# Experimental Studies of Harappan Steatite Carving and Firing Techniques

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During the Integration Era of the Harappa Phase (2600-1900 BC), Harappan craftspeople fashioned an impressive array of material goods from a variety of raw materials. Among the most common and important of these raw materials is steatite, a soft and easily workable stone comprised primarily of the mineral talc. Harappans utilised steatite to such an extent that it is ubiquitous at affiliated archaeological sites. Because of the importance of this material in the ancient Harappan world, the following research has focused on two aspects of Harappan steatite production: firing to harden the soft stone and carving techniques used to inscribe script and motifs. Samples of replica incised steatite seals or tablets were created using a set of tools similar to those that might have been used during the Harappan period. These samples were then subjected to firing experiments in order to observe the changes in color and hardness associated with different heating temperatures. Impressions of inscribed characters were then made and analyzed using Scanning Electron Microscopy (SEM) to examine the cut surfaces created using different tools. These experimental data were then compared with impressions of archaeological seals recovered from the site of Harappa by the Harappa Archaeological Research Project (HARP) in an attempt to identify aspects of carving and tool marks that will allow more precise reconstructions of actual tools used by Harappan craftsmen.

This research represents an introductory study focusing on technological aspects of steatite seal production in order to understand the nature and organization of this important industry. Preliminary results suggest that certain types of steatite will whiten and harden in as little as one minute when fired at temperatures of 1100° Celsius. These results indicate that the transformation of color and hardness in fired steatite could have taken place in a very short time when heated at high temperatures. The results of the SEM analysis highlight the utility of this technique for examining the cut surfaces created by different tools when carving seals. Comparisons with archaeological samples suggest that some Harappan seals may have been carved with copper tools, supporting the conclusions drawn in earlier research (Kenoyer 2003, 2005). Future research with additional samples using dynamic firing techniques will provide further insights into these important aspects of Harappan seal production. Such studies will advance our current understanding of ancient Harappan technology and craft production.

**Background**

The Indus Valley or Harappan Civilisation represents one of the world's earliest urban cultures. Today the remains of it are dispersed over one million square kilometers of diverse geographical regions in modern Pakistan and northwestern India (Fig. 1). The Harappan Civilisation was supported by the Indus River system, as well as another large river system known as the Ghaggar-Hakra or Sarasvati, which has dried up since the end of the Harappa Phase (Kenoyer 1998). Outside these river systems the geographic regions integrated within the Indus cultural area are diverse. These disparate regions played varied and important roles in the Harappan Civilisation; they were exploited for valuable resources that were not available in the fertile alluvial plains of the river systems, including steatite and other raw material sources. Archaeological research over the last century has significantly improved our understanding of this ancient cultural system.

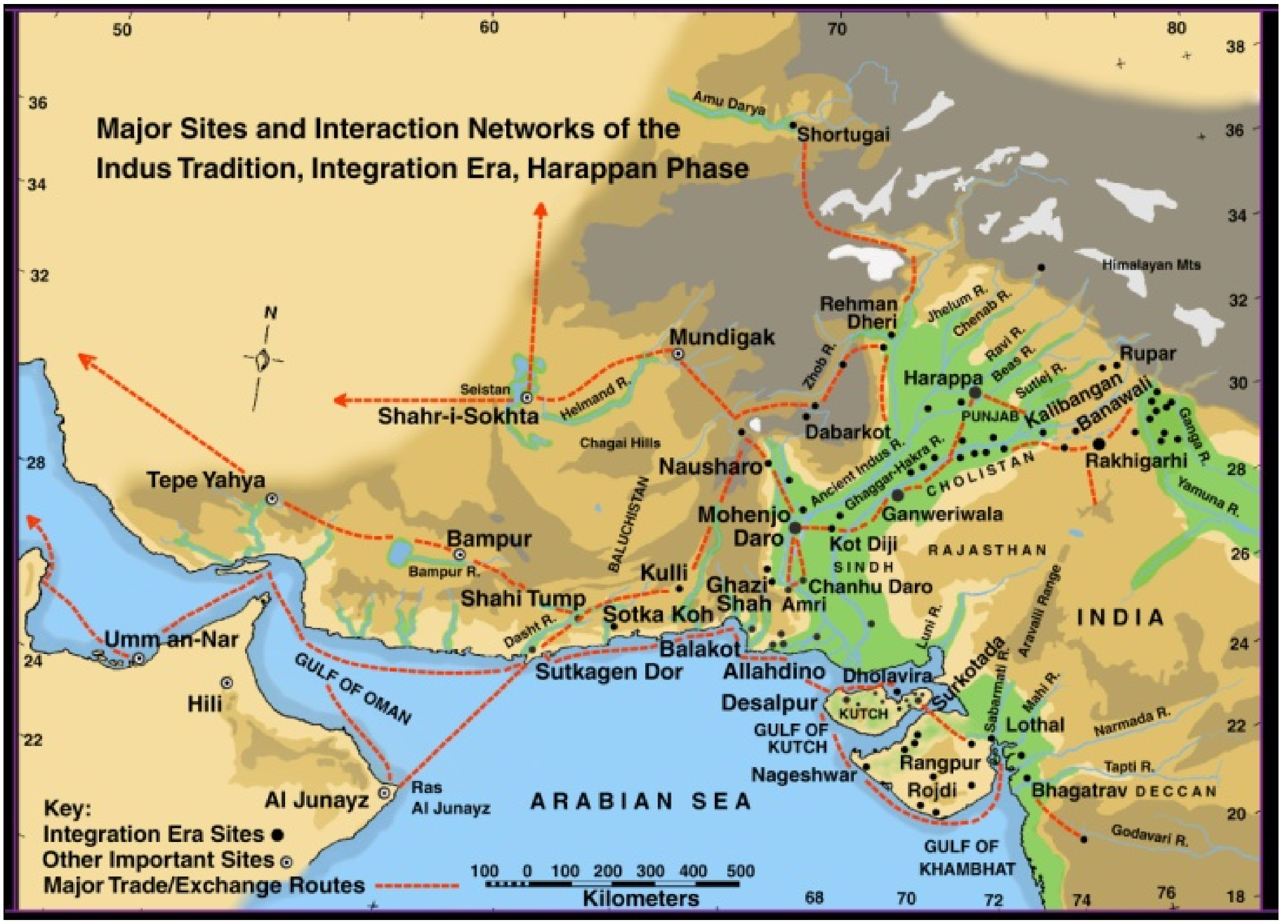


**Figure 1. Map of Integration Era Indus Sites (Courtesy Dr. J. M. Kenoyer).**

Over the last 20 years a considerable amount of scholarly energy has been devoted to developing and refining models that characterize the culture history of the Indus Valley. Today this chronological framework encompasses the history of human occupation in the subcontinent and consists of numerous Traditions, Eras, and Phases. For the purposes of this research the most important framework is known as the Indus Valley Tradition (Kenoyer 1991, 1998, 2008; Shaffer 1992). It is composed of five major Eras and associated Phases, spanning a period of approximately 9000 years (Table 1). The Indus Tradition represents not only the major period of urban floresence associated with the Indus Civilisation, but also its antecedents and the period of decentralization after its collapse. While the sophisticated urbanism that characterizes the Indus Civilisation reached its apex during the Integration Era of the Harappa Phase (2600-1900 BC), the processes responsible for these developments have their antecedents during the earlier Early Food-Producing and

Regionalization Eras. In addition to large, well-planned urban centers, the Integration Era is also characterized by material homogeneity throughout the entire Indus Cultural area, although recent studies indicate that regional variation can be observed in terms of settlement planning and artifact styles (Kenoyer 2008). The vast majority of the published corpus of Harappan seals with known stratigraphic contexts has been dated to the Integration Era. In this context it is the most important chronological period for this research.

