MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS VOLUME 267

Materials Issues in Art and Archaeology III

Symposium held April 27-May 1, 1992, San Francisco, California, U.S.A.

EDITORS:

Pamela B. Vandiver
Smithsonian Institution
Washington, D.C., U.S.A.

James R. Druzik
The Getty Conservation Institute
Marina Del Rey, California, U.S.A.

George Segan Wheeler
Metropolitan Museum of Art
New York, New York, U.S.A.

Ian C. Freestone
The British Museum
London, United Kindom

1992

MRS
MATERIALS RESEARCH SOCIETY
Pittsburgh, Pennsylvania

A new look at stone drills of the Indus Valley Tradition

J. Mark Kenoyer* and Massimo Vidale**

*J. Mark Kenoyer
Department of Anthropology, University of Wisconsin, Madison
**Massimo Vidale
Is. M. E. O. Rome, and Smithsonian Institution, Washington, D. C.

Abstract

Drilling technology of the Indus Valley Tradition was highly specialized and various types of chert and jasper were used to drill different types of materials. Earlier studies used primarily macroscopic observations to define features such as the manufacturing technique of drills, the raw materials and the mechanics of drilling. These generalizations can be revised given the discovery of important workshop areas and the availability of SEM, XRD and electron microprobe analysis. This paper will summarize the current state of drilling research and define two categories of drills that were used in antiquity; *tapered cylindrical drills* and *constricted cylindrical drills.* Directions for future research on the relationship between drilling and other contemporaneous technologies are discussed.

Introduction

Drilling technologies in general and, more specifically, the perforation of hard stones have been a major topic of research in South and West Asia since the discovery of the ancient Indus Valley Civilization in the 1920s and 30s (Figure 1). The urban phase of this culture dates from between 2600 B. C. to 1900 B.C., and has technological roots that can be traced back to 6500 B. C. in the early Neolithic period [1, 2]. Because of the fact that most of the tools, raw materials and manufacturing residues of ancient bead makers are preserved archaeologically, this craft may be efficiently used by archaeologists for reconstructing important aspects of the ancient organization of production [3].

In this article we will examine some of the previous research on prehistoric bead drilling in West and South Asia and propose new terminologies for discussing types of drills used for perforating stone beads during the long history of the Indus Valley Tradition (+6500 B. C. to 1300 B.C.). Two new terms are introduced to differentiate specific varieties of cylindrical drills with dimple impressions at the distal tip. The term *tapered cylindrical drill* refers to drills made on blades that were generally used for the decoration of soft stones and the perforation of short beads made from harder stone (Figure 2). Tapered cylindrical drills have a long historical use and are found in a wide range of cultural contexts spanning the entire region from the Mediterranean to the Indus Valley. In contrast, *constricted cylindrical drills* (Figure 3) are a unique form of standardized and specialized tool

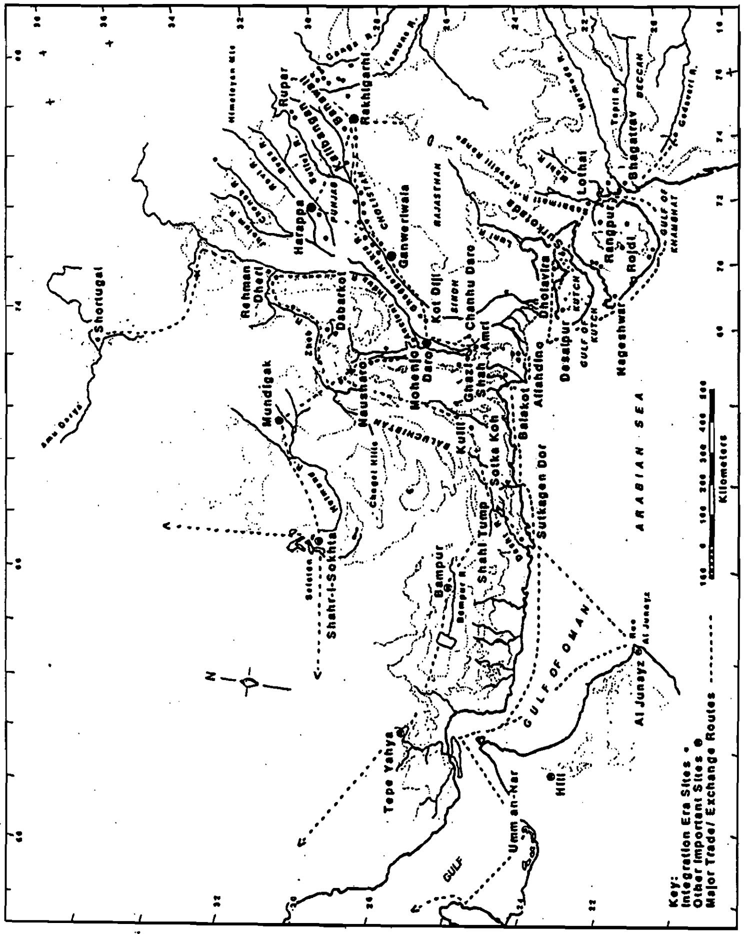


Figure 1. Major Sites of the Indus Valley Tradition, Integration Era, Harappan Phase.

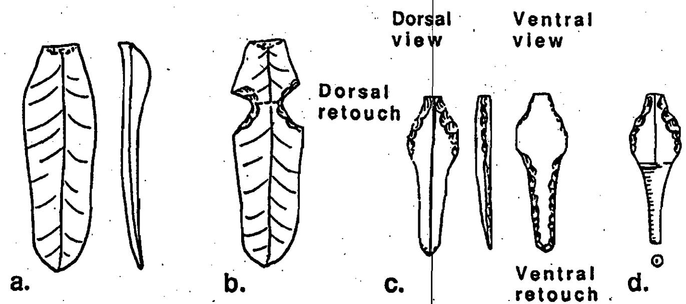


Figure 2. Tapered Cylindrical Drill Manufacture. a. unmodified blade; b. notched blade; c. finished drill; d. used drill with tapered cylindrical form.

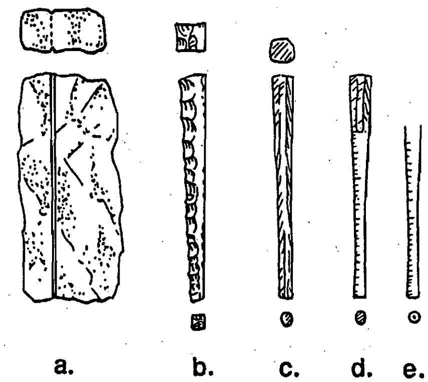


Figure 3. Constricted Cylindrical Drill Manufacture. a. grooved or sawn blocklet; b.chipped drill rough-out; c. longitudinally ground and faceted drill blank; d. finished drill with tapered midsection; e. used drill with distal depression.

developed by artisans in the cities of the Indus Valley region for the perforation of long beads made from agate/carnelian and jasper.

