of The British Museum. To create the etching solution, the study used sodium alginate as an alternative to Kirar plant juice, as well as sodium carbonate. Various temperatures and heating times were used in their trials to develop an optimized procedure (Holé, 2022). Guided by this experimentation, our lab developed our own procedure to recreate the etching process. We first bought carnelian samples and cut them 1–2 centimeters in both width and height to mimic the small surfaces of beads. In five out of seven trials, sodium alginate was used as the binding agent, excluding the first and last trials. In the first trial, mango juice was used as an alternative binding agent due to its status as a native fruit to Pakistan and Northwest India, where the Indus Valley Civilization was located (Yadav, 2017). In the last trial, caper juice, gum arabic, and borax were used concurrently as a binding agent. These resources were used to replicate the etching process more authentically, as capers are members of the same genus (*Capparis*) as the Kirar plant, and gum arabic is a natural plant resin that would have been available to ancient beadmakers (Singh & Singh, 2011; Simpson et al., 2020). Additionally, borax has been documented as serving a function in helping carnelian retain its color after firing, thus we included this material in our experimentation (Mackay, 1933).

For our general procedure, we mixed sodium carbonate with the respective binding agent for each trial. Designs were then applied and allowed to dry completely. Beads were then heated in an electric kiln at 400ºC–450ºC. In each of our trials, variations were introduced in the binding agent, drying time, kiln temperature, heating time, and proportions of chemicals. A detailed procedure for each individual trial is included in Appendix A.

Stylistic Comparison

Etched carnelian beads have been discovered in various contexts and locations across numerous studies. The quality of cut, polish, and design can be indicative of the beads' origins or determining if they are replicas. We conducted a literature review on etched carnelian bead findings to gain a basis with which we could compare our beads in order to formulate hypotheses of our samples' origins. Additionally, we microscopically analyzed Sample 6000 and Sample 1003 to determine whether their designs were the result of paint or a chemical reaction.

RESULTS

ATR-FT-IR

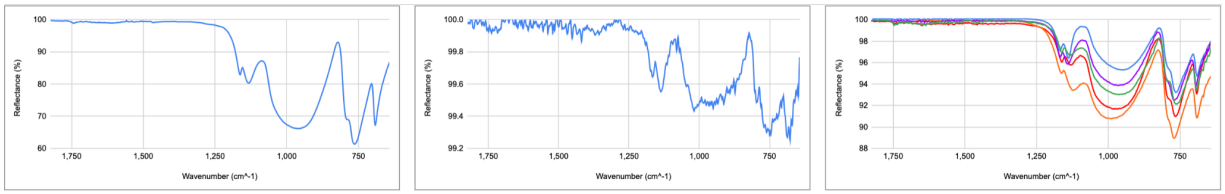


Figure 7: ATR-FT-IR spectra of samples. The spectra measure Reflectance vs. Wavenumber. (Left) Sample Field C.1 spectrum. (Middle) Sample 1003 spectrum. (Right) Samples Field C.2 (blue), 6000 (purple), 21026 (green), Field C.3 (red), and Reference (orange) spectra compared.

All ATR-FT-IR spectra in Figure 7 have distinct bands at 1140 cm^{-1} and 1000 cm^{-1}, along with a sharp doublet in the region from 760–800 cm^{-1}, and another sharp peak around 700 cm^{-1}. These characteristics strongly suggest that all of our samples contain α-quartz, which is a major component of carnelian (Launer & Arkles, 2013; Li et al., 2023).

The extent of this similarity was analyzed using both Pearson's and Spearman's Rank correlation coefficients, utilizing a range from negative one to one to report the degree of indirect or direct correlation.

Table I: Pearson's, Spearman's Rank Correlation, and t-Statistics

Sample ID	Pearson's (r)	t-statistic	Spearman's Rank (ρ)	t-statistic
Field C.1	0.983	402.875	0.940	136.291
Field C.2	0.947	232.819	0.829	73.349
Field C.3	0.977	342.080	0.927	122.374
6000	0.978	479.952	0.911	109.082
1003	0.943	143.043	0.851	80.390
21026	0.978	286.901	0.865	85.184

The critical t-statistic at a 1% significance level and 2453 degrees of freedom is 2.578. All t-statistics in Table I are greater than 2.578, indicating that the correlations are statistically significant. All of the high correlation coefficients (>0.8) indicate that these samples' ATR-FT-IR spectra closely resemble the reference rough-cut carnelian spectrum. Qualitative analysis also reveals varying hues of reddish-orange across the artifacts, which is often found in carnelian. Altogether, these results heavily indicate that all field artifacts are composed of carnelian.