**Table 1. Chronology of the Indus Tradition (after Kenoyer 2008).**

| Era | Phases | Time Period |
|---|---|---|
| Foraging Era | Mesolithic & Microlithic | 10,000-2000 BCE |
| Early Food Producing Era | Mehrgarh | 7000-5500 BCE |
| Regionalization Era | Early Harappan Phases:<br>Ravi, Hakra, Balakot, Amri,<br>Sheri Khan Tarakai,<br>Kot Diji, Sothi | 5500-2600 BCE |
| Integration Era | Harappan Phase:<br>Harappa Site Period 3A<br>Harappa Site Period 3B<br>Harappa Site Period 3C | 2600-1900 BCE<br>2600-2450 BCE<br>2450-2200 BCE<br>2200-1900 BCE |
| Localization Era | Late Harappan Phases:<br>Punjab, Jhukar, Rangpur | 1900-1300 BCE |

### *Craft Production and Steatite Seals*

Previous investigations of Indus craft production have emphasized the close relationship between craft production and power structures (Kenoyer 1989, 1992, 1995, 2000; Miller 2007; Vidale 2000; Vidale and Miller 2001). These studies indicate that elites living within the Indus cities were engaged in competition with each other, and that this competition was in part governed by strategies for controlling access to specific raw materials and the production of crafts using them. The ability to acquire desired raw materials through trade and exchange networks and the control of production using highly variable and often complex technologies were central aspects of such strategies (Kenoyer 1989, 1992, 1998, 2000). Crafts were controlled by elites through a variety of mechanisms, and the nature and scale of this control varied considerably (Kenoyer 1989). Detailed studies of individual craft traditions including ceramic production (Halim and Vidale 1984; Mery 1994; Wright 1989), bead manufacturing (Kenoyer et al. 1991), and shell working (Kenoyer 1984) to name but a few have proven to be useful methods for investigating aspects of Harappan social, economic, political, and ideological systems.

Studies of Harappan crafts have also resulted in new theoretical and interpretive frameworks for understanding the relationship between production and sociopolitical organization. Kenoyer (1992, 2000) and others (Vidale 2000; Vidale and Miller 2001) have developed a hierarchical scheme for investigating the potential for specific crafts to be used in economic competition by elites (Table 2). This system is based on access to raw materials, technological processes involved in production, and the ability to control both. Recent studies indicate that inscribed steatite seals would have been among the crafts at the top of this hierarchy, with production likely being controlled by elites (Kenoyer 2000). This control would have allowed elites to restrict access to the knowledge required to make seals as well as the ability to acquire and use the seals themselves. Unequal access to raw materials, technological processes, and finished goods are some of the fundamental mechanisms in creating and maintaining social inequality. The manipulation of steatite to produce crafts required the application of complex technologies and a sophisticated understanding of the raw material itself.

**Table 2. Hierarchy of Indus Crafts (after Kenoyer 2000).**

| Craft Group | Raw Material Type | Technology | Material Examples |
|---|---|---|---|
| 1 | Locally Available | Simple | Pottery, Basketry |
| 2 | Imported | Simple | Chipped Stone Tools |
| 3 | Locally Available | Complex | Stoneware Bangles |
| 4 | Imported | Complex | Seals, Metalworking |

Steatite is a soft and easily workable stone comprised primarily of the mineral talc (Deer et al. 1992). In its massive form talc is classified as soapstone, and steatite is also commonly known by this name. Steatite belongs to the Silicate family of rocks, and its crystalline structure is variable, influenced by mineral inclusions (Deer et al. 1992). It has a Specific Gravity of between 2.6-2.8 and usually ranges between 1-3 on Moh's Scale, again depending upon mineral inclusions. These inclusions often include calcite, chromite, dolomite, magnecite, quartz, and serpentine to name but a few. Steatite is derived from dolomitic and metamorphic parent formations, and is found in many places throughout the world, including the South Asian subcontinent. It is infusible but will harden and change chemically as intercrystalline water evaporates through heat treatment (Deer et al. 1992). Ongoing studies by Dr. Randall Law indicate that the Harappans were utilizing steatite from a variety of sources throughout the subcontinent to produce important craft items (Law 2005, 2008).

Steatite crafts are ubiquitous at Harappan sites, leading an early researcher to describe it as 'A Steatite Civilization' (Beck 1940; as cited in Vidale 2000). Ancient Harappan craftspeople used this material not only to make seals, but also other important objects like beads. The acquisition of steatite would have relied on long distance exchange networks, as local sources are not available in the alluvial plains where most sites are located. The transformation of raw steatite into finished goods required the use of multiple technological processes, some of them very complex. Archaeological excavations at Mehrgarh, the most important site of the Early Food Producing Era, indicate that craftspeople were creating beads using this material from as early as 7000 BC (Jarrige 1979, 1991; de Saizieu and Bouquillon 1997; Vidale 2000). Through a combination of surface survey at Mohenjo-daro and detailed experimental studies, researchers have been able to reconstruct the complex technological processes involved in steatite bead production (Vidale 1984, 1986, 1987, 1989). Some of these same technologies would have been used to create seals and tablets (Kenoyer 2005a), and considering that the production of steatite beads predates seals by several thousand years, it is likely that the history of seal production in the Indus Tradition combines both continuities and innovations in technological processes.

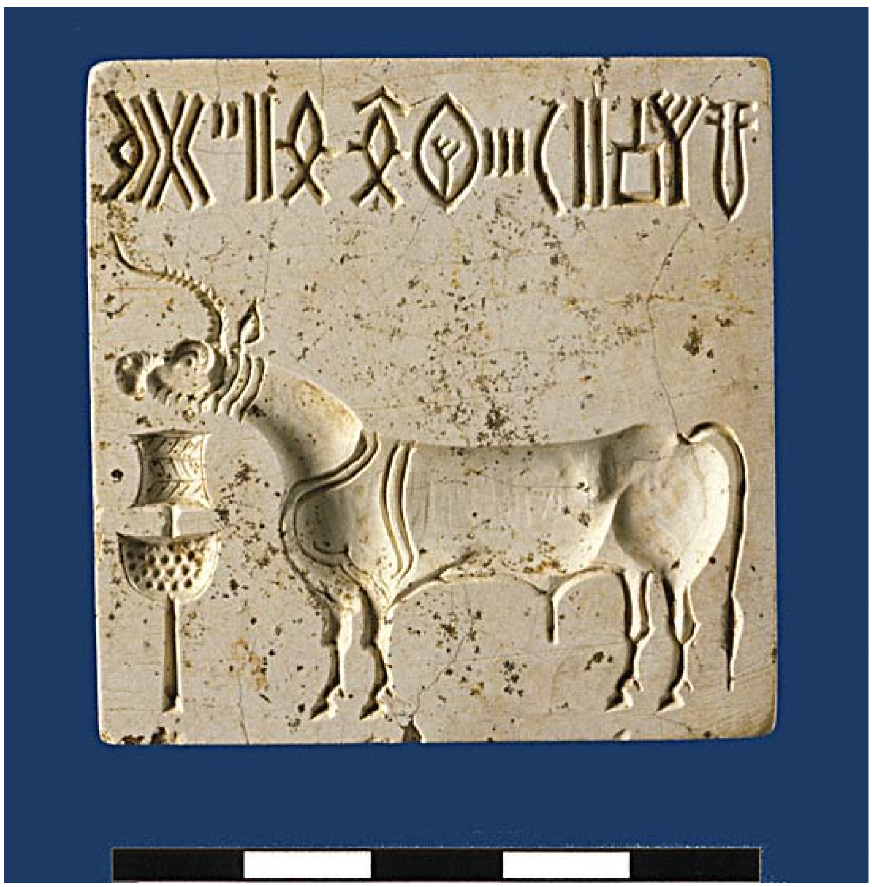

**Figure 2. Harappan Stamp Seal with Unicorn Motif (courtesy of Harappa.com).**

Inscribed steatite seals are among the most important and enigmatic components of Harappan material culture preserved today. Seals have served important purposes in a variety of cultural contexts throughout history and continue to be used in many societies today. Harappan seals represent the most well-known form of inscribed objects from the

Indus Civilisation (Rissman 1989). While there is a considerable amount of variation in the types and sizes of inscribed seals from the Indus, the most common are often referred to as stamp seals (Mackay 1931; Possehl 1996). They are called stamp seals because of the interpretation that they were used to stamp wet clay, and this has been supported by archaeological evidence of seal impressions and sealings preserved in ceramics and terracotta. Within the category of Harappan stamp seals there are two principal types, square seals that usually depict a line or two of script with an accompanying animal motif (Fig. 2) and rectangular seals or tablets that often depict only script (Rissman 1989). Generally stamp seals are carved intaglio so that when impressions are created they are viewed in relief.