The cultural implications of these two types of drills are significantly different. Tapered cylindrical drills represent a common technology used in a wide range of production contexts. These drills were made from a variety of materials and were used to perforate different types of materials. On the other hand, the use of constricted cylindrical drills involved a more complex series of procurement and manufacturing processes. These drills were used primarily for the perforation of long beads, which were not only much harder to drill, but appear to have been considerably more valuable than the types of beads commonly manufactured with the tapered cylindrical drills. The use of constricted cylindrical drills is clearly associated with specialized production in the context of a state level society and may represent a technology that was restricted or controlled. This control could have been achieved through the restricted acquisition of the drill and bead raw materials, the skills needed to manufacture the drill bits, and the techniques used for the drilling of long beads.

The constricted drills also appear to have been the prototype for later diamond drilling technology that developed in Western India during the first millennium B.C. The connection between state controlled production, constricted stone drills and the development of diamond drilling are not the subject of this paper, but will be discussed briefly in the conclusion.

Current research by the authors involves the examination of drills and drilled surfaces using a combination of experimental and analytical techniques to understand the nature of the raw materials used to manufacture drills and the effects of the drills on the material being drilled. These techniques include experimental reconstructions of drills and drilling techniques along with the analysis of both experimental and archaeological materials using scanning electron microscopy (SEM), scanning electron microscopy with energy dispersive x-ray spectrometry (SEM EDS), x-ray diffraction (XRD) and electron microprobe x-ray analysis. The drills and drill impressions were examined at many different magnifications under the SEM, but the magnifications of 100x to 300x appear to be optimal for determining the different types of abrasive properties and effects.

Background and Previous Research

The first major research on drilling technology of the greater Indus region focused on bead drilling in Sindh and was carried out by E. J. H. Mackay [4-6]. At both Mohenjo-daro and Chanhu-daro (Figure 1) Mackay discovered various types of tiny stone drills that were used to perforate stone beads. Unfortunately he did not differentiate between the two types discussed above and he was not conclusive in his published interpretations of the role of these stone drills in the perforation of long carnelian beads. At the site of Chanhu-daro Mackay discovered large quantities of unfinished and finished drills that were

directly associated with long carnelian bead production, but these were only briefly reported in his publication and he died before he could complete their study. He suggested that instead of stone drills, copper drills used with abrasives might have been utilized to perforate long beads made from carnelian and jasper [4-6].

The confusion regarding the role of stone drills was next addressed in the course of research by Piperno and Tosi on the stone bead drilling represented at Shahr-i Sokhta, Iran (Figure 1)[7, 8]. These studies were a part of a larger research on stone bead making industries of the Third Millennium B.C., carried out at sites in eastern Iran such as Tappeh Hesar and Shahdad, and at various sites in Turkmenia (for bibliography see [9]). Most of these studies were conducted using macroscopic or low magnification microscopic observations and demonstrated that drills made from stone blades were used to perforate lapis lazuli and turquoise beads.

In the workshop areas of Shahr-i Sokhta (dated about to 2700 BC) actual stone drills have been recovered with lapis lazuli dust adhering to the surface, but all of the drill bits are larger than 1 mm in diameter [10]. These stone drills were undoubtedly used for drilling lapis lazuli beads and may have been used for drilling other materials. There were however, beads with tiny perforations less than 1 mm in diameter, and smaller than any of the stone drills recovered from the excavations. The lack of tiny chert drills that would match the size of these holes has led Piperno and others to suggest that the tiny drill holes were made by copper drills and abrasives [7, 8]. Here again we see the proposition that metal drills with abrasives were used by the protohistoric artisans of South Asia. On the other hand, the tiny stone drills needed to perforate such beads may have been discarded in areas of the site that were not excavated or blown away by the strong winds that deflated many areas of the site.

Another site where there is evidence for the use of stone drills is at the site of Shahdad in Eastern Iran. During the protohistoric period, different colors of semi translucent cherts and jaspers were used at Shahdad to perforate large amounts of small carnelian beads (short truncated bicones). Most of these drills appear to have been made from burin spalls, and are comparable with drill bits from Tappeh Hesar, while others were made from tiny blades [11]. On the whole, the picture we get from Eastern Iran and Central Asia is of well established regional technological traditions capable of coping with the material properties and marketing constraints of locally exploited semiprecious stones.

Another variety of drill found both at Shahr-i Sokhta, Iran and Mehrgarh, Pakistan [1] was produced from a fine grained jasper-like rock with conchoidal fracture and good chipping properties, distinguished by a uniform light greenish color. It was originally called *pthanite* [7] but this term should be discarded because it is not an officially recognized scientific term. The precise characterization of this green rock is still incomplete, but preliminary X-ray Diffraction of a sample from Shahr-i-Sokhta suggests that it is some form of iron magnesium silicate. More precise identification must await detailed petrographic analysis.

All of the drills mentioned above have generally been described as being cylindrical in shape with a concave dimple at the tip and have been compared with those found by Mackay at Chanhu-daro and Mohenjo-daro. While the distal tip is cylindrical and has a dimple impression, the drill bit tang usually has an irregular section, triangular or trapezoidal due to the fact that these drill bits were made from blades (Figure 2). It is quite clear that these drills are not the same as those reported by Mackay from Chanhu-daro and should be identified as tapered cylindrical drills (see below).

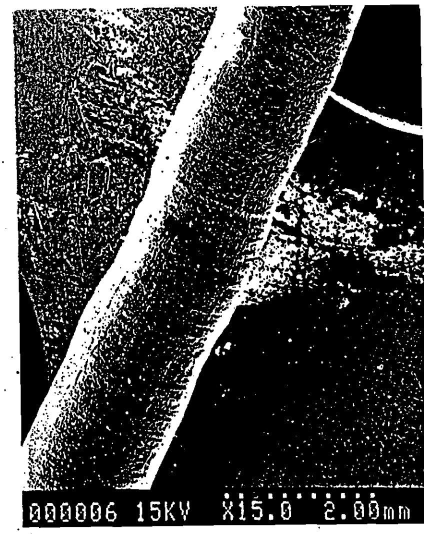
Other studies on West and South Asian material have been made using potentially more powerful instruments, such as SEM on silicone impressions of bead drill holes [12-16]. Unfortunately these studies did not involve primary analysis of the types of stone drills that are the focus of our paper. Furthermore, the interpretations of drilling technology made by the authors have been based primarily on the examination of silicone impressions at a very low magnification (around 10X to 15X) and therefore cannot be adequately compared with the results of our studies.

