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**Conference Paper** · January 2008



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# South Asian Archaeology 2007

Proceedings of the 19th International Conference of the
European Association of South Asian Archaeology
Ravenna, Italy, 2-6 July 2007

## Volume I
## Prehistoric Periods

Edited by

Dennys Frenez
Maurizio Tosi

BAR International Series
2012

# INAA OF AGATE SOURCES AND ARTIFACTS FROM THE INDUS, HELMAND, AND THAILAND REGIONS

Randall Law, Alison Carter, Kuldeep Bhan, Arun Malik & Michael D. Glascock

Agate was one of the ancient world's premier prestige goods, especially the red-orange variety known as carnelian. The stone was utilized by and traded between societies from Africa to eastern Asia (Inizan 1993; Insoll et al. 2004; Theunissen et al. 2000). In this paper, we present the results of a series of instrumental neutron activation analyses (INAA) of agate samples and artifacts from sources and/or sites in the Indus, Helmand, and Thailand regions. This study represents the beginning of a broad-scale, long-term project aimed at identifying Old World agate sources and the regional and inter-regional trade networks through which this important stone was exchanged in both raw and finished form.

Our main goal at this initial stage was to determine if agate sources could be effectively differentiated from one another using INAA-derived data. To this end, sets of samples representing multiple geologic occurrences were analyzed at two different research reactors – the University of Wisconsin's Nuclear Reactor (UWNR) and the University of Missouri Research Reactor (MURR). It was found that good-to-excellent (≈ 85 % to 95 %) statistical separation between different sources could be achieved when the INAA results from these facilities were evaluated using canonical discriminant analysis (CDA). A set of agate artifacts from the Indus Civilization sites of Harappa and Nagwada along with a set of carnelian beads of unknown archaeological provenience were also analyzed. Although the geologic dataset they were compared to is, at present, limited, the results both support and challenge past assumptions regarding the acquisition of agate in proto-historic South Asia.

We begin with brief overviews of agate, agate occurrences and the analytical methods employed previously and in this study. The UWNR and MURR analyses are then discussed separately in turn. The different datasets and research questions examined are outlined in each of those sections. Lastly, the implications of this study for the future of agate provenience research are discussed.

*Agate, agate occurrences and previous provenience studies*

Agates are translucent microcrystalline sedimentary rocks that form when silica precipitates into cavities within some type of host rock. The mechanisms behind their growth, frequent banding and other distinctive characteristics are subjects of much debate (see Moxon 1996 for more on these matters). As they erode from their host rocks, which can also be sedimentary but are more commonly volcanic, agates (many retaining the nodular shapes of the cavities in which they formed) may be carried away by fluvial action and end up reconsolidated in conglomerate or loose in the beds of rivers, streams, nalas and wadis. Such secondary contexts are sometimes far removed from original host formations and can potentially contain agates from multiple geologic occurrences located across an enormous geographic area. It is for reasons such as these that some scholars feel identifying the sources of agate artifacts might be problematic (see discussion by Vidale 2000: 42).

Geologically speaking, agate is not a particularly uncommon rock. Figure 1 is a map on which a few dozen or so of the more notable occurrences in Asia are identified (details including citations for these can be found in Law 2011, Chapter 8). However, good agate – i.e, that which ancient lapidaries would have found suitable for beadmaking – is not widely available. Nodules of the size and quality required to make Harappan-style long-barrel carnelian beads are, in fact, extremely rare.

There have been two recent geologic provenience studies involving agate. Theunissen and others (2000) employed PIXE/PIGME in an effort to shed light on the historic era carnelian trade in Southeast Asia. Their dataset consisted of 51 agate artifacts (beads and manufacturing debris) from sites in Sri Lanka, Thailand and India and two geologic samples from a Thai quarry. Insoll and others (2004) used UV-LA-ICP-MS to examine the carnelian trade between India and Africa. Their dataset contained 13 samples (archaeological debris and modern raw material) from the Ratanpur region of Gujarat, India and 13 artifacts (ornaments and debris) from sites in western Africa. Each study was laudable in that the methods employed were non-destructive (or minimally destructive) and produced useable data on range of major and minor elements. The results of both, however, were equivocal.