Bead Perforation Qualities

Bead	Image *not to scale	Drill Hole Internal Texture?	Straight Hole?	Polished internally?	Circular drill hole?	Tapered?	Met in the middle?	Translucent?	DHTV(s)
21025		Smooth with Fine Rings	1	1	1	1	0	0	0.156
6000 (etched)		Fine Rings	0	1	1	1	1	0	0.00445 0.00538
1003 (etched)		Fine Parallel Rings	0	1	1	0	1	1	0.148 0.142
21026		Smooth	1	1	0	1	1	0	0.592 0.855
7015 Field C.1		Rough, Fine Parallel Rings	0	0	1	0	1	0	0.0199 0.0224
7015 Field C.2		Unpolished/ Rough (potential for dirt), Fine Rings	0	0	1	0	1	1	0.00699 0.0147
7015 Field C.3		Unpolished/ Rough (potential for dirt), Fine Rings	0	0	1	0	1	1	0.00 0.00194
NP		Smooth (some dirt), Fine Rings	1	0	1	1	0	1	0.00138

Figure 8: Organized drill hole results. Aggregates qualitative and quantitative observations for each bead's drill hole. Columns 1 and 2 identify the beads. Column 3 describes the ringing internal texture of the bore holes. Columns 4–9 present qualitative bead properties as boolean variables in which a "1" indicates that the bead possesses the given trait while a "0" designates that it does not.
A drill hole was deemed to have a noteworthy taper and assigned a "1" in column 7 if its DHTV had a nonzero tenths place. Beads with a "1" in Column 10 were eligible for the Secondary Back-Light Test. Calculated DHTV are then included in the rightmost column; bead-specific calculations are located in Appendix C.

Sample 21025

Sample 21025 had a convex bicone shape; its drill hole had a flake scar on both sides, and a deeper, collared ridge at its entrance. The hole was also smooth, tapered, and straight through. It also had a DHTV of 0.156, indicating a slight taper. Its impression further confirmed the taper and smoothness of the drill hole, it also revealed that the drill hole had fine rings on it.

(Etched) Sample 6000

Sample 6000 was a longitudinal circle with a rectangular axis. Its design featured a cross with dots (called a Cross Hac) on both faces with lines on its sides. Its drill hole was circular and met in the middle, creating a slight angle. Its two DHTVs were 0.00445 and 0.00538 indicating an almost nonexistent taper. Its impression revealed fine rings on the drill hole.

(Etched) Sample 1003

Sample 1003 was a spherical bead that featured three eye-like designs. Its drill hole met in the middle, meeting at a sharp angle. Its drill hole was circular and both sides were the same width. Sample 1003 had two DHTVs since it met in the middle. These two values were 0.148 and 0.142, indicating a slight taper. The Secondary Back-Light test corroborated an angled drill hole. The drill hole impression confirmed the above and showed fine, parallel rings.

Sample 21026

Sample 21026 had a rectangular profile with circular faces. Its drill hole was smooth and met in the middle with good centering; the bead featured large flake scars and an extreme taper. Its DHTVs were 0.592 and 0.855. Impressions confirmed these findings.

Sample 7015 Field C.1

Sample 7015 Field C.1 had a rectangular profile and octagonal faces. Its hole was drilled from two sides with poor centering, leading to an angle. Its drill hole was rough and circular with

fine, parallel rings; the impression also took out some dirt. Sample 7015 Field C.1 did not have a significant taper; its DHTVs were 0.0199 and 0.0224.

Sample 7015 Field C.2

The shape of 7015 field C.2 had a rectangular profile with octagonal faces, featuring double sided drilling with each perforation untapered. The two DHTVs were 0.00699 and 0.0147. The inside of the drill was textured and unpolished but circular with fine rings.