Our studies of drill hole impressions indicate that at 15X it is often difficult to differentiate the type of abrasive action and surface modification resulting from different types of drills (Figure 4). Drill hole impressions were made from a carnelian bead perforated by a double diamond tipped drill in Khambhat, India [17, 18], a carnelian bead perforated by a Harappan stone drill and a pre-Columbian quartz bead drilled with an unknown abrasive. When these same drill hole impressions are viewed at 100X to 300X the differences in drill cutting action and surface modification become clearly apparent (Figure 5).

In summary previous studies have confused two or more different types of drills and their technological performance. In the following sections we will outline the distinctions between two major types of drills and present the results of our recent studies of constricted cylindrical drills from major sites of the greater Indus Valley.

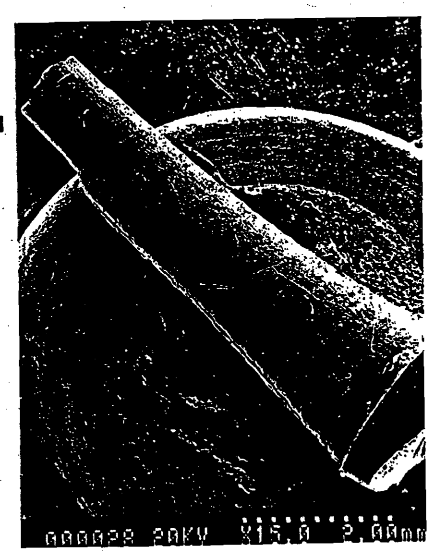
Tapered Cylindrical Drills

The important morphological feature of this type of drill is that the drilling shaft portion is tapered, with the distal end being significantly smaller than the medial portion of the drill bit. Because of this feature we suggest that these drill bits should be called tapered cylindrical drills in order to distinguish them from another variety of drill bit found at the major settlements of the Indus Valley Civilization.



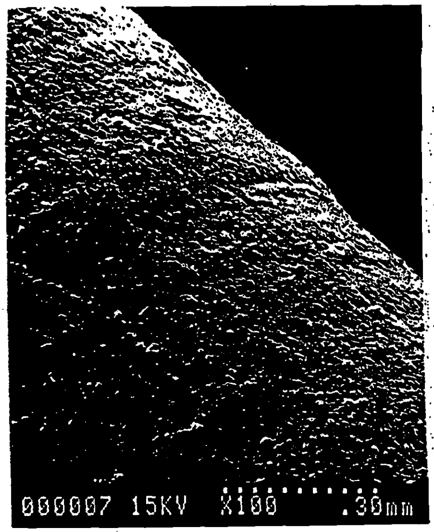
a.

b.

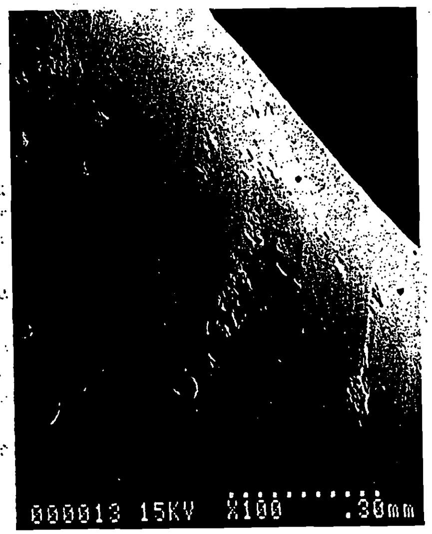


c.

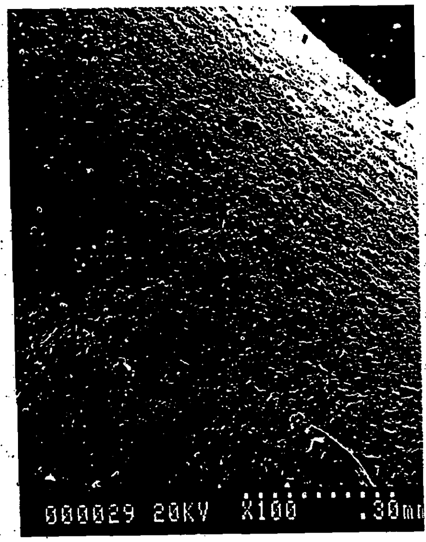
Figure 4. SEM photographs of drill hole silicone impressions at 15X. a. drill hole impression of a carnelian bead from Khambhat, India, perforated with a double diamond drill; b. drill hole impression of a carnelian bead from Harappa, Pakistan probably perforated with a constricted cylindrical stone drill; c. drill hole impression of a Pre-Columbian quartz bead from South America (possibly Tirona Culture), perforated with an unidentified drill and abrasive.



a.



b.



c.

Figure 5. SEM photographs of drill hole silicone impressions at 100X. a. drill hole impression of a carnelian bead from Khambhat, India, perforated with a double diamond drill; b. drill hole impression of a carnelian bead from Harappa, Pakistan probably perforated with a constricted cylindrical stone drill; c. drill hole impression of a Pre-Columbian quartz bead from South America (possibly Tirona Culture), perforated with an unidentified drill and abrasive.

At Indus Valley sites, the raw materials used to make this type of drill bit include both fine grained greenish silicates (similar in appearance to those found at Shahr-i-Sokhta), as well as grey-black jaspers, and colored cherts. No petrographic or mineralogical analyses have been reported on these materials, however we have been able to analyze two samples of green stone from Mehrgarh using X-ray diffraction. One sample corresponds to the pattern available for vesuvianite (calcium magnesium aluminum silicate hydroxide) while another sample is more closely comparable to the iron magnesium silicate from Shahr-i-Sokhta mentioned above. While these identifications are still inconclusive, it is interesting to note that more than one variety of greenish stone was being used at Mehrgarh to manufacture of such drills.

Tapered cylindrical drills are usually made from a thin flake or parallel sided blade that has a single ridge which is used to center the drill. Occasionally a double ridged blade may be used if the ridges are close together. This usually results in a very sturdy and thick drill. These drill bits are not very long as the raw material is brittle and tends to flake very easily and snap. The drilling portion of the drill bit usually falls between 4 to 7 mm although longer examples are on record (for example from Shahr-i-Sokhta).