Although some meaningful groupings were observed among samples when each dataset was examined using principal component analysis and/or cluster analysis, regional differences were difficult to define and evaluate. The problem, in our opinion, lay not so much with the methodologies that were employed but with the datasets that were examined. Theunissen and others' dataset was almost entirely made up of agate artifacts while that analyzed by Insoll's group contained geologic samples from what was essentially a single extensive deposit (Ratanpur). In order to begin to confidently source agate artifacts it is necessary to compare them to a large number samples collected from multiple geologic occurrences. This is the approach we have taken in the current study. Moreover, we have employed an analytic technique (INAA) that, while destructive, has a long history of success in provenience studies of archaeological stone and a method of data evaluation (CDA) that is especially well-suited to differentiating between known geologic sources and assigning artifacts to them.

*Instrumental neutron activation analysis and canonical discriminant analysis*

INAA is a highly accurate and precise method for quantifying the elemental compositions of materials. Archaeologists around the world have long employed it in efforts to determine the proveniences of a wide range of artifacts (see Glascock and Neff 2003 for a detailed account of this technique and its application). In brief, INAA involves the irradiation (or activation) of elements within artifacts and/or source samples by exposing them to a neutron flux. Following varying periods of decay, the gamma ray emissions they produce are detected and counted. After the results are screened of elements that failed to be detected in all samples or had high count-rate standard deviations, the data are evaluated.

For this study, CDA was deemed to be the most effective statistical method with which to use multivariate INAA data to differentiate agate sources from one another and to assign a possible provenience to agate artifacts. During CDA (see Baxter 1994 for a full discussion of this method), linear combinations of variables called discriminant functions are generated that produce a maximum degree of separation (discrimination) between various defined groups of cases, which in this instance are the individual sets of samples collected from different agate sources. Discrimination success is evaluated by a cross-validation technique in which each case is left out its group in turn and compared to the dataset as an ungrouped case. A percentage is generated based on the number of cases that were correctly assigned to the groups to which they actually belong. Agate artifacts are plotted as ungrouped cases and assigned to the group whose center (or centroid) in multidimensional space they are nearest. The data are displayed on a bivariate plot using the first and second discriminant functions.

*UWNR study: Agate artifacts from Harappa and Nagwada compared to agate samples from Gujarat and eastern Iran*

The Indian state of Gujarat is widely believed to have been an important source area, perhaps even the primary source area, for the agates used by peoples of the Indus Civilization (c. 2600 to 1900 BC). There are many good reasons for this. Firstly, Indus peoples were present there, often in very close proximity to some significant occurrences (Fig. 2). In fact, ornamental stones were probably among the resources (some other being marine shell, salt and pasturage) that attracted them to the region in the first place. Secondly, although occurrences of agate can be found in many parts of Asia, the extent, diversity and sheer richness of sources in Gujarat is unparalleled. The region could aptly be called the 'Saudi Arabia' of agate. Lastly, Gujarat was a historically important source area. Greek (McCrindle 1885: 77, 334), Mughal (Khan 1756: 250) and early European colonial (Barbosa 1517: 66-7) records all make reference to the agate resources there. The city of Khambhat (Cambay) has been a major center for the manufacture of agate ornaments since at least the 16th century (Arkell 1936) and the traditional methods still employed there have been the subject of several ethnoarchaeological studies (Kenoyer et al. 1991; Possehl 1981; Roux 2000).

It has long been assumed (from Pascoe 1931: 681 to Vidale 2000: 42) that, within Gujarat, Harappan agate primarily came from the extensive deposits of the Ratanpur area in the southern part of the state. However, noting that there are also deposits in the Kutch area, Shereen Ratnagar recently asked (2004: 146) 'did the Harappan inhabitants of Dholavira know of these sources?' This was a good question. Agate occurrences in northern Gujarat should have been far more accessible to the peoples of that city than the Ratanpur deposits, which are located hundreds of kilometers to the southeast. Although no artifacts from Dholavira were available for this analysis, it was reasoned that if Gujarat was the principal region from which Indus Civilization peoples obtained agate resources, then it should be possible address the question through provenience analyses of artifacts from other Indus sites in Gujarat and the Indus Valley proper. For this study, 24 agate artifacts (debris fragments and broken beads) from Harappa in the Punjab and three from Nagwada in Saurashtra region of Gujarat were subjected to INAA at the UWNR. These were compared to agate samples collected from three deposits in Gujarat as well as a set of agate artifacts from the site of Shahr-i-Sokhta, which served as proxy samples for a source in eastern Iran.