Sample 7015 Field C.3

Sample 7015 field C.3's shape had a rectangular profile with octagonal faces. Internally, the bore hole had an unpolished, rough texture. The impression revealed that there were rings on the drill hole. The perforations were perfectly cylindrical, meeting in the center with essentially no taper. 7015 Field C.3's DHTVs were 0.00 and 0.00194.

Sample "No Provenience" (NP)

Sample NP was a sphere with a straight perforation. The hole had virtually no taper with a DHTV of 0.00138. Sample NP had flake scarring; this meant it likely was drilled from one side. The Secondary Back Light Test further supported that it was drilled from a single side. Its impression showed fine rings on the drill hole as well.

Stylistic Connections

Stylistic analyses were performed on Samples 6000 and 1003, as these were the two etched beads found in Bull's collection. Sample 6000, as seen in Figure 2, is a longitudinal circle with a rectangular axis, with two circular surfaces and a thin edge. On one side, there is an equal-armed cross that separates the bead into four sections. In each section, there is a small dot. There is a white line that runs along the edge of the bead. The other side has a similar design but of poorer quality. This bead has an uneven surface with several small chips, cracks, divots, and dark spots, which can potentially be impurities or sediment from burial.

As seen in Figure 2, the smaller etched bead is relatively spherical in shape. The bead features three eye pattern designs, consisting of concentric circles. The surface is smooth, with no major imperfections. The eye pattern has shown to be prevalent in etched carnelian bead designs, particularly in the Indus Valley (Prabhakar, 2018; Beck, 1933; Kenoyer, 2013). The white lines are visible, but slightly fainter than Sample 6000.

Both beads are slightly translucent, but Sample 6000 is more opaque than Sample 1003, indicating that the bead-makers did not heat the beads extensively, as a higher temperature or a longer firing time results in a deeper red color (Then-Obłuska, 2013). Close examination of Sample 6000 and Sample 1003 under a microscope provided evidence that the white etched patterns are truly etched rather than painted on.

Time Periods

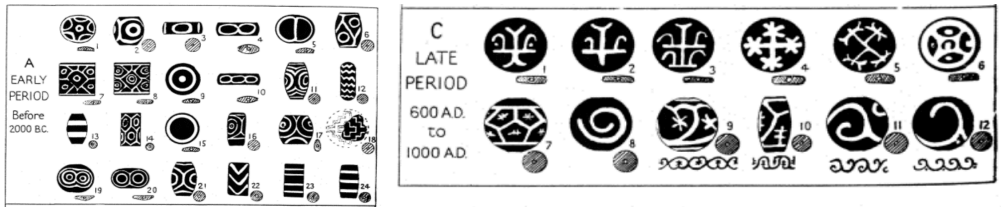


Figure 9: **Beck's bead design chronology.** Horace Beck's guide on bead patterns was used for comparison with the excavated beads to find their chronological origin. Reprinted from Beck, H. C. (1933). Etched Carnelian Beads. The Antiquaries Journal, 13(4), 384–398. doi:10.1017/S000358150003883X.

Using Horace Beck's bead design chronology, we attempted to match Sample 6000 and 1003's designs to corresponding time periods (Figure 9). This reference chronologically maps out certain motifs, such as "eye" patterns or concentric circles, as originating before 2000 BCE, and different "cross" patterns emerging more recently, from circa 600 to 1000 CE.