The blade is flaked with different techniques to produce a pointed distal end and a thick proximal end that is used for hafting. Usually the distal end is modified with inverse backing retouch (flakes being removed from the ventral surface of the blade), but occasionally the tip is bevelled with the backing retouch being normal on one edge (i.e. on the dorsal surface) and inverse on the other (Figure 2). The proximal end or tang of the drill bit is usually shaped with bidirectional backing retouch to form a trapezoidal or triangular section. Through repeated use in drilling a hard material, the angular or bevelled distal portion of the drill becomes chipped and abraded until a tapered cylindrical shape is formed. Archaeological examples of tapered cylindrical drills usually have a concave depression at the tip.

Drills that can be classified as tapered cylindrical in shape have been reported from sites in Mesopotamia [19] and Eastern Iran [11, 20, 21]. In the greater Indus Valley these types of drills are found at the sites of Mehrgarh [22] (Figure 6), Ghazi Shah [23], Rehmandheri [24] and Nagwada [25].

Experimental Studies and Analysis of Drilling

The authors have conducted replicative experiments using tapered cylindrical drills made from flakes of greenish rock recovered from Shahr-i-Sokhta and Mehrgarh, as well as with similar greenish rock collected in Khambhat, Gujarat. The drills were chipped and shaped in order to replicate the archaeological examples. After chipping, they

Figure 6. Tapered Cylindrical Drills, Mehrgarh, Pakistan, Period III (circa 3500 B.C.). (Courtesy J.-F. Jarrige, Photo by M. Tosi).

were hafted in wooden shafts using lac (insect resin), a material that would have been available to the ancient Harappan artisans. The bead blank to be drilled was held in a wooden vise and drilled using a hand powered bow drill (Figure 7). A continuous stream of water was used to cool the drill and wash out the abrading materials. The tapered drill is efficient for making shallow holes in wood, shell, pottery, bone and rocks such as lapis lazuli, steatite, hematite, limestone and sandstone. When the drill tip becomes totally cylindrical it is no longer suitable for drilling softer substances, however it may still be used effectively on harder materials.

The perforation of the softer materials is achieved by the gouging or cutting out of the material. Silicone molds of the drill hole show that the drilling striae are irregular in depth and fairly parallel. The best SEM magnification for observing these striae is between 100 and 300 x. The pitted surface is not polished in the depths of the grooves, but often the tops of the grooves are abraded and polished.

When green stone drills are used on a hard material such as agate, the drill and the drill hole become highly polished. Due to the tapered form of the drill bit, the abraded surface is not confined to the tip, but

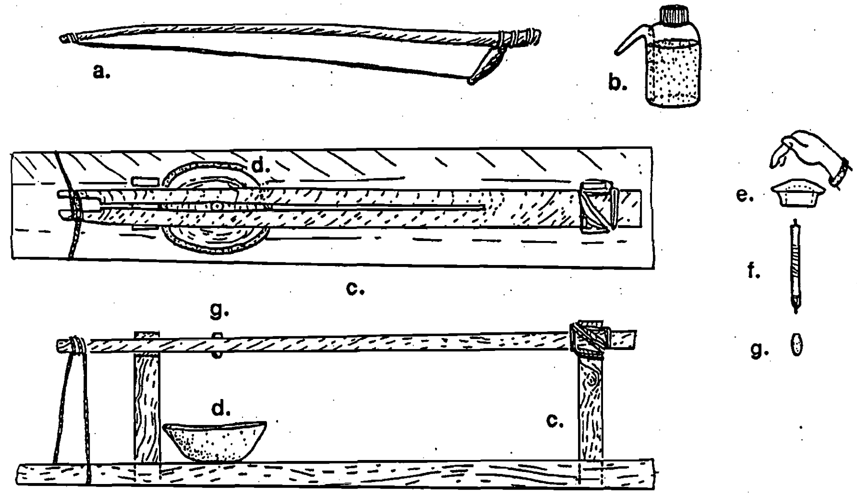


Figure 7. Experimental Drilling apparatus.
a. bow; b. squirt bottle; c. wooden vise; d. and container for water; e. drill back; f. drill; g. bead.

includes the entire tapered shaft of the drill bit. This increased area of abrasion and friction slows down the drilling process and the drill bit is difficult to cool due to the lack of space for water to flow between the drill shaft and the bead surface. The fact that there is no room for lateral movement as the drill is being rotated and the difficulties in cooling the drill bit result in considerable breakage.

Initially the distal tip of the drill is jagged but through repeated use on hard materials, such as carnelian, it becomes rounded. Through continued drilling without any further modification of the tip we found that the tip remained rounded and lost its cutting power. Furthermore, the tip did not form a concave depression as has been seen on archaeological drill bits. In order to increase the cutting performance of the drill bit we began to repeatedly flatten the tip by grinding on a silicon carbide grinding stone. The drill tip was carefully cleaned before resuming the drilling. Through this process of flattening and drilling, the drill gradually developed a concave depression at the tip. This experimental simulation suggests that the concave depression is not simply the result of normal drilling dynamics as previously proposed by Piperno [7], but results from a combination of drilling dynamics and intentional modification.

The rate of perforation using a bow drill was difficult to measure because of repeated interruptions to cool the hot drill back (Figure 7), wash out the drill hole, and to grind the drill tip. However, these same factors are also present in drilling with a constricted cylindrical drill or a double diamond drill and therefore the rates of drilling between these different types of drill can be compared and will be discussed in more detail below.

Constricted cylindrical drills

The disadvantages present in the tapered cylindrical drill seem to have been addressed by artisans of the Indus Valley Tradition at the sites of Mohenjo-daro, Chanhu-daro and Harappa. Although they still continued to use tapered cylindrical drills for some perforation activities, they also invented a new form of drill which we will call the constricted cylindrical drill. The constricted cylindrical drill has a long cylindrical shape that is wide at the tip and constricted in the midsection (Figure 3). This type of drill was made from a single type of raw material that was used to produce standardized bead drills having a specialized morphology and size grading.

Raw materials

The raw material used for making constricted cylindrical drills has been found as angular blocks at the sites of Mohenjo-daro, Chanhu-daro and Harappa (Figure 8). Visually the rock is composed of a mottled greyish-green to yellow-brown matrix with irregular dark brown to black patches or dendritic formations. Fault lines in the stone are visible and often stained with reddish color, possibly due to iron oxide. These fault lines are strongly bonded and cleavage of the block often cuts across visible fault lines. There is no pattern of large scale conchoidal fracture as normally seen in chert or jaspers, but within its irregular cleavage planes the stone, although very hard, has excellent chipping properties. The stone feels quite heavy to the touch, but the specific gravity is difficult to calculate due to the fact that it is composed of different minerals. Two samples of combined dark brown -black and yellow-brown matrix had a specific gravity of 2.26 to 2.35. Sillimanite ranges from 6 to 7 1/2 hardness on the Mohs' scale and has a specific gravity of 3.25. The sample rock can easily scratch quartz but is unable to scratch beryl and therefore falls between 7 and 8 on the Moh's scale of hardness. Nevertheless, the rough surface of the rock can be grooved by a chert blade, and chert is generally between 6 1/2 and 7 hardness.