Agate sources sampled in Gujarat

Among the low hills around the village of Ratanpur, Bharuch District, Gujarat, there are hundreds (if not thousands) of agate mining pits and shafts sunk into the Miocene conglomerate called the Babaguru Formation. Although these workings are often referred to as the 'Rajpipla' deposits/mines (as they were within the confines of that princely state prior to 1947), 'Ratanpur' is a more appropriate designation (Ball 1886: 238). All occur within 15 kilometers of Ratanpur village and the hilltop tomb/shrine of Gori Pir (or Baba Ghor) – a Muslim saint who is said to have come from Africa in the 15th century and established bead-making operations at nearby settlements such as Limodara (Kenoyer and Bhan 2005). Samples for this study were collected from pits, shafts and tailings along a zone that extended from the base of Gori Pir Hill three kilometers toward the southeast. Because the Babaguru Formation is a secondary context agate deposit, an attempt to assess geochemical variation across that zone was deemed to have little utility. All samples from this occurrence are, therefore, treated as coming from a single source.

There are numerous agate of occurrences in central and eastern Kutch (Geological Survey of India 2001: 47; Merh 1995: Fig. 17; Wynne 1872: 72-3) that would have been directly accessible to Indus Civilization peoples settled in northern Gujarat. A source near Khandek village was brought to our attention by R. S. Bisht, the excavator of the Harappan city of Dholavira, which is located some 70 km to its west-northwest on the island of Khadir. Ravaji Solanki – the local stone expert (pattarwala) at Dholavira – provided directions to Khandek and his brother Narsingh, who resided there, guided co-author Randall Law to the source itself. A pavement-like layer of loose agates (natural carnelian, yellow-brown agate, clear chalcedony, moss agate) and other microcrystalline silicates (red, green, brown and variegated jaspers) covers an area of two or three hectares just east of the village. This source is located around five kilometers from the small fortified Indus Civilization settlement of Surkotada (Joshi 1990). Although no prehistoric workings or cultural materials were identified, numerous 'window' flakes (pieces of cortex that were struck from nodules in order to observe the quality of the agate inside) were found that indicate it had been exploited for materials at some time in the past.

The agate deposits on the island (bet) of Mardak, in the salt marsh southeast of Kutch known as the 'Little Rann', can be difficult to reach due to seasonal flooding of the area surrounding them (Trivedi 1964: 11). A sampling trip by authors Law and Arun Malik in early 2003 ended with both researchers stuck in the mud within sight of the island. A second attempt by Law, Malik and Dr. Kuldeep Bhan later that same year just prior to the summer monsoons was successful. Mardak Bet is a thinly-shaped, east-west oriented island around 12 km in length with a maximum width of about 1.25 km. The agate beds are found in two main areas. The most extensive is located near the island's constricted mid-section, which Malik designated 'nana.' Another occurs 3 km to the east, around the base of its highest hill (≈ 40 m above the salt flats), which was designated 'mota.' A wide range of microcrystalline silicates are found at both locations. Brownish-gray agate is by far the most abundant type but nodules of natural carnelian, clear chalcedony and moss agate are not uncommon. Red, green, yellow-brown and variegated jaspers (including bloodstone) are also found. No prehistoric settlements are known to exist on Mardak Bet and no clearly ancient workings in the island's agate beds were identified during our short visits to them. Mining pits and sorting areas related to modern extraction activities have likely obscured any evidence of earlier ones. There are, nonetheless, indications that ancient peoples did exploit these deposits. Numerous agate and jasper flakes, some with a heavy patina suggesting great antiquity, were found on the hillside at 'mota' Mardak Bet.