Pattern Comparison

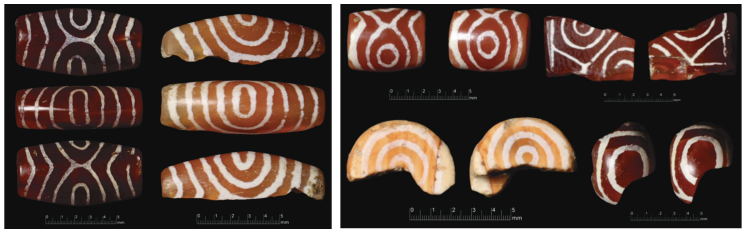


Figure 10: Beads and bead fragments found from the Indus Valley Site of Dholavira. These beads were compared with our samples to examine quality control. It is evident that lines are solid and clean, and surfaces are smooth and polished. Prabhakar, V. N. (2018). Decorated carnelian beads from the Indus Civilization site of Dholavira (Great Rann of Kachchha, Gujarat). In D. Frenez, G. M. Jamison, R. W. Law, M. Vidale, & R. H. Meadow (Eds.), *Walking with the unicorn: Social organization and material culture in ancient South Asia: Jonathan Mark Kenoyer felicitation volume* (pp. 475–485). Archaeopress. https://doi.org/10.2307/j.ctv19vbgkc.35.

A study performed on carnelian beads from Kish, Iraq, found that the refinement of the white design on two etched beads was not consistent with Indus production standards, suggesting that they were not produced with the same oversight as Indus bead workshops (Kenoyer et al., 2026). Similarly, the etched white design on Sample 6000 lacks a high level of refinement, which may indicate that it was not produced in an authentic Indus workshop. In comparison to other excavated etched carnelian beads that were of Indus origin, the lines were less crisp and the design was not clear. Furthermore, the bead's surfaces were uneven, unlike the Indus Valley beads, which had smooth facets, neat edges, and signs of polishing (Figure 10).

Regions/Locations

The cross-and-dots pattern on Sample 6000 resembles a Cross Hac, a common symbol used before Christianity. It has been traditionally featured on Turkish kilims, which are flat-woven rugs. According to Anatolian religion, the Cross Hac splits the evil eye into four parts, which diminishes its power and protects from harm (Keskin, 2018). The Cross Hac design has been found in beads excavated in multiple areas, including the Perm region of western Siberia, Kamunta, and northern Iraq (British Museum, 2022; Eger, 2014; Simpson, 2020). The bead excavated in the Perm region is questioned to be of Turkish origin, as mentioned in the

British Museum's curator comments. Furthermore, other variations of the Cross Hac design have been found near regions such as Crimea and Baghdad (Beck, 1933). These variations include lines intersecting the ends of the cross (Erbek, 1988). Versions of the Cross Hac have also been featured on two lamps and several coins that were excavated from Caesarea Maritima by Robert Bull's team (*Artifacts from Caesarea Maritima*, 2018). One such lamp was found in Field A, the same field as Sample 6000.

For Sample 1003 in Figure 2, the concentric pattern mirrors a human eye. In Indus culture, these eye motifs were believed to keep the wearer safe from evil spirits (Kenoyer, 2013). Many cultures shared this belief as beads with similar eye designs have been found in excavation sites across Southeast Asia (Glover & Bellina, 2003).

Experimental Results

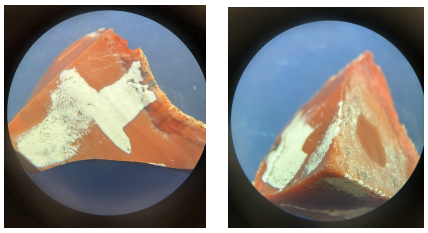


Figure 11: Experimentally etched carnelian beads. These beads were experimentally etched in our lab using a mixture of washing soda (Na_2CO_3), caper berry juice, gum arabic, and borax ($Na_2B_4O_7 \cdot 10H_2O$). The etched pattern was successfully applied to the stone, however the designs are somewhat uneven and imprecise.

The experimental recreation trials we conducted demonstrated the particularity of the etching process. Out of seven trials conducted, six were unsuccessful in producing a visible bleached pattern in the carnelian stone. In the first trial using mango juice, the etching solution left only a faint, transparent outline of the pattern applied on the stone, and the expected thermal-alkali transformation did not occur. The next five trials were unable to produce any visible results. However, in our last trial, although the designs were rather imprecise, we were able to effectively recreate the white bleached pattern. (Figure 11). The high rate of failure we experienced across our trials was likely impacted by differences in proportions of chemicals, drying time, and firing methods. Nevertheless, difficulty in recreating the etching process is not uncommon; some researchers have been unable to produce more than cloudy white patches on carnelian stone in their experiments (Glover & Bellina, 2003). Additionally, it must be noted that whilst the experimental recreation at The British Museum was successful, the design created was a simple smiling face and required extensive trial and error to generate successful outputs (Holé, 2022). Thus, the frequency of unsuccessful outcomes provides insight into the high skill level required to produce these etched beads.