In order to determine the characteristics of this rock, a sample from Mohenjo-daro was selected for x-ray diffraction and electron microprobe analysis. Samples of the yellow-brown matrix and the brown-black portions were analyzed separately. Based on the XRD spectrum and the calculation of the unit cell values, the yellow brown matrix is made up primarily of quartz and sillimanite [26]. (XRD interpretation was made by Dr. S. Bailey, Department of Geology,

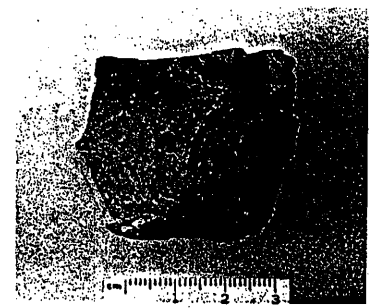


Figure 8. "Ernestite" sample from Mohenjo-daro.

University of Wisconsin, Madison). However, there are some peaks in the XRD spectrum that may represent the presence of mullite or an intermediate phase that has not been identified. The brown-black portion appears to be primarily quartz with hematite and some sillimanite/mullite. It is important to note that the sample from Mohenjo-daro has no trace of cordierite or corundum which are often associated with mullite and are common in rocks called porcellanite [27, I. Freestone, personal comunication].

The electron microprobe x-ray analysis of the yellow brown and the brown-black components revealed a matrix of quartz with concentrations of iron/titanium oxide phase. The concentrations of hematite and iron-titanium oxides endow the rock with cutting and polishing properties, while the matrix of quartz (probably as quartzite) and sillimanite results in a strongly bonded structure capable of withstanding the stresses of drilling. The abrading surface of the drill retains a rough irregular surface (Figure 9) that helps in cutting the carnelian, which is not as strongly bonded. Abrasion is probably attained because of the inherent tenacity or toughness of the sillimanite matrix and through the concentration of iron-titanium oxides in the rough surface of the drill bit as these minerals gradually erode from the drill itself.

Although we have been able to identify the major components of this sample, it has not been possible to come to a final conclusion regarding its classification. We propose "Ernestite" (after Ernest J. H. Mackay) as a temporary name for this material until further petrographic studies can complete the characterization. We can say that it is a fine-grained metamorphic rock composed primarily of quartz, sillimanite, mullite, hematite and titanium-oxide phases. The samples of "Ernestite" from Mohenjo-daro, Chanhu-daro and Harappa that we have been able to examine are clearly tougher than normal sillimanite and and were used quite effectively for drilling carnelian, agate, jasper and other ornamental rocks.

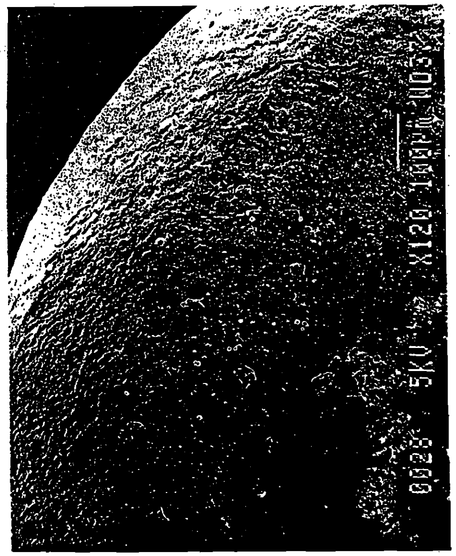


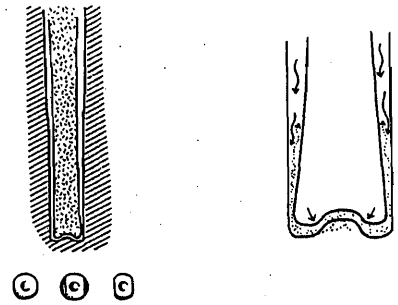
Figure 9. Detail of drill tip at 120X showing rough surface after use. Archaeological sample from Mohenjo-daro.

Drill Morphology

The distinctive morphology of the constricted cylindrical drills can be divided into three components for discussion purposes: 1) the distal tip, 2) the constricted medial portion and 3) the proximal tang portion.

1. The distal tip of this drill is wider than the medial shaft and ensures that the entire cutting pressure is focused on the area of the rotating circular tip. The tip begins as a flattened oval that is gradually rounded into a circular ring with a concave dimple depression in the center (Figure 10a). At this point the cutting pressure becomes even more concentrated, being primarily the circular ring shaped cutting edge. Due to the fact that a circular ring does not have a leading edge, the edges of the circular tip of the drill were repeatedly ground flat on two faces, essentially creating two facets. These facets result in two leading edges that increase the cutting ability of the drill tip, exposing new areas of abrasive raw material of which the drill itself is composed.

After each phase of resharpening or faceting, the drill tip becomes smaller and requires additional thinning of the medial portion. This results in progressively thinner and short drills that must eventually be discarded or used for drilling smaller sizes of beads.



a. b.

Figure 10. Detail of Constricted Cylindrical Drill Tip. a. round and faceted drill tip with concave depression. b. schematic section of drilling to show movement of abraded particles and water flow.

Once formed, the concave dimple depression appears to have been an important component of the drilling dynamics. The concave dimple of the drill tip leaves a convex projecting "nipple" at the center of the drill hole. The lateral movement of the drill itself results in pressure on the nipple such that it becomes chipped and broken quite rapidly whenever it begins to form.

The tiny chips of broken nipple become ground into a slurry beneath the spinning drill tip or are sucked out through the plunger motion of the drill bit at it is moved up and down in the drill hole (Figure 10b).

2. The drilling mechanism of the tip is closely associated with the constricted medial portion. The space between the drill and the drill-hole wall was increased by making the drill itself narrower in the medial portion behind the tip. This feature reduced the amount of friction between the drill and the bead and it allowed minimal lateral movement without snapping of the drill bit or the bead. Furthermore, it provided space for the exit of the drilling slurry and entrance for cooling water through a vertical plunging motion of the drill bit in the perforation. Most of the long carnelian beads broken in manufacture are snapped at the middle, where heat from drilling friction would have been difficult to control and where the maximum effect of lateral movement was present.