### Iranian sources

In order for us to best assess whether or not Harappans were acquiring agate from Gujarat it was necessary to have samples from different region in the geologic dataset. Iran is an underappreciated potential source area. The 'most celebrated Iranian agate localities are in the central and eastern' part of the country (Nazari 2004: 21). Around the Khur area, primary context banded agate nodules occur within tuffaceous andesite (*ibid*.). Extensive secondary context deposits can be found in Iran's broad salt deserts (dasht) and inland deltas. The explorer Henry Savage Landor marveled (1902: 79) at the 'handsome agates' spread across the wastes of the Dasht-e Lut. Ali Hakemi wrote (1997: 15) that 'carnelian is found in considerable quantities in the Lut flood plain'. Finally, Maurizio Tosi noted (1969: 374) that 'with regard to cornelian … numbers of little pebbles of this stone, with a diameter often exceeding 3 cm, may be collected along the dried out beds and ancient branches' of the Helmand River delta near the site of Shahr-i-Sokhta. For this study, a set of 14 agate flakes and nodule fragments from that site were used as proxy samples for a source in eastern Iran.

### UWNR study results

Twenty samples each from the Ratanpur, Mardak Bet and Khandek sources along with the 14 proxy source samples from Shahr-i-Sokhta were analyzed at the UWNR. From the INAA data that were returned, ten elements[1] – Al, Co, Cr, Eu, Fe, La, Na, Sb, Sc, and V – were selected for use in CDA (Fig.3). Good separation between the three Gujarati sources and the Iranian proxy source was achieved. Exactly 85.1% of leave-one-out cross-validated grouped geologic cases were classified correctly. Most of the misclassification (overlap) that occurred was among the Gujarati sources. Only one sample from Shahr-i-Sokhta (S-i-S_14, noted on Fig. 3) was classified as belonging to a Gujarati source (Mardak Bet) when it was cross-validated. Overall, however, it is clear that the Shahr-i-Sokhta agates are geochemically distinct from those found in Gujarat. When the artifacts from Harappa and Nagwada were plotted as ungrouped cases all but four from Harappa (AH-1, 2, 9 and 20) were assigned by CDA to either Ratanpur (n = 3), Mardak Bet (n = 13) or Khandek (n = 7). Although agate samples from many other regions will eventually need to be analyzed, these results seem to confirm what scholars have long assumed – that Indus peoples mainly used Gujarati agate. The four artifacts from Harappa assigned to the Shahr-i-Sokhta group do suggest that residents of the site sometimes utilized agate from sources in other areas. However, until samples from actual deposits near Shahr-i-Sokhta can be analyzed (instead of artifacts) it would be premature to firmly state that those sources were in eastern Iran.

Next, the three agate sources in Gujarat were compared to one another alone, without the Shahr-i-Sokhta proxy source-group (Fig. 4). Although good separation between the three was achieved, it was only slightly better than that for the original CDA. Exactly 86.7% of leave-one-out cross-validated grouped cases were classified correctly this time whereas 85.1% were classified

[1] These data can be found in Law 2008: appendices 8.1 through 8.5.

correctly when the S-i-S source-group was included in the analysis. This again shows that nearly all of the overlap (misclassification of grouped cases) in the dataset is among Gujarati sources rather than between them and the Iranian artifact/proxy source samples. In this instance, the misclassifications were among the Mardak Bet samples (one was predicted to belong to Ratanpur) and the Ratanpur samples (one was predicted to belong to Mardak Bet and three to Khandek).

On Figure 4, the Harappan artifacts (excluding the four had previously been predicted to belong to the Iranian proxy source-group) are plotted as ungrouped cases in relation to the three Gujarati source-groups. In this instance, 14 were assigned to Mardak Bet, seven to Khandek, and only two (one each from Harappa and Nagwada) to Ratanpur. These results, although preliminary, suggest that, contrary to what many scholars have assumed, Indus Civilization peoples were not heavily exploiting the Ratanpur area agate deposits. Instead, most of their agate appears to have been derived from sources in northern Gujarat.

*MURR study: Agate beads from Afghanistan compared to samples from Gujarat, Iran and Thailand*

For the next phase the project, we shifted our analyses to the University of Missouri Research Reactor (MURR) in order to take advantage of the longer INAA count times employed at that facility. The geologic dataset was expanded to include samples from an agate source in Thailand. In addition, 15 beads from Afghanistan of unknown provenance were analyzed.

The agate source at Ban Khao Mogul, Thailand

Agate beads recovered at archaeological sites in Southeast Asia are often assumed to have originated from sources in India and are widely believed to be among the first signs of contact between those two regions during the early Iron Age period (c. 500 BC to AD 500). Some scholars treat such beads as proxies for Indian political and cultural influence (Francis 1996; Glover 1989). However, others suspect that many of the agate ornaments found in mainland Southeast Asia may have been produced by indigenous groups rather than imported from South Asia (Theunissen et al. 2000). One possible raw material source for local bead manufacturing that has been discussed in the literature (Glover 1989; Theunissen et al. 2000) is found at Ban Khao Mogul in Lopburi Province, Thailand. The deposit there consists of small nodules of agate and other microcrystalline materials eroding from a small limestone outcrop.