DISCUSSION

Before any archaeological interpretations regarding manufacturing techniques, chronology, or provenance could be made, it was first necessary to ensure that all of the artifacts were indeed true carnelian rather than aforementioned visually similar substitutes. Due to minor variances in the crystal-lattice structure, the samples interacted with different amounts of infrared radiation, resulting in valleys of disparate magnitudes. Therefore, we chose to compare the relative shapes of the spectra, rather than their magnitudes. The ATR-FT-IR spectra of all the analyzed samples exhibited characteristic features of α-quartz, including notably prominent

bands around 1140, 1000, 760, and 700 cm^{-1}, consistent with the mineral composition expected of carnelian (Figure 6). Furthermore, both the Pearson's and Spearman's rank correlation coefficients yielded a statistically significant agreement between each artifact and the carnelian reference sample. Establishing that all the analyzed artifacts were indeed authentic carnelian was essential because it provided the basis for the subsequent comparisons of both morphological and stylistic characteristics.

Due to the pervasiveness of drilling techniques across the world, determining the absolute history of a bead from a drill hole analysis is unreliable. For the purpose of this study, drill hole analyses would be best suited for intra-site conclusions and broad assumptions of their chronology rather than directly connecting a bead to its origins. Our collection functions as a microcosm, providing greater insight into the broader ancient traditions and practices of the Near East. It is vital to understand the techniques employed by the workshops and how they produced beads. Workshops and craftspeople hyperspecialized in their methods and materials to streamline production, meaning it was more than likely that beads with a high degree of variance had different origins and vice versa (Kenoyer et al., 2025).

It is evident that six of the eight beads were drilled using a meet-at-the-center technique, as seen through impression analysis: samples 21026, 7015 C.1, 7015 C.2, 7015 C.3, 6000, and 1003 (Figure 8). However, there was varying severity of misalignment of the two drill holes. When meet-at-the-center drilling results in a large angle between drill holes, it may indicate an unskilled craftsperson, whereas smaller angles suggest high expertise (Kenoyer et al., 2025). The range of DHTVs in our samples further indicated productions of differing skill levels. For example, Sample 21025 had extremely large taper values of 0.855 and 0.592 while Sample NP had an extremely small taper value of 0.00138. This level of variation further suggests that the collection does not share a common workshop.

Microscopic observations of the molds revealed that the majority of our beads' drill holes are consistent with diamond drilling characteristics, displaying smooth, cylindrical drill holes with parallel rings and minimal taper (Kenoyer et al., 2025). Samples 6000, 7015 C.1, 7015 C.2, 7015 C.3, and NP fit this description (Figure 8). The diamond drilling technique was ubiquitous circa 1 CE due to its efficiency and effectiveness (Ludvik et al., 2022). As a result, it provides some chronological context to the beads' production but little insight into their specific geographical origins. It does little to support that the beads have any common provenance. While within our sample set, diamond drilling from two sides was most prevalent, Sample NP is likely the product of single-sided diamond drilling. Sample NP lacks a circular drill hole on the drill bit exit side, aligning the bead with others of the single-sided technique (Kenoyer et al., 2025). Due to a workshop's tendency to narrowly specialize in bead style and production techniques, it is unlikely that a single shop would employ both single-sided and double-side methods.

Another prominent outlier is Sample 21026, which had a high DHTV and did not have circular drill holes. This indicates that the primitive drilling technique of pecking was used, suggesting it was made earlier than the rest of our beads (Ludvik et al., 2022) (Figure 4). This finding reveals that our collection represents a broad chronological range of production techniques, suggesting that the beads studied were produced in different workshops.