3. The constricted cylindrical drills involved considerable labour for the preparation of a regular and symmetrical tang. This tang was probably wrapped with a cord and hafted by pressure into a specially designed drill shaft. No traces of adhesive had been found on the

specimens observed so far, either macroscopically or with SEM. In contrast, adhesive residues are relatively common on other types of stone drills, both in the greater Indus Valley and Eastern Iran. The careful shaping of symmetric tangs optimized the centering of the drill bits into the wooden shaft, and this could reduce the danger of breaking expensive beads because of lateral movements and eccentric pressure.

After the drill bits were broken or worn down, the tangs were often reused as pivots on the back of the drill shaft. This form of industrial recycling has been reported from the Moneer site at Mohenjo-daro, on the basis of macroscopic and SEM observations of distinctive wear traces on the back of the tang [9]. This evidence is an additional indicator of the high levels of efficiency which characterize the making and use of the constricted cylindrical drills.

Constricted Cylindrical Drill Manufacture

The recovery of constricted cylindrical drill making debitage at Mohenjo-daro, Harappa and Chanhu-daro allows a preliminary reconstruction of their manufacturing sequence. The manufacture begins with the cleavage of a large lump into small angular blocklets (Figure 3a). These blocklets were then scored with longitudinal grooves, apparently made with chert blades. Our experimental studies show that chert blades can incise a shallow groove in the blocklets. With the assistance of these guiding grooves which encircled the blocklet, a small square sectioned drill rough-out was detached. In the Third millennium B.C., grooving and splitting was a common technique for cutting relatively soft stones such as limestone, lapis lazuli or steatite, but craftsmen of the Indus Valley were able to apply it to a much harder and heterogeneous material. The drill rough-outs are thicker at one extremity, which was to become the proximal end or tang of the drill bit (Figure 3b).

The square sectioned drill rough-out was further reduced to a slender square column (Figure 3b), using primarily pressure flaking, although inverse indirect percussion appears to have been used in some instances. The micro-debitage from this operation (in the form of tiny, scale-like flakes) has been found in the lapidary activity area of the Moneer site in Mohenjo-daro, together with finished and unfinished constricted cylindrical drills [9].

In the subsequent stage of manufacture, the slender, square column was ground longitudinally and at an oblique angle to form a faceted polyhedron (Figure 3c and Figure 12) [28]. In the final stages of grinding, only the distal portion was modified and this was done by grinding the polyhedron into first a cylindrical shape and then a constricted cylinder (Figure 3d). The constriction resulted in the distal point of the drill bit being greater in diameter or width, than the medial portion of the drill bit.

Grinding stones used to shape the drill bits were made from very hard and fine grained sandstones or quartzite. These grinding stones are found in different shapes, ranging from small tabular pieces to irregular columnar shapes. Their use for shaping drills can be defined on the basis of association (as at Chanhu-daro) and by the nature of the grinding facets and striae.

Prior to actual drilling, the distal tip of the drill was ground flat and the edges of the tip were faceted, resulting in a oval shaped distal end (Figure 10a). Through repeated drilling the flattened oval form of the distal end becomes rounded and develops a concave dimple in the center (see above for discussion). In order to resharpen the drill bit, the edges were repeatedly faceted to provide additional cutting potential.

Drill Sizes and Use

In order to drill carnelian beads that were between 70 and 100 mm long, the ancient artisans appear to have used several sizes of drills. Most of the long carnelian beads made during the Harappan Phase of the Indus Valley Tradition reveal that three or four different sizes of drills were used to perforate one half of the bead (Figure 11). The bead was then turned over and the opposite side was perforated. In most cases the bipolar perforations meet precisely in the center of the bead. The use of drills of different sizes is often clearly visible in drill sections of translucent beads as well as in the silicone impressions of their perforations.

Figure 11. Detail of silicone impression of carnelian bead drill hole showing the use of different drill sizes. Archaeological bead from Chanhu-daro (Museum of Fine Arts, Boston).

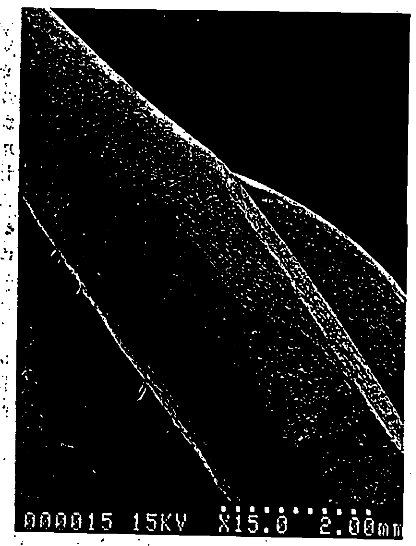


Figure 12. Drill tang portion showing faceted polyhedral section. Archaeological drill from Mohenjo-daro.

On the basis of experimental reconstructions and ethnographic observations of traditional bead drilling, the drilling was most probably accomplished with a bow drill cooled with dripping water or by keeping the bead and drill totally immersed in water [17, 18]. In the drilling process, the drill would have been held very rigid to avoid excessive lateral movement as this would snap the delicate drill bit. On the other hand there would have been repeated vertical movement, moving the drill bit up and down inside the perforation like a plunger. This movement would remove particles of chalcedony chips and powder and introduce cool water that was essential in order to avoid thermal fracture of the carnelian and the drill point (Figure 10b).

Experimental drilling using different drills made from the same blocklet of "Ernestite" (collected from Chanhu-daro) resulted in slightly different rates of abrasion (Table 2). All of the drilling was conducted on similar qualities of heat treated carnelian and the drilling itself was done by Kenoyer to maintain a standard level of technical expertise. Initial experiments in 1991 resulted in a drilling rate of 1 mm in 15 to 20 minutes. Experiments in 1992, using several different drills and bead blanks made from similar colors of carnelian. averaged 2.37 mm per hour. These results can be compared with the green jasper-like rock (discussed above) which has a drilling rate of approximately 0.83 mm per hour.

These preliminary results show that the drills made from "Ernestite" are more than twice as efficient as those made from the green rock. Experimental drilling with copper drills using ground silicon carbide (220 mesh) and ground corundum (ruby) had rates of drilling at 2.62 mm per hour and 1.26 mm per hour respectively.

It appears that "Ernestite" drills are much more efficient than copper with corundum when using a bow drill and manually applied abrasive. This may explain why the use of abrasives in drilling carnelian, agate or jasper beads has not been documented from any Indus Valley site.