In addition to the stamp seals described above, there are also examples of molded and raised script seals and tablets known primarily from Harappa and Mohenjo-daro. Inscriptions have also been documented on tools, ceramics, personal ornaments, and architectural features such as ringstones (Kenoyer 2005b). The uses and function of the Indus script would have been diverse and included the recording of various economic transactions, administrative activities, important rituals, and personal identification and ownership (Kenoyer 1998, 2005b; Meadow and Kenoyer 2001). Recent investigations at the site of Harappa have uncovered changes in the styles of seals at this site over time, evidenced through controlled stratigraphic excavations (Kenoyer 2005b). These discoveries indicate that the uses of seals and writing at Harappan sites were not static and unchanging over a period of 700 years. Moreover, discoveries from the Early Harappan or Kot Dijian Phase (2800-2600 BC) levels at Harappa have also uncovered evidence of an early writing system and the production of seals during this period, indicating that the technologies of both seal production and writing have antecedents before the Integration Era (Kenoyer 2005b). In fact seals have a long and important history of research in Harappan studies.

***Previous Investigations***

The study of Harappan seals is almost as old as our knowledge of the Indus Valley Civilisation itself. In fact the discovery of inscribed steatite seals at the sites of Harappa and Mohenjo-daro resulted in the announcement that a new civilization had been discovered. E.

J. H. Mackay conducted the earliest and one of the most important studies of Harappan seal production. His chapter in Marshall's (1931) Mohenjo-daro site volume was concerned with documenting the seals themselves, rather than the inscriptions engraved on them. Specifically, Mackay was interested in the 'technical aspects' of the seals, 'leaving to others the interpretations of the signs engraved upon them' (Mackay 1931: 370). He was aware of the importance of the seals and studied them not as written records but as artifacts, products of technological processes that at the time were poorly understood. In this respect he was a pioneer in the study of Indus seals and his work remains relevant today.

Mackay categorized the seals from Mohenjo-daro, identifying ten different types (Mackay 1931). Each type was classified based on shape as well as other features such as the presence or absence of a boss. By identifying saw marks on unfinished seals he correctly concluded that the first step in seal production would have been to saw the stone into the desired shape. He also hypothesized that the boss would have been prepared during the early stages of production, and that a knife and drill would have been required for this stage of manufacture. This description implies that seal production would have been complex, requiring the use of multiple tools. Another important interpretation was that the seals were engraved with a burin, often expertly wielded by the carvers (Mackay 1931). Mackay argued that unlike their counterparts from ancient Elam and Sumer, Harappan craftspeople did not use a drill to outline figures before engraving them when making their seals. Drills were used to add details, but carvers did not use them to outline shapes and forms prior to engraving them. Mackay further believed that the seals would have been fully prepared before being engraved with characters, although he noted that exceptions to this pattern do exist (Mackay 1931). He also reported that in some cases the cramping and crookedness of inscribed characters suggests that they were occasionally added later. Mackay also discussed surface treatments and concluded that they were applied, and that they were made from the same substance as the seals themselves (Mackay 1931). He believed that it may have been applied before firing, and that the purpose of such treatment would have been to conceal any imperfections in the steatite body. The seals would have then been baked in a kiln, in order to whiten the surface and increase the hardness of the soft stone (Mackay

1931). Another important observation was that the interior of the broken seal was often a different color than the exterior, leading him to the conclusion that this was an important reason for firing. These observations represent the earliest discussion of Harappan seal production, and Mackay followed upon this pioneering study in several additional publications (Mackay 1938; 1943). His influential studies paved the way for future researchers focusing on similar problems.

M. S. Vats published his monograph on excavations at Harappa in 1940. Like Mackay, Vats was also concerned with the descriptive characteristics of seals, in this case those recovered from Harappa. While Vats was not specifically interested in the production of these goods, he did discuss some important characteristics of the seals from Harappa. For example, he cited several examples of seals from Harappa that appear to have been engraved before they were finished, because the boss was not fully carved (Vats 1940). He also presented a typology of 39 different classes of seals and sealings from Harappa, made of steatite, terracotta, and faience. Of particular importance in his discussion of seals from Harappa are the miniature seals or amulets. Again Vats is not specifically concerned with production here, and he incorrectly believed that they were predecessors to the larger square stamp seals. Regardless, this is the earliest description of these important artifacts and he did identify the duplicate inscriptions present on some of these small seals (Vats 1940). The rest of his chapter on seals was dedicated to describing the animal motifs and tabulating all of the finds from Harappa. Following Vats and Mackay other researchers would pursue detailed investigations of seal production at other sites.

S. R. Rao, the principal excavator of Lothal, had a keen interest in the Harappan writing system and the seals recovered at the site. Rao discussed the nature of the seals at Lothal in a descriptive manner, much like his predecessors. He identified three different kinds of raw materials used to make seals, and seven different types recovered at Lothal (Rao 1985). He then went on to describe the process of producing the seals, following the work of Mackay. The seals would have been first sawed into blanks using copper tools such as saws and wires, depending on the raw material being used (Rao 1985). At Lothal the boss was fully prepared before the obverse of the seal was engraved, and bronze drills would have been used to bore the hole through the boss. Drilling was conducted bi-directionally and into the body of the steatite to reduce the chances of fracture and ensure that it could still be used after the boss did break (Rao 1985). The seals at Lothal were engraved with a variety of tools, again depending on the parent material. Some of these included chert, ivory and bone, shell, copper, and bronze (Rao 1985). Purportedly some of these were recovered at the site although direct associations with seal production are not evident.

Curiously, he refuted Mackay's earlier claim that the seals were engraved with a burin, arguing that this technique of lithic production was not practiced in the Indus Civilisation (Rao 1985). Through an examination of unfinished seals at the site Rao also offered further insights into the *chaine operatoire* of seal production at Lothal. Sometimes the script would have been carved first, and in other cases the animal motif would have preceded the inscriptions. In concluding he discussed the coating applied to the seals, echoing the previous research of Mackay (Rao 1985). His consideration of seal production at Lothal was important because it addressed local production and attempted to highlight differences in seal manufacturing at the site. Following this early work it would be left to the next generation of researchers to build upon these studies.

Recently Dr. J. M. Kenoyer, co-director of the Harappa Archaeological Research Project (HARP) has made further advances into our understanding of Harappan seal production. Since 1986 the HARP team has excavated and analyzed numerous objects from the Harappa, including a number of seals, incised, and molded tablets. The discovery of a faience workshop in Trench 54 on the western edge of Mound E in 2001 was of particular importance because it represents the first stratigraphically excavated feature of its kind. Horizontal and stratigraphic excavations indicate that the workshop area may have been located in a courtyard enclosed by four walls, suggesting that production may have been regulated, although ongoing explorations have revealed new data that may alter our understanding of the layout of this important facility (Kenoyer 2007, personal communication). These investigations indicate that both steatite and faience were being crafted in this area, and that the people working there made different types of objects (Kenoyer 2003, 2004, 2005a). Among the different types of objects produced here were incised steatite and molded faience tablets, and for the first time archaeologists have been able to reconstruct these processes.