Samples 21025 and 1003 were also unique in their drilling style. Their drill holes were smooth and had significant DHTVs; these qualities are consistent with stone drilling (Figure 8). Ernestite drilling is a type of stone drilling that can be used as a distinctive marker of Indus production. Samples 21025 and 1003 are short and thus lack the indicator of Ernestite found in longer beads (the cylindrical tiers) needed to differentiate Ernestite from other types of stone drilling; however, other features of these beads are consistent with Indus Valley standards. They both have a highly polished finish and smoothed out flake scars–a marker of Indus quality control (Kenoyer, 2013; Kenoyer et al., 2024). Additionally, Sample 1003 is etched with an "eye," which was a prominent etching pattern of Indus craftspeople. If the beads were produced by the Indus, it is likely that they circulated in trade networks for a substantial amount of time before reaching Caesarea, and they likely entered Caesarea by means of Indian Ocean Sea Routes rather than land-based routes like the Silk Road. The study will continue under the assumption that Sample 21025 came from the Indus Valley. Regardless, the qualities of Samples 21025 and 1003 corroborate the conclusion that our collection of beads are the result of trade.

Sample 6000 contrasts with Sample 1003 despite both beads having etched designs. Sample 6000 appears to be diamond drilled, placing it around the Hellenistic Age or later (Ludvik et al., 2022). Its Cross Hac design is rooted in Anatolian religion and culture, specifically the spreading of early Christianity (Keskin, 2018)[1]. The Anatolian Peninsula is a likely region for which the bead was produced because it contained workshops organized and developed by the Indus Valley (Glover & Bellina, 2003). This peninsula is located very close to Caesarea, as both regions border the Mediterranean Sea, so the bead was likely brought to Caesarea by Indian Ocean trade routes. Another possibility is that the Cross Hac spread from Anatolia to regions like Iraq and Siberia, incorporated into cultural objects, and then diffused into Caesarea, since Cross Hac beads were found in these locations (British Museum, 2022; Eger, 2014; Simpson, 2020). Other excavated artifacts from Caesarea that contain the Cross Hac suggest that trade resulted in the diffusion of the symbol to this city (*Artifacts from Caesarea Maritima*, 2018). Sample 6000 was also produced more recently compared to Sample 1003, given it was manufactured with diamond drilling (Ludvik et al., 2022). With this in mind, the bead was likely circulating through trade networks for a much shorter period than its counterpart and had a far shorter journey to Caesarea. There is considerable variability amongst the two etched beads, indicating that they too did not share a workshop.

The analysis of the three beads from provenience 7015 (C.1, C.2, C.3) revealed distinct similarities between them. Each bead had a two-sided drill hole with very low DHTVs, a circular shape, and a rough finish. Each bead had poor centering where the two drill holes met; however, from looking at the molds under the microscope, it is reasonable to conclude that this rough finish is the result of dirt, dust, and rock that did not come out when the beads were washed rather than the drilling technique. Under the debris, though, there were conspicuous rings from drilling. Given that the drill holes have these qualities, we concluded that they all were produced using diamond tipped drilling (Kenoyer et al., 2025). Sample Field C.2 looked to have been drilled using a single bit followed by a double bit while the other two employed just a single bit or double bit (Ludvik, 2022). Furthermore, they all shared the same rectangular shape with octagonal faces; they did have differing lengths, however. Such similarities lead the study to

[1] This paper was translated from Turkish into English by NotebookLM under the following prompt "Translate the attached paper without making any changes to the actual text" (Google, 2026).

propose that these beads (at least C.1 and C.3), unlike the other five excavated beads, shared a workshop. It then becomes necessary to question whether the beads were produced in Caesarea or were the byproduct of trade.

Given the wide variety of drilling techniques and lack of beads excavated in Caesarea, we have concluded that none of the beads are originally from Caesarea. The archaeological principle of "Criterion of Abundance" establishes that where a distinct style of artifact is most abundant is its most probable location of production (Rice, 2015). Extrapolating the converse of this notion to the excavated carnelian collection lends to the conclusion that the beads are the result of trade into Caesarea. That is, there were too few beads uncovered in Caesarea for it to have been a manufacturing hub. This is consistent with Caesarea's history as a major trading city (Bull, 1982). Although the beads from locus 7015 were likely made by the same workshop, it is more probable that they were produced elsewhere and brought to Caesarea by the same merchant. It must also be stressed that there are no reported deposits of carnelian rock near Caesarea Maritima, which further decreases the likelihood of the beads having been both produced and excavated in the same area (Moutsiou & Kassianidou, 2019).