A drill made with the double diamond mounting [17] had a rate of 81.16 mm per hour when used by Kenoyer (Table 1). In stark contrast, the professional bead drillers in Khambhat have an average rate of 536.45 mm per hour (n=102). When drilling beads from 73 to 82 mm the rate drops to 500 mm per hour (n=5) and for beads between 90 and 100 mm the rate is even lower, at 388 mm per hour (n=7). There is no doubt that the ancient Harappan bead drillers would have drilled much faster than in our experimental reconstruction, but given the reduced cutting ability of the "Ernestite" drills, it is unlikely that they would have been six times faster as is the case with the average for diamond drilling.

Table 1. Experimental Drilling Rates

Drill Type	mm per hour
"Ernestite" (constricted cylindrical drill) Average Drilling Rate (n=5 drilling experiments)	2.37
Green Jasper (tapered cylindrical drill) Drilling Rate	0.83
Copper drill with corundum	1.26
Copper drill with commercial silcon carbide	2.62
Double diamond drill (drilled by Kenoyer, n = 1)	81.16

Conclusions

On a superficial level, the tapered cylindrical drills of the protohistoric period in West and South Asia are easily confused with the constricted cylindrical drills of the Harappan phase of the Indus Tradition. The visual differences between these two types of drills may seem very insignificant, but in fact they involve two very different types of drilling mechanics and represent two contrasting technological concepts. In the tapered specimens, the general cylindrical shape of the bit is a by-product of the friction between the drill and the perforation; in the constricted drills, the general cylindrical shape is due to an intentional choice involving the delicate shaping of the bit and having substantial functional implications. The combination of the features of drill tip, medial portion and tang make constricted cylindrical drills the most complex and refined perforation tools of protohistoric West and South Asia (Figure 13).

Our studies on agate bead making suggest that, during the Third millennium B.C., the focus of the production of extremely long beads, particularly of carnelian resulted in the specialization in manufacture of long cylindrical bead drills. The demand for the long beads required by the elites of the cities of the Indus valley lead the artisans to discover and systematically exploit a new rock containing minerals particularly suitable for the drills. Specific manufacturing techniques were developed for making these drills and they were probably transmitted through a closely monitored apprenticeship. The need to control the drilling process more and more efficiently resulted in significant innovations involving the tang and the medial section of the drills.

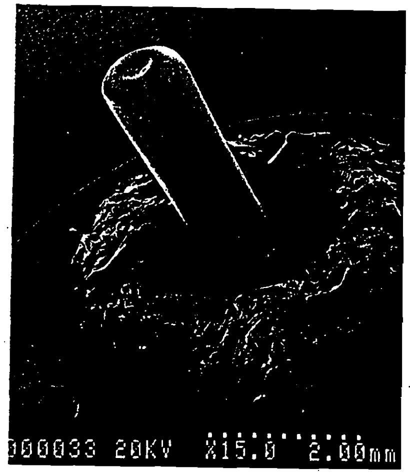


Figure 13. SEM of Constricted cylindrical drill, Mohenjo-daro. Side view showing the constricted medial portion of the drill.

Furthermore, the artisans learned to resharpen the rounded tips of the constricted drills to improve their cutting potential.

The distinctive constricted form of the stone drill shaft and the oval shaped tip with faceted edges may have provided a template for the later invention of double diamond drilling in the early historic period [17]. The double diamond drills still used in the agate workshops of Khambhat are constructed with a metal (iron) shaft that is constricted behind the drilling tip (Figure 14a). The tip itself is set with two tiny rounded diamond chips resulting in an oval shaped distal tip and a depression forms in the center of the tip during the drilling process (Figure 14b).

While it is not impossible that the similarities in shape are simply coincidental, our current research indicates that the constricted cylindrical stone drills and the double diamond drill technique are both unique to the Indian subcontinent. The invention of the double diamond drill technique is still not well documented but current research by the authors on carnelian beads from the site of Nagra (near Khambhat) has determined that it was present sometime prior to 600 B.C. in western India [29]. Although there has been considerable scope for technological diffusion, there is no evidence for the use of these techniques in the regions to the west, and even today, only single diamond drilling is practiced in Afghanistan.

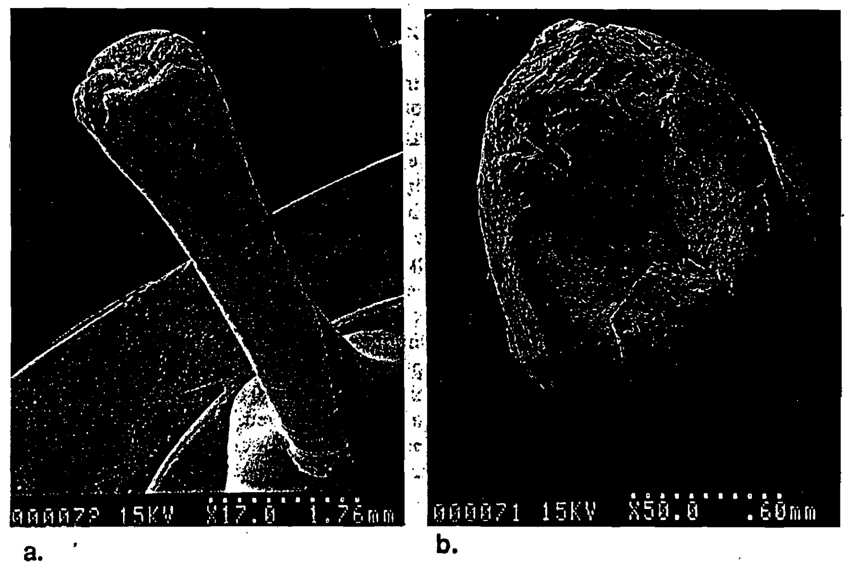


Figure 14. SEM of Double Diamond Drill from Khambhat a. side view at 15X showing the constricted medial portion of the drill; b. plan view at 50X showing the oval shape of the distal tip with a concave depression in the center.

The connection between constricted cylindrical stone drills and the constricted cylindrical double diamond drills raises the question of the cultural continuity or discontinuity between the Harappan phase of the Indus tradition and the early historic period in western South Asia. This question has been debated at length by several scholars, with little consensus. In this regard, the detailed study of protohistoric technologies and the evaluation of their social implications is a rewarding field of enquiry. For example, the reconstruction of the Harappan stoneware bangles manufacture [30, 31] shows that this peculiar technology developed out of a technological know-how widely spread in the Subcontinent from very ancient times , i.e. ceramic firing at high temperatures in reduced conditions within closed containers. However, at the end of the Harappan phase, the sophisticated stoneware technology disappeared along with the social context of production and use.