Two agate samples from Ban Khao Mogul were included in the study by Theunissen and others (2000) discussed earlier in this paper. Although those results were inconclusive, they did suggest that some agate beads from Southeast Asia may not have originated in India. In February 2007, Alison Carter traveled to Ban Khao Mogul in order to collect additional samples for a more thorough analysis. The age of the quarry at this location is not known. As recently as 10 years ago, several villagers were producing polished stones and cabochons from the local agate to use as ring settings (Nigel Chang personal communication 2007). However, during Carter's visit only one villager was still practicing this craft. Twenty samples from Ban Khao Mogul were sent to MURR for INAA.

A set of beads from Afghanistan

Unfortunately, no agate artifacts from Southeast Asian sites were available for this analysis. However, Dr Mark Kenoyer kindly provided a large number of carnelian beads he obtained from Haji Ashoor – an Afghani jeweler working in Peshawar, Pakistan who deals in ornaments from Afghanistan. The age and provenance of the 184 heavily worn examples given to us was not known. Therefore, prior to INAA, a morphological study of these beads was conducted in the hope that it would provide clues as to when and where they were made.

One of the best ways to narrow down when and where a bead was made is by looking its drill hole. As Kenoyer (1992: 86) notes, 'the drill hole reflects an important cultural choice that represents very different technologies'. During the Harappan period, most beads were perforated using either chert or a type of flint clay known informally as 'Ernestite'. However, during the Early Historic period (beginning c. 600 BC) drills tipped with diamonds were introduced. These allowed for faster and easier perforation of hard stone like agate-carnelian and are still used by beadmakers today. Based on research by Kenoyer, Vidale, and Bhan (1994) there are two primary diamond-drilling techniques. In the first, two diamonds are affixed to the drill tip (double-diamond drilling). This technique is unique to South Asia and generally results in a larger hole. The second technique employs a drill tipped with one diamond (single-diamond drilling). Historically, it is practiced in Central Asia and results in a comparatively smaller hole.

The 184 beads were analyzed and classified (by Carter) using a bead coding system developed by Kenoyer for use at Harappa. Characteristics such as shape, length and width measurements were recorded. The interior perforations were measured and impressions of the drill holes were made. The preliminary results indicated that the beads were made using both single and double-diamond tipped drills. Fifteen examples were sent to MURR for INAA. Ten were selected from the double-diamond drilling group and five were chosen from the single-diamond drilling group. We hypothesized that the double-diamond drilled beads would likely be more compositionally related to the Gujarati sources, as they were made using the South Asian technique, whereas the Central Asian-style single-diamond drilled beads might be more closely related to geologic samples from the Iranian proxy source.

MURR study results

Along with the 20 Ban Khao Mogul samples and the 15 Afghani beads, sets of agate from Mardak Bet (n = 14), Ratanpur (n = 15) and Shahr-i-Sokhta (n = 15) were analyzed at the MURR. From the data that were returned, ten elements[2] – Al, Ce, Co, Fe, La, Mn, Na, Sb, Sc, and Sm – were selected for use in CDA (Fig. 5). An outstanding degree of separation between the different sources was achieved with 95.1% of cross-validated grouped geologic cases classifying correctly. Most of what little misclassification occurred was between the two Gujarati sources. The Thai samples are highly distinct, which has exciting implications for future studies of long-distance trade between India in Southeast Asia. Although many more sources will need to be analyzed (especially those in eastern India), our results suggests that, using INAA, archaeologists working in Southeast Asia should be able to clearly differentiate between agate beads imported from South Asia and those being made from local stone. Understandably, researchers might be reluctant to subject rare and/or finished objects to such a destructive analytical technique. However, it may be possible to source agate artifacts using other non-destructive (or less destructive) methods (such as PIXE/PIGME or UV-LA-ICP-MS) provided that a suitable compositional database of different geologic sources against which to compare them is established.