With their distinct drilling techniques and designs, each bead is a unique snapshot of the historical environment in which it was created. As a trading center of the Mediterranean, Caesarea Maritima acted as a melting pot of many different cultures, symbolized by the presence of our extracted beads. Beads were not a major staple of everyday trade in Roman life. However, Caesarea's unique situation as a trade hub enabled luxury goods from other places–like the Indus Valley or the Middle East–to be brought to the city. This trade underscores the value of carnelian beads, especially etched ones. They had the power to make themselves sought after and valuable even in foreign regions and cultures.

Potential Sources of Error/Obstacles

A major drawback of this study was the instrumentation available. Similar modern studies utilize X-ray imaging, scanning electron microscopy (SEM), and digital microscopes for the imaging of their beads (Kenoyer & Frenez, 2020). This technology was not available for this study. Methods selected circumvented these limitations, but could not achieve the exact levels of precision offered by more advanced instrumentation. Similarly, we were unable to access tools such as LA-ICP-MS, GD-MS, or electron microprobes. Some of these methods are destructive, requiring the pulverization of samples for analysis (Kenoyer et al., 2025). Due to the rarity and limited number of samples within our research pool, non-destructive methods were chosen. ATR-FT-IR analysis proved to be difficult due to the uneven shape and large size of several of the beads, such as Samples 21025 and NP. Additionally, drill hole taper values (DHTV) could be slightly imprecise due to the silicone-like consistency of vinyl polysiloxane, meaning the calipers may have been able to dig into the impression, providing slightly smaller dimensions than in reality.

CONCLUSION

This study ultimately demonstrated that the carnelian beads excavated by Dr. Robert Bull from Caesarea Maritima are genuine carnelian artifacts representing multiple, disparate traditional manufacturing methods rather than a single workshop or production in Caesarea. The evidence presented supported that these beads were products of extensive trade networks linking

Caesarea Maritima to the Indus Valley and the Anatolian Peninsula. Both Samples 1003 and 6000 have etched designs that were confirmed to be genuine. Samples 1003 and 21025 likely originated in the Indus Valley while Sample 6000 likely originated in the Anatolian Peninsula. Future investigations should utilize higher resolution imaging techniques such as SEM, X-Ray, or elemental characterization employing LA-ICP-MS to further narrow down the provenance and chronology of these artifacts. Future studies should also investigate trade and bead-making in Caesarea and Anatolia. Furthermore, a Drew University Master's Thesis posits that there were 619 total beads found in Caesarea. Of those 619, 25 were carnelian and only eight were found in the archives. If located, and with more time, a further study could be conducted on the remaining 17 carnelian beads, comparing them to the eight already analyzed (Pfeiffer, 1982).

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Appendix A: Specific Experimental Procedures

Materials:

- Carnelian samples
- Mango slices
- Caper berries
- Gauze or Cheesecloth
- Sodium carbonate (Na_2CO_3)
- Arm & Hammer Super Washing Soda (Na_2CO_3)
- Sodium alginate ($C_6H_7NaO_6$)
- Gum Arabic
- Borax ($Na_2B_4O_7 \cdot 10H_2O$)
- Deionized (DI) water
- Warm tap water
- Toothpicks
- Beakers
- Scale for mass
- Barnstead Thermolyne 1300 Furnace

Trial 1: Sodium Carbonate + Fruit Juice

1. Crush mangoes using a mortar and pestle.
2. Extract 5 mL of juice from fruit using gauze as a cheesecloth substitute.
3. Add 5.1 grams of sodium carbonate to a beaker.
   ($5g\ Na_2CO_3 \cdot 5mL$ juice $\cdot$ (1.02 g/1mL) = 5.1 g)
4. Pour mango juice into the beaker and mix until the solution is an even consistency.
5. Apply etching mixture to two stones in the desired pattern and allow the design to dry for 10–15 minutes.
6. Heat stones in an electric kiln at 400ºC for 10 minutes.