The production of molded faience tablets was an extremely complex process. Faience production was highly sophisticated in the Indus Valley, and recent studies indicate that Harappan faience was stronger and technologically superior to that of ancient Egypt and Mesopotamia (Kenoyer 2003, 2005a). In order to make faience tablets artisans first sawed pieces of steatite into tiny blocks and then engraved characters of the Indus script into them. These pieces served as molds that were used to make the faience tablets, which were then fired in coarse-tempered ceramic canisters that could withstand high temperatures (Kenoyer 2003, 2005a). Based on Kenoyer's reconstruction, the tablets were placed inside the terra cotta containers, forming a miniature kiln, which was then placed in an open fire. To ensure that the faience didn't melt into the walls of these canisters, the interior was coated with a powder consisting of bone and ground steatite (Kenoyer 2003, 2005a).

Further studies of materials recovered from this workshop have yielded additional information regarding seal production at Harappa. SEM analyses have yielded evidence that at least some of these tablets were likely engraved with copper tools (Kenoyer 2003, 2005a, personal communication). Equally important was the discovery of 22 three-sided steatite tablets engraved with the same sets of inscriptions on all three faces. Although the tablets were inscribed with the same characters, they were clearly engraved by different hands and different sets of tools. More important is the fact that some of the styles of writing are distinctive, indicating idiosyncratic carving styles of individual craftsmen (Kenoyer 2003, 2005a, personal communication). The implications are that within this workshop there were probably at least three different people engraving these tablets, represented by three distinct carving styles. This, in concert with the discovery of other types of steatite and faience goods within the workshop, strongly indicates that multiple individuals were employed there and that they were producing more than one type of finished good (Kenoyer 2003, 2004, 2005a, personal communication).

These recent studies represent the most comprehensive analyses of Harappan seal production to date. The combination of stratigraphically controlled excavations and powerful analytical techniques such as SEM has yielded important information about where seals were being manufactured and the organization of production in specific workshops. Furthermore, detailed experimental studies focusing on replicating materials recovered in this workshop have allowed Kenoyer to reconstruct the *chaine operatoire* of seal production within a specified context at Harappa. This research attempts to build upon these studies through an examination of pyrotechnological aspects of seal making and production using different tools.

### Methods

The first step this study was to acquire the necessary raw materials and tools to fashion the replica seals. Dr. Randall Law graciously provided me with one steatite nodule that he procured during previous fieldwork in Pakistan. The nodule was derived from the Daradar valley, located in the Kurram Agency of the Northwestern Frontier Province, coded by Dr. Law as PD-7 (Fig. 3). Instrumental Neutron Activation Analysis (INAA) conducted by Dr. Law as part of his dissertation thesis has indicated that steatite from this source was used by the Harappans, as evidenced by its presence in the unfired steatite assemblage from the site of Harappa.

Tools for crafting the replica seals were acquired from Dr. J. M. Kenoyer or produced by the author. The tools used in this study included a small, modern steel-bladed hacksaw with blade measuring 0.8 cm in thickness, a modern steel-tipped Xacto knife, a cold hammered copper rod sharpened to create an engraving point, a chert flake retouched to create an engraving point fashioned by the author, a modern fired red clay brick used in place of a Harappan fired brick, a small whetstone, and a ¼" thick piece of plywood. The steel-tipped Xacto knife was chosen in lieu of a bronze tool because I was unable to forge or acquire one for this study, used in order to evaluate the effectiveness of a harder carving tool. Copper and chert tools were selected to approximate the uses of pure copper and chert engraving tools that may have been used by the Harappans. The brick, whetstone, and plywood were used as grinding and polishing tools. Based on discussions with Kenoyer, I chose to use three different grades of grinding and polishing materials. A modern fired brick was chosen to approximate a coarse, rough grinding surface, and a commercial waterstone grinding stone (4000 grit grade) was used for smoother, finer grinding. The plywood was used for final polishing of the samples, following earlier studies highlighting the use of wooden wheels for polishing stone beads in modern Khambhat, India (Kenoyer et al. 1991). After acquiring the raw materials and necessary tools the experiments were undertaken in the Laboratory for Experimental Archaeology, University of Wisconsin, Madison.