When the 15 Afghani beads were compared to the geologic sources/proxy sources, eleven were predicted to belong to one of the Gujarati deposits – nine to Ratanpur and two to Mardak Bet. This is an interesting reversal of the pattern seen during the Harappan Period when all but two agate artifacts assigned to occurrences in Gujarat seem to have come from deposits in that northern part of that state. It makes sense though that a large number of the 15 diamond-drilled beads would have come from Ratanpur in the south, which by all accounts was a far more important agate source during the historic period. Also interesting is the fact that of the four beads (labeled on Fig. 5) assigned to the Shahr-i-Sokhta group, three were single-diamond drilled. Agate sources in the Helmand region or related ones elsewhere in Iran or Afghanistan would have been among the nearest to the places where beadmakers were employing this Central Asian drilling technique.

No beads were assigned to Ban Khao Mogul, which was both expected and reassuring. It is highly unlikely that South or Central Asian beadmakers would have imported agate all the way from Southeast Asia when there were closer and richer sources. The fact that none of the Afghani beads even remotely resembled the Thai deposit lends further support to our finding that agates from these different regions are chemically distinct from one another.

*Conclusions*

The results of our study bode very well for future research of this kind. The UWNR analysis showed that it is possible to differentiate samples from three agate deposits in Gujarat reasonably well and that, contrary to the expectations of many scholars, Harappan beadmakers were probably obtaining much of their raw material from sources in the northern part of that state rather than from Ratanpur. An excellent degree of discrimination was achieved when the Gujarati deposits were compared to a set of artifacts presumably from sources in eastern Iran. This suggests that it is possible, at the very least, to confidently assign a regional geologic provenience to Harappan agate. The results of the MURR study lent further support to this conclusion. Agate from deposits in Gujarat, the group of Iranian artifacts and the Thai samples were all shown to be highly distinct from one another. There is very good reason to expect that when the geologic dataset is eventually expanded to include samples from occurrences in Sindh, Balochistan, Afghanistan, Arabia, Tibet and Central Asia it will also be possible to differentiate those source areas and assign a regional geologic provenience to agate artifacts.

*Acknowledgements*

The authors wish to thank Drs Richard Meadow and J. Mark Kenoyer – co-directors of the Harappa Archaeological Research Project, for providing us access to the agate artifacts from Harappa and to Dr. Fazal Dad Kakar – Director-General of Archaeology and Museums, Government of Pakistan, for allowing us to analyze those artifacts in the United States. In addition, we are deeply grateful to Professor Maurizio Tosi and Dr. Massimo Vidale for supplementing this study with agate fragments from the site of Shahr-i-Sokhta. Thanks also to Dr. Nigel Chang, Dr. Bill Boyd, and Sompong Paekosae. Special thanks to Robert Agasie and Kevin Austin at the University of Wisconsin's Nuclear Reactor Laboratory. Support for this project was provided by the United States Department of Energy Reactor Sharing Program, the Wenner-Gren Foundation (Gr. 7066), the Bead Society of Greater Chicago, the Ruth Dickie Graduate Women in Science Grants-in-Aid program, and the National Science Foundation (BCS-0327246 & BCS-0504015).

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[2] These data may be downloaded at:

http://spreadsheets.google.com/pub?key=pNc4HHJLeWSAnL1nns0uPFg

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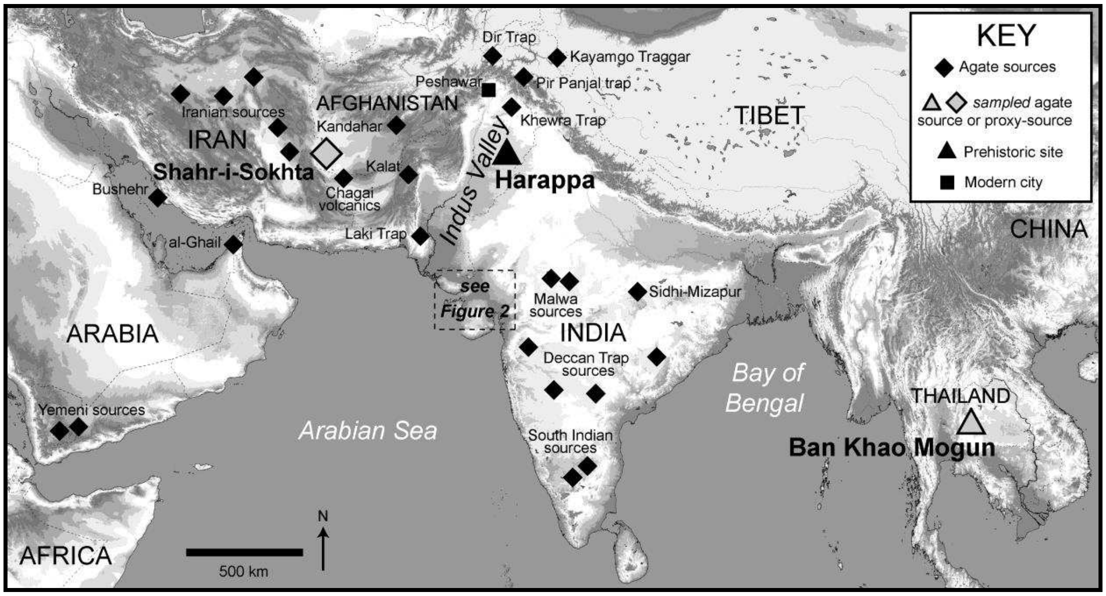


Fig.1 - Select agate sources and archaeological sites in Asia.

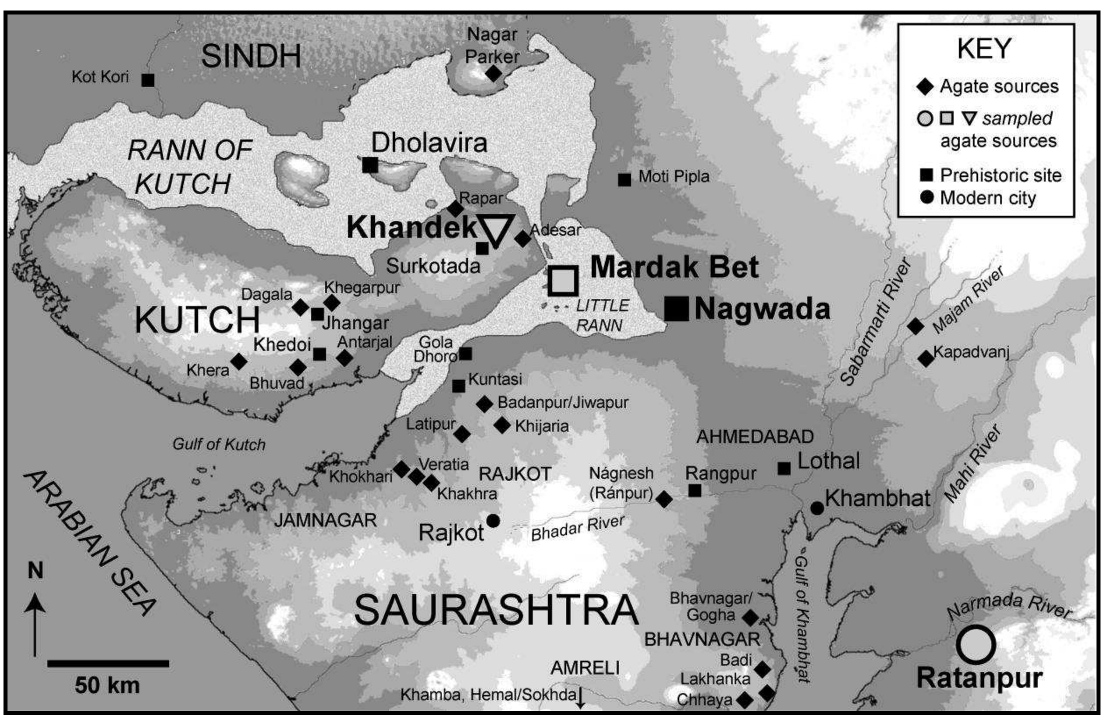


Fig. 2 - Select agate sources and archaeological sites in Gujarat, India.