Trial 2-4 Sodium Carbonate + Sodium Alginate + DI water

1. Grind 3g sodium carbonate to a fine consistency using a mortar and pestle.
2. Pour 5mL of DI water into a beaker and add sodium carbonate little by little until dissolved.
3. Mix in ~0.2g sodium alginate to thicken mixture.
4. Apply etching mixture to three stones in the desired pattern and allow the design to dry.
   - Trial 2/3 - 10-15 minute drying time
   - Trial 4 - 48 hour overnight drying time
5. Heat stones in an electric kiln.
   - Trial 2 - 450ºC, Stone 1 - 5 minutes, Stone 2 - 10 minutes, Stone 3 - 15 minutes
   - Trial 3 - 450ºC, Stone 1 - 20 minutes, Stone 2 - 25 minute, Stone 3 - 30 minutes
   - Trial 4 - 450ºC, Stone 1 - 10 minutes, Stone 2 - 15 minutes, Stone 3 - 20 minutes

Trial 5: Sodium Carbonate + Sodium Alginate + Warm Water

1. Grind 6g sodium carbonate to a fine consistency using a mortar and pestle.
2. Pour sodium carbonate into a beaker, then add warm water until dissolved approximately 14 mL.
3. Mix in ~0.3g sodium alginate to thicken mixture.

4. Apply etching mixture to three stones in the desired pattern and allow the design to dry for 10-15 minutes.
5. Place stones in an electric kiln as it warms to 450ºC, then heat at 450ºC for 15 minutes.

Trial 6: Arm & Hammer Washing Soda + Sodium Alginate + DI Water

1. Measure 1.25g washing soda and 0.15g sodium alginate.
2. Add washing soda to 10mL of DI water and mix until dissolved.
3. Add 0.15g sodium alginate to thicken mixture so it can be applied to the stone.
4. Apply etching mixture to three stones in the desired pattern and allow the design to dry overnight.
5. Place stones in an electric kiln as it warms to 450ºC, heat at 450ºC for 15 minutes, then allow stones to cool naturally.

Trial 7: Arm & Hammer Washing Soda + Gum Arabic + Borax + Caper Berries + DI Water

1. Measure 6.5g washing soda and 0.6g borax.
2. Crush 5 caper berries using a mortar and pestle.
3. Extract 25 mL of juice from caper berries using cheesecloth.
4. Add washing soda and borax to a beaker and combine.
5. Add 0.6g of gum arabic to thicken mixture.
6. If needed, add water until mixture is viscous.
7. Apply etching mixture to three stones in the desired pattern and allow the design to dry for 48 hours.
8. Place stones in an electric kiln as it warms to 450ºC, heat at 450ºC for 1 hour, then allow stones to cool naturally.

Appendix B: Formulas

Pearson's correlation coefficient

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (1)$$

Spearman's rank correlation coefficient

$$\rho = 1 - \frac{6\sum d^2}{n(n^2 - 1)} \quad (2)$$

DHTV Formula

$$DHTV = \frac{Width\ 1\ (W1) - Width\ 2\ (W2)}{Depth\ 1\ (D1)} \quad (3)$$

Appendix C: DHTV Raw Measurement Values

Bead	**Width 1 (mm)**	**Width 2 (mm)**	**Depth (mm)**	**DHTV**
21025	1.88	1.30	3.72	0.156
6000 (Side #1)	2.11	2.08	6.74	0.00445
6000 (Side #2)	2.21	2.19	3.72	0.00538
1003 (Side #1)	1.39	1.06	2.23	0.148
1003 (Side #2	1.34	1.06	1.97	0.142
21026 (Side #1)	2.50	1.08	2.40	0.592
21026 (Side #2)	2.54	1.12	1.66	0.855
Field C.1 (Side #1)	1.75	1.52	11.55	0.0199
Field C.1 (Side #2)	1.74	1.58	7.15	0.0224
Field C.2 (Side #1)	1.65	1.60	7.15	0.00699
Field C.2 (Side #2)	1.71	1.65	4.09	0.0147
Field C.3 (Side #1)	1.65	1.65	5.20	0.00
Field C.3 (Side #2)	1.66	1.65	5.16	0.00194
No Provenience	1.84	1.83	7.23	0.00138