While the disappearance of the Harappan stoneware bangle technology would point towards discontinuity, the evolution of carnelian drilling techniques beginning with stone drills and then diamond tipped metal drills, suggests a specific process of cultural continuity. The continued use of carnelian, agate and jasper beads by the elites of the subcontinent provided the need for continuity in drilling technology. It is also possible that an increased demand and a larger market spurred the experimentation with different materials to find a more efficient cutting tool. Corundum is commonly available in northern Pakistan and western India, but diamonds are found primarily in the central peninsular subcontinent [32]. It is not unlikely that the expansion of the Early Historic states into peninsular India was stimulated by the promise of new resources and the need to produce elite commodities more efficiently. On the basis of Early Historic texts [33], agate and carnelian bead production were an important commodity for the state and therefore needed to be properly controlled.

The important connections between resource availability, socio-political needs and technology can be addressed and it is important not to loose sight of these issues when one becomes engulfed with the details of modern archaeometric techniques. We are only beginning to be able to articulate these complex processes thanks to the collection of extensive, well documented bodies of archaeological data and new archaeometric research methods. Through continued research and dialogue with we hope to develop more precise interpretations of these cultural and technological processes.

Acknowledgements

Our research on drilling technology and bead manufacture has been supported by grants from the Smithsonian Institution Foreign Currency Program and Short Term Fellowships at the Conservation Analytical Laboratory. J. M. Kenoyer has carried out much of his research on ancient technologies through a National Science Foundation Presidential Young Investigator Award and M. Vidale has received support through a NATO Fellowship. Additional support has been provided by our respective institutions.

Special thanks to Dr. S. Bailey and Dr. E. Glover, U.W. Madison, Department of Geology, for their assistance in the use of the X-Ray Diffraction and Electron Microprobe equipment. We would like to thank Nancy Lawrence, SEM Lab, Department of Entomology, U.W. Madison for her patience and expertise in taking the SEM photographs.

We would also like to thank the editors and reviewers whose comments were very constructive and helped to refine the presentation of this paper considerably.

References

1. J. F. Jarrige, in <u>Harappan Civilization</u>, edited by G. L. Possehl (Oxford and IBH Publishing Co., New Delhi, 1982), p. 79-84.
2. J. F. Jarrige and R. Meadow, Scientific American <u>243</u> (2), 122-133 (1980).
3. J. M. Kenoyer, in <u>Old Problems and New Perspectives in the Archaeology of South Asia</u>, edited by J. M. Kenoyer (Dept. of Anthropology, U.W.-Madison, Madison, WI, 1989), p. 183-192.
4. E. J. Mackay, Journal of the American Oriental Society <u>57</u> 1-15 (1937).
5. E. J. H. Mackay, <u>Further Excavations at Mohenjo-daro</u>, (Government of India, New Delhi, 1938).
6. E. J. H. Mackay, <u>Chanhu-Daro Excavations 1935-36</u>, (American Oriental Society, New Haven, CN, 1943).
7. M. Piperno, in <u>South Asian Archaeology 1971</u>, edited by N. Hammond (Duckworth, London, 1973), p. 119-130.
8. M. Piperno, East and West <u>23</u> (1-2), (1973).
9. M. Vidale, in <u>Interim Reports Vol. 2</u>, edited by M. Jansen and G. Urban (IsMEO-Aachen, Aachen, 1987), p. 113-150.
10. M. Tosi and M. Piperno, Expedition <u>16</u> (1), 15-23 (1973).
11. S. Salvatori and M. Vidale, Rivista di Archeologia <u>6</u> 5-10 (1982).
12. L. Gorelick and A. J. Gwinnett, Expedition <u>23</u> (4), 17-30 (1981).
13. L. Gorelick and A. J. Gwinnett, Archeomaterials <u>3</u> 39-46 (1989).
14. L. Gorelick and A. J. Gwinnett, Expedition <u>25</u> (3), 40-47 (1983).
15. A. J. Gwinnett and L. Gorelick, Expedition <u>22</u> (1), 17-32 (1979).
16. A. J. Gwinnett and L. Gorelick, Expedition <u>24</u> (1), 10-23 (1981).
17. J. M. Kenoyer, M. Vidale and K. K. Bhan, World Archaeology <u>23</u> (1), 44-63 (1991).
18. J. M. Kenoyer, Ornament <u>10</u> (1), 18-23 (1986).
19. E. J. H. Mackay, in <u>Anthropology Memorial</u> (Field Museum of Natural History, New York, 1929).
20. G. M. Bulgarelli, in <u>South Asian Archaeology 1977</u>, edited by M. Taddei (Istituto Universitario Orientale, Naples, 1979), p. 39-54.
21. M. Tosi, in <u>Tappeh Hesar: Reports of the Restudy Project, 1976</u>, edited by R. H. Dyson and S. M. Howard (Casa Editrice Le Lettre, Firenze, 1989), p. 13-24.
22. J. F. Jarrige, in <u>South Asian Archaeology 1979</u>, edited by H. Härtel (Dietrich Reimer, Berlin, 1981), p. 93-114.
23. L. Flam, in <u>Harappan Civilization (2nd Edition)</u>, edited by G. L. Possehl (Oxford and IBH, New Delhi, 1992 in press)
24. F. A. Durrani, Ancient Pakistan <u>6</u> 1-232 (1988).
25. K. T. M. Hegde, V. H. Sonawane, D. R. Shah, K. K. Bhan, Ajitprasad, K. Krishnan and S. P. Chardnan, Man and Environment <u>12</u> 55-65 (1988).

26. W. L. d. Keyser, Transactions of the British Ceramic Society 50 349-365 (1951).
27. S. O. Agrell and J. M. Langley, Proceedings of the Royal Irish Academy 59 (B-7), 95-110 (1958).
28. M. Vidale, East and West 40 (1-4), 301-314 (1990).
29. J. M. Kenoyer, K. K. Bhan and M. Vidale, Agate Beadmaking: An Ethnoarchaeological Study. (In Preparation, 1993).
30. M. A. Halim and M. Vidale, in Interim Reports Vol. 1, edited by M. Jansen and G. Urban (RWTH-IsMEO, Aachen, 1984), p. 63-97.
31. M. Vidale, in Old Problems and New Perspectives in the Archaeology of South Asia, edited by J. M. Kenoyer (Wisconsin Archaeological Reports, Madison, WI, 1989), p. 171-182.
32. O. H. K. Spate, India and Pakistan: A General and Regional Geography. (Methuen and Co. Ltd., New London, 1963 reprinted).
33. K. Prasad, Cities, Crafts and Commerce under the Kusanas. (Agam Kala Prakashan, Delhi, 1984).