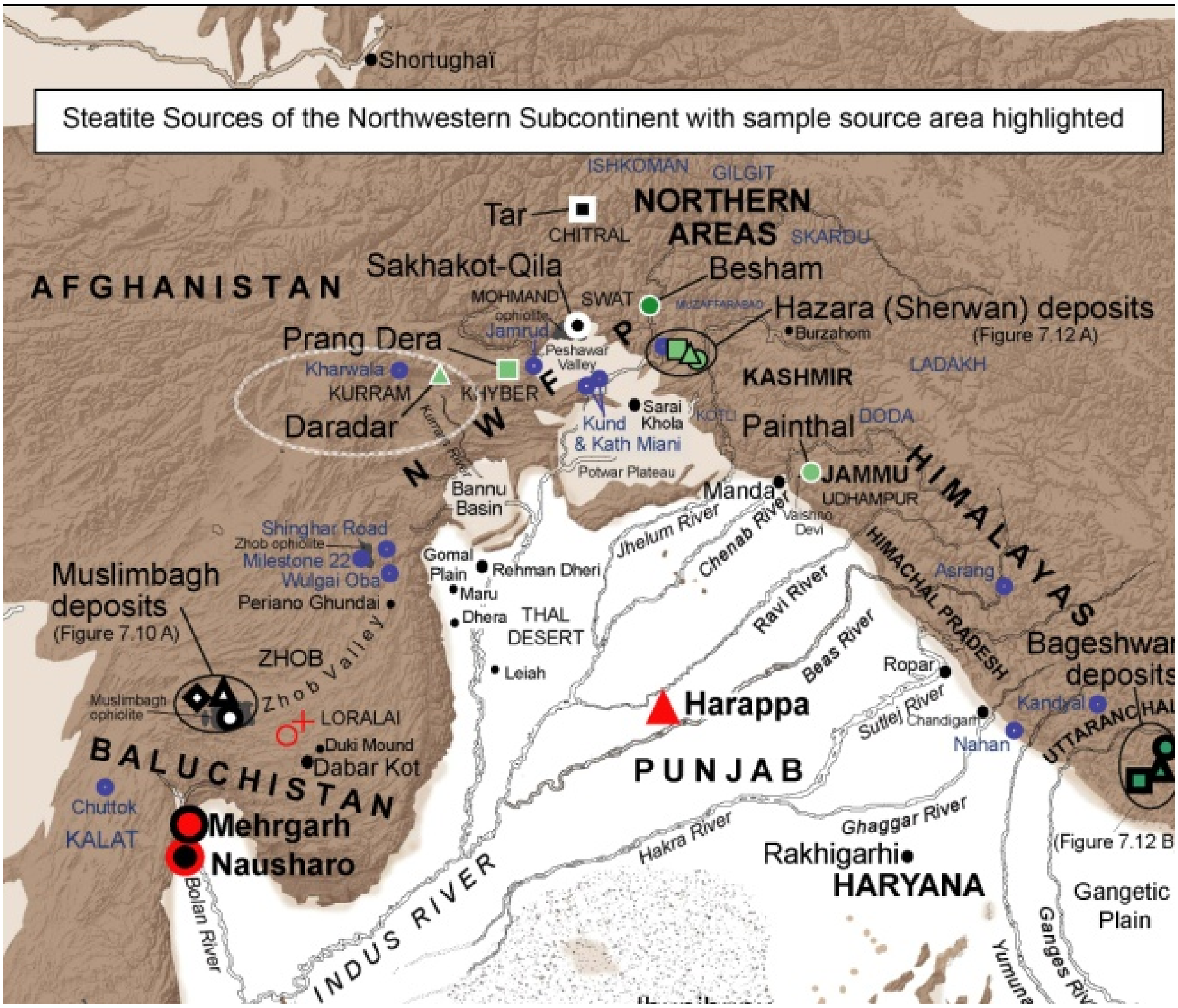


**Figure 3. Source Location for PD-7 Steatite Samples (after Law 2008).**

The first step in seal replication was to saw the nodule into blanks using the hacksaw. The nodule was cut from the top and bottom in order to detach a blank without cracking. Six blanks and four larger pieces of debitage were recovered and included in the firing experiments, which will be documented below. The sawn blanks were first ground on the flat surface of the fired brick to shape them into flat rectangular blanks. A second stage of grinding was done on the fine-grained whetstone to create a smooth surface suitable for incising. Finally, the samples were polished using the smooth surface of a ¼" thick piece of plywood. This process smoothed the samples and removed most of the traces of sawing from the surfaces of the rectangular blanks.

Next the replica seals were engraved with several common characters of the Indus script. Three different tools were used to engrave the inscriptions, in order to analyze the impressions created by them using Scanning Electron Microscopy (SEM). Three of the samples were engraved with a replica Harappan style copper engraving tool, two with the steel-tipped Xacto knife, and one with the small retouched chert flake engraver. After carving, the samples were polished again in preparation for firing and metric and descriptive data for each were recorded, including maximum length, width, thickness, weight, and color. Color designations were assigned using a Munsell Rock Color Chart. Simple scratch tests were then conducted in order to determine the hardness of the samples before firing.

Firing was conducted in a Lindberg Muffle Furnace in the Laboratory for Archaeological Chemistry, Department of Anthropology, University of Wisconsin, under the direction of Drs. T. D. Price and J. H. Burton. All six of the replica seals, as well as the four larger pieces of unmodified debitage, were fired at a temperature of 1100° Celsius. Static firing experiments were conducted in which the samples were placed in the furnace when the targeted temperature had been reached. The replica seals were fired at various times ranging from one minute to one hour in order to observe the changes in color and hardness caused by heating at different time intervals. After firing the samples were carefully weighed and measured again, and changes in color and hardness were documented using the Munsell chart and additional scratch tests (Fig. 4; Table 3).

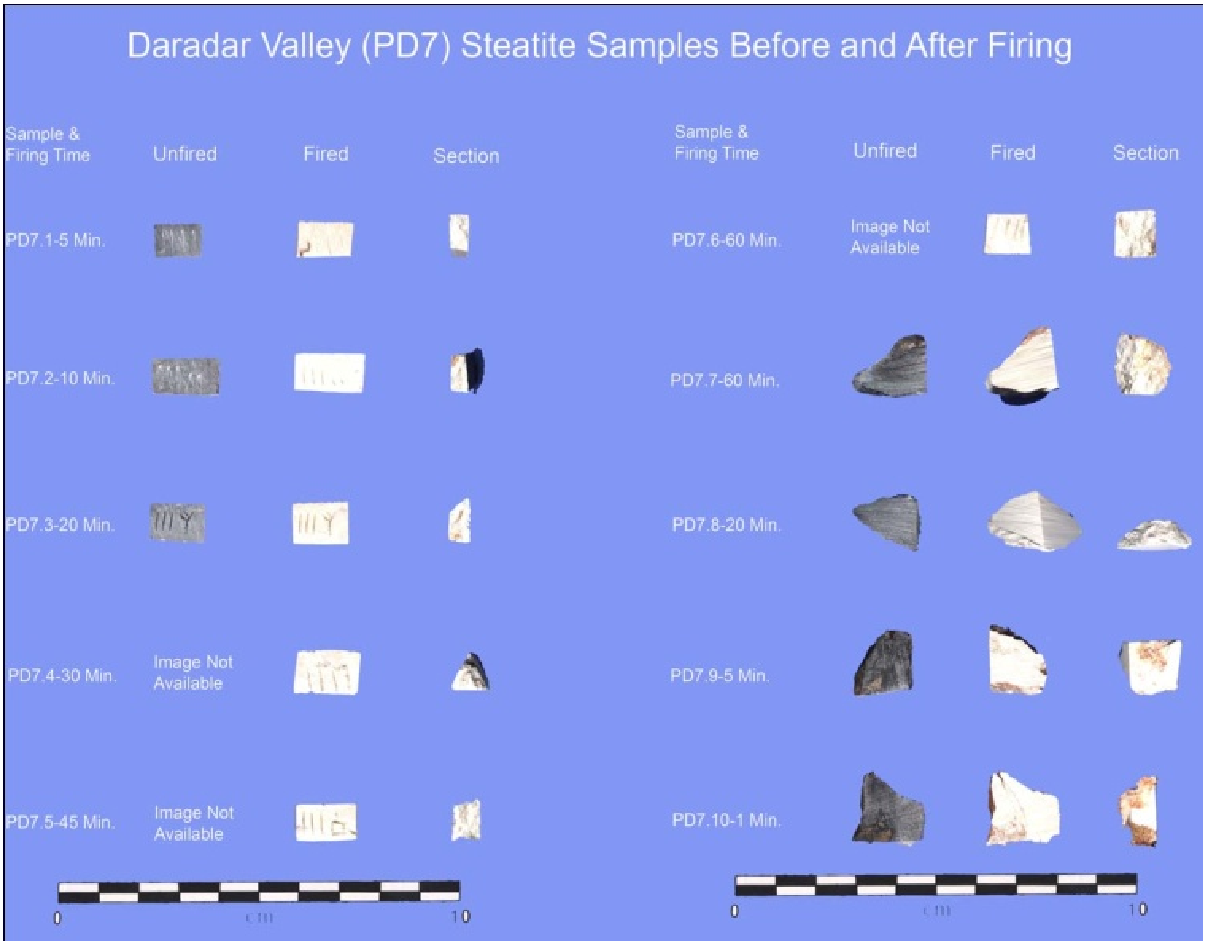


**Figure 4. PD-7 Steatite Samples Before and After Firing.**

Following this the samples were sawn again to expose interior sections of the steatite body in order to evaluate the depth of firing. Immediately it became clear that the samples had become much harder as a result of the firing process. It was extremely difficult to cut the fired steatite with a regular hardened steel hacksaw and several of the samples broke as a result of this process. Two samples were split open by hammering on a steel anvil in order to create the sections. The exposed sections were scanned and photographed and the firing depth was calculated using a digital calipers. During this process the inscriptions were not damaged to ensure that I could make impressions for analysis using SEM. The SEM analysis was conducted in the Department of Animal Sciences at the University of Wisconsin using an Hitachi S-570 machine, under the supervision of and with the assistance of Dr. J. M. Kenoyer. The SEM analysis concluded the experiments conducted in this research.