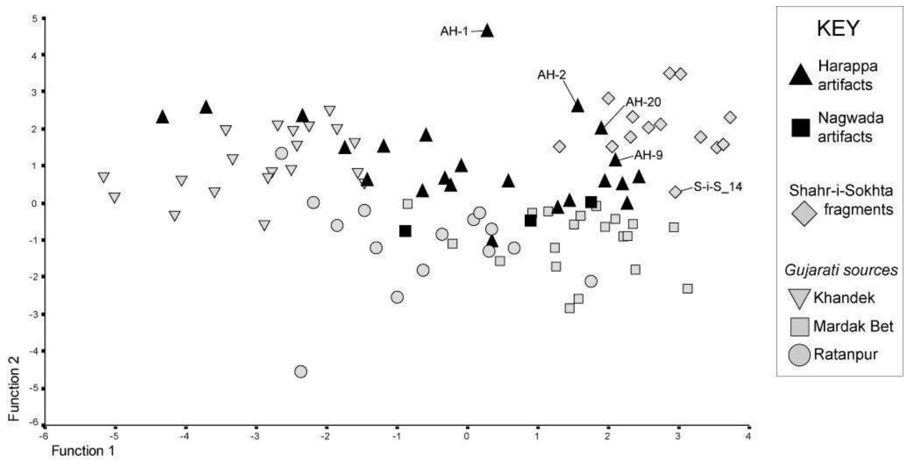


Fig. 3 - CDA of Harappan agate artifacts compared to Gujarati and Iranian sources.

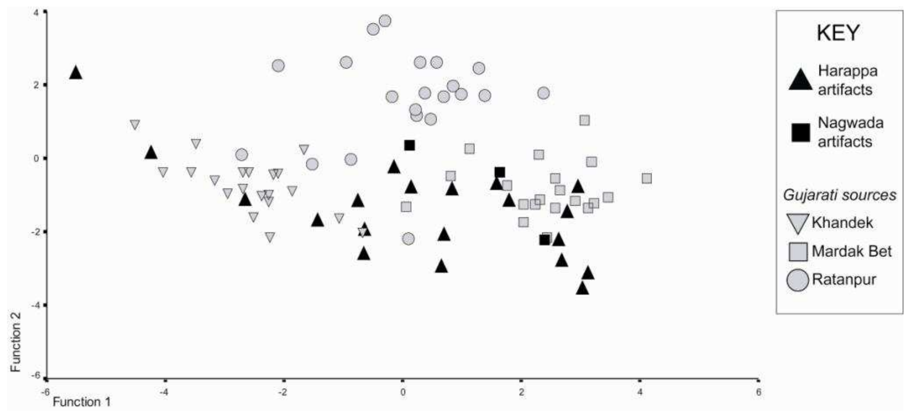


Fig. 4 - CDA of select Harappan agate artifacts compared to Gujarati sources.

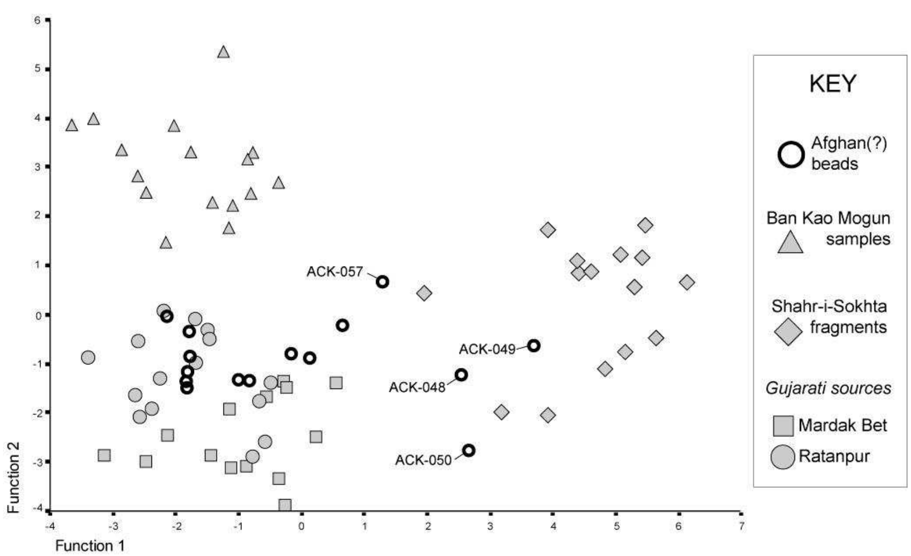


Fig. 5 - CDA of Afghani agate beads compared to Gujarati, Iranian and Thai sources.