**Table 3. Descriptive Statistics for PD-7 Steatite Samples before and after Firing.**

| **Sample** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Firing Time (min.)** | 5 | 10 | 20 | 30 | 45 | 60 | 60 | 20 | 5 | 1 |
| **carving technique** | copper | copper | Xacto | chert | Xacto | copper | n/a | n/a | n/a | n/a |
| **Max. L (mm)** | 14.18 | 17.41 | 14.0 | 15.78 | 16.33 | 11.3 | 18.16 | 16.66 | 15.52 | 18.33 |
| **Max W (mm)** | 8.47 | 9.19 | 9.45 | 9.79 | 8.13 | 10.46 | 14.46 | 13.54 | 15.63 | 17.55 |
| **Max. thickness (mm)** | 4.81 | 4.78 | 5.26 | 8.54 | 6.62 | 8.48 | 15.2 | 16.71 | 13.48 | 12.25 |
| **Volume (pre-fire)** | 577.7 | 764.79 | 695.9 | 1319.31 | 878.89 | 1002.32 | 3991.42 | 3769.38 | 3269.95 | 3940.72 |
| **Volume (postfire)** | 577.02 | 762.79 | 695.66 | 1313.73 | 889.44 | 991.29 | 3950.08 | 3750.27 | 3227.32 | 3933.21 |
| **% change** | -.001 | -.002 | -.0003 | -.004 | -.012 | -.011 | -.01 | -.005 | -.013 | -.002 |
| **Weight g (pre-fire)** | 1.2929 | 1.6579 | 1.717 | 1.7831 | 2.1987 | 2.3753 | 5.5614 | 3.1479 | 4.6775 | 3.7382 |
| **Weight g (postfire)** | 1.2337 | 1.5677 | 1.6264 | 1.6904 | 2.0899 | 2.1872 | 5.1026 | 2.9948 | 3.594 | 3.3212 |
| **% change** | -.048 | -.054 | -.053 | -.052 | -.049 | -.08 | -.082 | -.049 | -.02316 | -.1234 |
| **Munsell (prefire)** | N6 | N6 | N6 | N6 | N6 | N6 | N6 | N6 | N6 | N6 |
| **Munsell (postfire)** | N9 | N9 | N9 | N9 | N9 | N9 w/trace 5YR8/4 | N9 | N9 | N9 w/ 5YR8/4 | N9 w/ 10R6/6 & 5YR8/4 |
| **Hardness (prefire)** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Hardness (postfire)** | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 |
| **Firing Depth (mm)** | 4.81 | 4.78 | 5.26 | 8.54 | 6.62 | 8.48 | 15.2 | 16.71 | 13.48 | 12.25 |

## Results

The results of this study will be discussed in two sections, the first describing the color changes associated with firing and the second concerning the SEM analysis. Before proceeding, however, it will be useful to briefly discuss the basic descriptive statistics of the sample (Table 3). First, it is clear that all of the samples underwent marked changes in volume and weight as a result of the firing process. The changes in total volume were minor and may be attributed to recording error, shrinking, or cracking as a result of firing. The latter may be the most plausible explanation, as cracks were visible in every sample after firing. Conversely, the weight of each sample did change significantly, in each case it was reduced as a result of the firing process. This is not surprising, rather it is expected and is related to the decomposition of talc into enstatite as a result of heating (Santos and Yada 1988). As talc decomposes into enstatite water evaporates, and this water loss likely accounts for the weight changes observed here. In 8 of 10 samples the weight loss is around 5% (mean 5.8%), while in the last 2 samples the weight loss is considerably greater, 23.16 and 12.34 % respectively. This higher weight loss is probably due to the presence of powdered mineral inclusions in the steatite that were observed in the bottom of the crucibles after firing. This powder was collected and weighed with the fired samples but it was not possible to recover all of it from the crucibles.

Another important result worth mentioning here is that all of the samples became considerably harder as a result of the firing process, regardless of firing time. This is significant because one of the major advantages of heating steatite is that it becomes much harder, and therefore more durable and tenacious. As stated above, talc, the primary mineral in steatite, will decompose into enstatite with the application of heat. While talc has a hardness of 1 on Moh’s scale, enstatite generally registers between 5 and 6 (Deer et al. 1992). The fact that all but one of the fired samples required a piece of chert to scratch them indicates that the hardening of this particular steatite through firing happens very quickly at temperatures of at least 1100° Celsius. This will be discussed in greater detail in the next section.

### *Color Change and Firing Depth*

One of the most important results of this study is associated with color change and firing depth. It is clear that specific types of steatite, in particular from the Daradar Valley, Kurram Agency, northern Pakistan, one that was purportedly utilized by the Harappans, will fire white when heated to 1100° Celsius. Of the ten samples in this study, all fired white when heated at this temperature. Moreover, not only did the exterior surfaces of the 10 samples fire white, upon exposing the interior sections of the samples they were found to have fired white all the way through, with the exception of minor mineral staining that was present in all of the samples (Fig. 4). One of the goals of this research was to document the depth of the color change, but this exercise was rendered meaningless upon discovering that they had fired white all the way through. It had been hypothesized that firing depth would be related to heating time, that samples fired longer would have greater firing depths. In this respect the samples did not respond to the firing process in the way that had been expected.

This indicates that certain steatite sources will whiten in a very short period of time when fired at high enough temperatures. Specifically, the data demonstrate that with this particular type of steatite the transformation in color and hardness can be accomplished in as little as 1 minute when fired at 1100° Celsius. Previous X-Ray Diffraction analyses of fired steatite artifacts from the sites of Mehrgarh and Harappa have yielded phases of the minerals enstatite and cristobalite, which occur as a result of the decomposition of talc, both of which can develop at temperatures of 1100° Celsius (de Saizieu and Bouquillon 1994). While the firing technique employed here likely does not adequately replicate Harappan practices, these previous studies indicate that a temperature of 1100° Celsius may have been attained by ancient Harappan craftspeople. It is possible that Harappans may have been able to achieve the desired effect of hardened, whitened steatite ornaments and seals by firing for a very short period of time at high temperatures, but this hypothesis will require further testing before it can be validated. Regardless, it appears that temperature plays a greater role than time in changing the color of fired steatite, at least in this experiment.

### *SEM Analysis*

Scanning Electron Microscopy (SEM) analyses were conducted on impressions from three of the experimental seals (Fig. 5) and one archaeological seal from the site of Harappa. Unfortunately the impression from the archaeological sample was found to have an extremely weathered cut surface, rendering comparisons with the experimental impressions difficult. The SEM scan of this sample was found to be blurred and unclear, and this unexpected and unfortunate result underscores the need for well-preserved archaeological seals in order for this type of analysis to be fruitful. However, SEM on the experimental materials was successful, and the data was compared with previously conducted SEM results from additional seals from the site of Harappa.

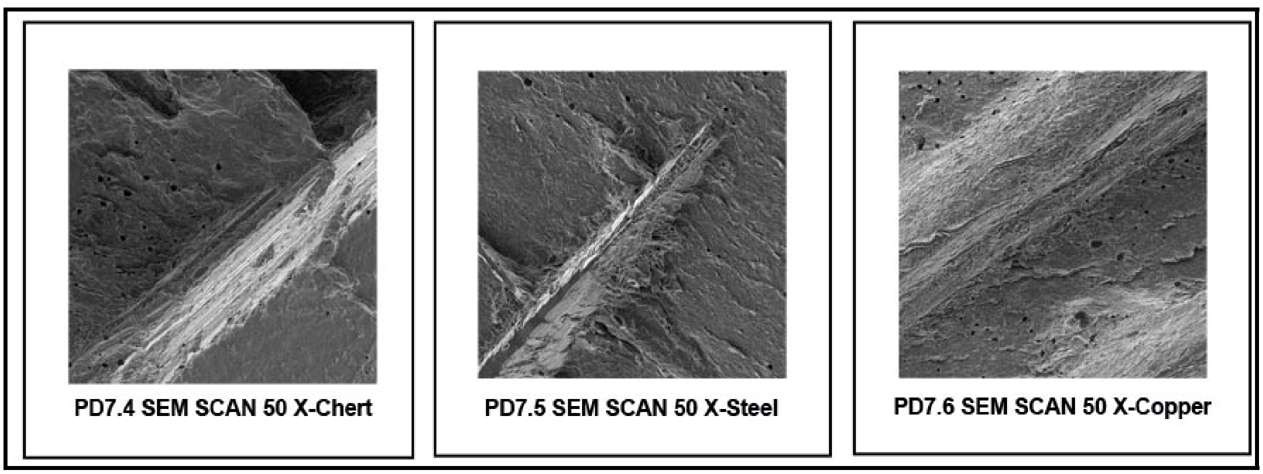


**Figure 5. SEM Scans of Replica Harappan Tablets.**

Sample PD-7.4 was the first experimental sample to be analyzed. It was inscribed with a small chert flake engraver. Two of the inscribed characters were analyzed, and each was examined at 20, 50, 100, and 300x power magnification. The results of this analysis indicate that carving with a chert tool creates a very distinct cut surface (Fig. 6). The edges of this surface are sharp and clearly demarcated, easily distinguished from the unaffected steatite surface at the edge of the incision. The body of the engraved surface is rough and has clearly visible parallel striations running horizontally along the axis of the incision. These striations were likely caused by the uneven surface of the engraving tool and suggest that carving with chert tools produces clear signatures that can be easily seen using SEM.

The similarity between the two impressions made from the inscribed characters on this sample also indicates that they were carved with the same tool.

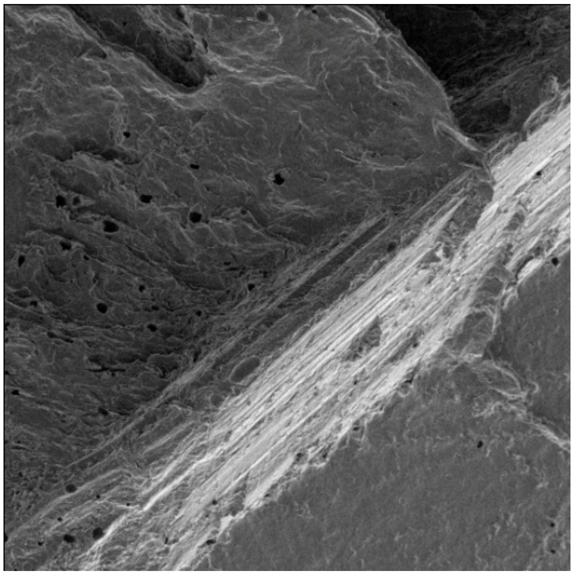

**Figure 6. SEM Scan of Sample PD-7.4 at 50x Magnification.**

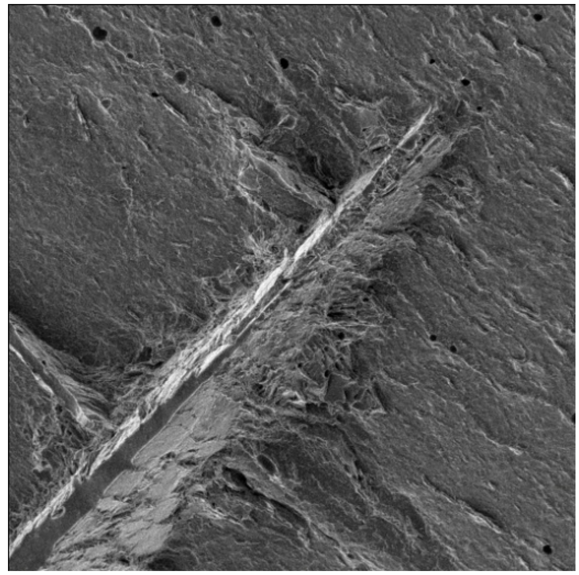

**Figure 7. SEM Scan of PD-7.5 at 50x Magnification.**

The next sample to be analyzed was PD-7.5, carved with a steel-tipped Xacto knife blade, used to approximate a hard, sharp cutting tool. Three of the inscribed characters were analyzed, under the same magnification as that described for PD-7.4. The impressions of the cut surface created with the Xacto knife are also quite distinct (Fig. 7). The edges are sharp and clear, the boundary of the inscribed character is clearly visible in the impression analyzed under SEM. However the body of the cut surface is quite distinct from that created by the chert tool. It is very smooth and has few striations, contrasting with the many striations visible in the impression created by the chert tool. This indicates that the surface was cut with a sharpened, fine-edged tool. Although Harappans did not have Xacto blades to incise their steatite, some of their bronze tools may have been almost as hard and sharp as this type of modern tool. Studies by Kenoyer (1984, 1998) have demonstrated that Harappan bronze saws had a hardness that was comparable to steel in their cutting ability. The results of this study also significant because they demonstrate that different tools create distinct impressions that are clearly distinct under SEM. The similarities between the impressions of the two inscribed characters from sample PD-7.5 indicate that they were cut with the same tool, similar to the results described above for the samples engraved with chert.

Sample PD-7.6 was the last experimental sample to be analyzed under SEM. This piece was carved with the replica Harappan style copper engraving tool and two of the inscribed characters were examined under the same magnification levels as the others. The copper tool also creates a distinct impression; one easily distinguished from the other two (Fig. 8). Unlike the other two tools the edges created with this tool are rough and blurred. As opposed to the sharp, well-defined boundaries created with the steel and chert tools, those made with the softer copper tool are cracked, rounded, and irregular. The body of the cut surface is not as rough as the one created with the chert tool or as smooth as that engraved with the Xacto knife. The parallel striations visible near the edge of the cut surface are the result of multiple incisions with the tool during the engraving process. They are indicative of a specific carving style that was employed and are visible on both of the inscribed surfaces. The rough, rounded edges of the engraved surfaces of this sample indicate that it was carved with a tool less sharp and hard than the other two. Part of this likely relates to the fact that copper is a softer material than chert and steel, but the pattern may also be explained by the comparative dullness of the tool. As with the other samples, the similarity between the two cut-marks analyzed suggests that they were carved with the same tool.

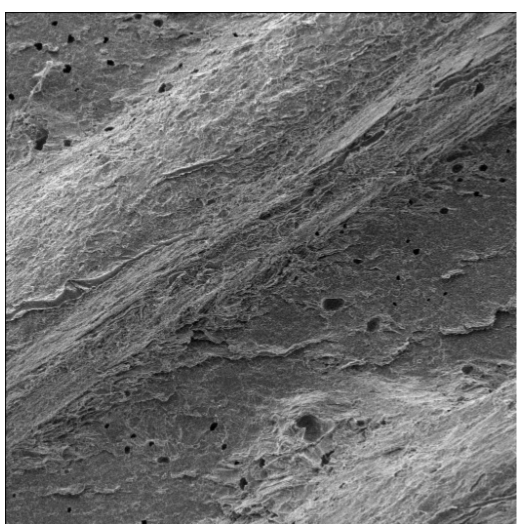

**Figure 8. SEM Scan of PD7.6 at 50x Magnification.**

The results of this preliminary SEM analysis indicate that different engraving tools will create distinct cut surfaces that can be identified using SEM. These findings support conclusions drawn in earlier research (Kenoyer 2003, 2005a). Whereas chert and the Xacto knife created sharp and clearly defined edges, the comparatively dull copper tool created rough, rounded edges that are distinct from the others. The highly sharpened and fine-edged harder Xacto knife created a smooth cut surface, and the uneven cutting edge of the chert tool produced a series of clearly visible parallel striations. At this point it will be useful compare these results with a few archaeological samples.

The three impressions depicted below (Fig. 9) were taken from incised steatite tablets recovered at Harappa from a single excavation unit, lot 8040, Trench 11, on Mound E. They were recovered during the 1997 field season and can be used for comparative SEM analyses. They bear the same inscriptions and the impressions created by them have similar cut-marks. Although the impressions of the inscribed characters are weathered, all three of the samples have cut marks with rough, rounded edges and rough surfaces. The two cut marks from H97-3319 have rough, rounded edges and bear similar parallel striations on the impacted surfaces, indicating that they were engraved with the same tool. Previous studies suggest that these tablets were engraved with a copper tool (Kenoyer 2003, 2005a). PD-7.6 was engraved with a replica Harappan style copper tool and the similarities between impressions from this sample and the archaeological materials (Fig. 10) provides further support for the interpretation that they may have been carved with a copper tool.

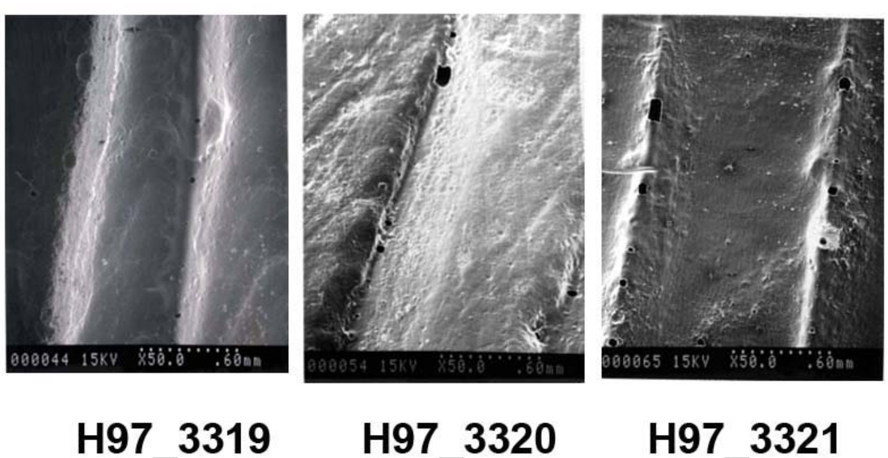


**Figure 9. SEM Scans of seals recovered at Harappa (Courtesy of J. M. Kenoyer).**

Before concluding it will be useful to highlight another archaeological example (Fig. 11). This impression was also created from a seal recovered at Harappa. It has a great level of detail visible in the impression made from the cut marks. Edges are sharp and well defined, suggesting they may have been carved with sharp, finely pointed tools made of durable materials. Further, the unicorn seal appears to have been made with multiple tools, the cut marks visible on the body are distinct from those created by engraving the characters. This may represent a distinct carving style practiced at Harappa. It also underscores the level of detail necessary in order to analyze seal carving traditions using this technique. Understanding carving techniques may help identify workshop styles and traditions, which will ultimately help us understand the nature and organization of seal production.

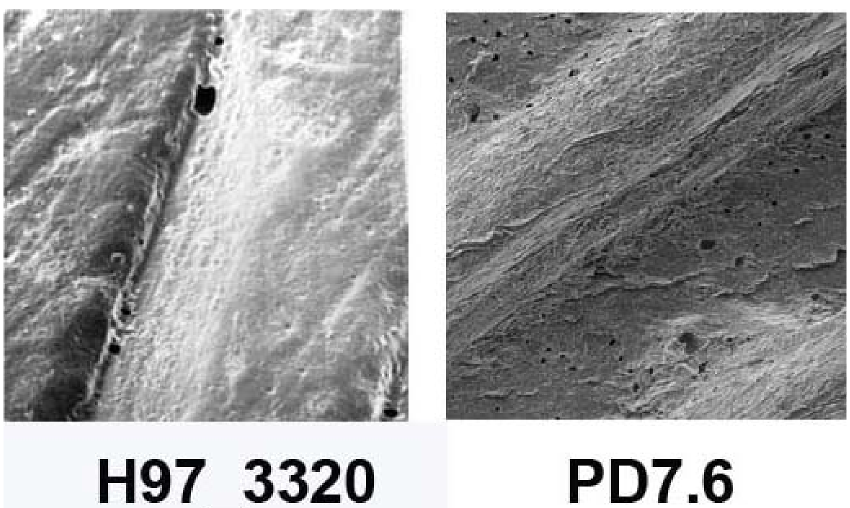


Figure 10. SEM Scans of H97_3320 & PD7.6


Figure 11. SEM Scan of Harappan Unicorn Seal (Courtesy of HARP & Dr. J. M. Kenoyer).

## Discussion

The results of this study provide preliminary insights into carving and firing aspects of Harappan steatite seal production. It is clear from the firing experiments that the transformation in color and hardness associated with the thermal alteration of steatite do not take long when fired at high temperatures. Previous research (de Saizieu and Bouquillon

1997; Law 2005, 2008; Mackay 1938) suggests that the Harappans and their predecessors were firing most of their steatite objects white. At temperatures of 1100° Celsius, this transformation takes place in as little as one minute with specific types of steatite. While it is not possible to know whether or not the Harappans were firing their steatite at temperatures this high, previous X-Ray Diffraction (XRD) analyses (de Saizieu and Bouquillon 1994, 1997) of beads from Mehrgarh and Harappa have revealed phases of enstatite and cristobalite, both of which can be well-developed in steatite that has been fired to 1100° Celsius. The presence of these two mineral phases in steatite artifacts from Harappa and Mehrgarh indicates that they may have been fired at high temperatures as well. Conversely, it is also possible that enstatite and cristobalite may have developed as a result of firing steatite at lower temperatures for longer periods of time. This hypothesis will require further testing, and future experiments using X-Ray Diffraction (XRD) analyses will focus on the mineralogical changes associated with firing steatite at varying temperatures and times. These studies will also be conducted in order to examine color and hardness changes associated with heating steatite in dynamic environments that will replicate Harappan firing techniques. Nonetheless, this research builds on earlier studies and supports the conclusion that changes in the color and hardness of steatite through firing can be easily observed in experimental studies.

Scanning Electron Microscopy (SEM) analyses also support previous research and indicate that this is a useful technique for identifying differences in the engraved surfaces of steatite created using different tools. Each of the three tools used to carve the experimental seals produced cut surfaces that were clearly distinct using SEM. Comparisons between the experimental samples and archaeological samples from the site of Harappa have demonstrated clear similarities between the impressions of materials carved with a copper tool. This suggests that some seals may have been carved using copper implements, supporting the conclusions drawn in previous studies (Kenoyer 2003, 2005a). Ongoing research is directed towards generating an expanded sample set in order to determine if the tools create similar engraved surfaces on multiple replica seals. Additional tools will be fashioned and used to identify further similarities and differences created through engraving steatite. These will then be used for comparative studies with archaeological seals from Harappa and if possible other sites. Future research will undoubtedly provide further insights into these important aspects of Harappan seal production.

## Conclusion

The Integration Era of the Harappan Phase (2600-1900 BC) witnessed the floresence of many distinct and important craft traditions that characterize the Indus Valley Civilisation (Kenoyer 1998). Incised steatite seals were among the most important artifacts produced by Harappan craftspeople, used by ruling elites as symbols of wealth and power to legitimize their authority and reinforce the social order (Kenoyer 2000). Because of the significance of these objects in the Indus Civilisation, this research has focused on two aspects of Harappan seal production, firing and carving techniques. A sample of replica steatite tablets were subjected to firing experiments and SEM analysis in order to gain further insights into how these processes may have been executed during Harappan times. The results of this study suggest that certain types of steatite will harden and whiten in as little as one minute when fired at temperatures of 1100° Celsius. This study also supports earlier research that has highlighted the utility of SEM as a technique for examining the differences in cut surfaces created using different engraving tools. The data indicates that different tools create impressions that can easily be seen under SEM. Comparisons with archaeological samples suggest that some Harappan seals may have been engraved using copper tools. Further research with more samples, both experimental and archaeological, as well as dynamic firing environments that will attempt to replicate Harappan techniques more accurately, will provide additional insights into these important aspects of Harappan seal production. Continued research will increase our understanding of the technological processes involved in seal production and contribute to the substantial and significant body of existing knowledge regarding ancient Harappan craft production.

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