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A new approach to tracking connections between the Indus Valley and Mesopotamia: initial results of strontium isotope analyses from Harappa and Ur

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ABSTRACT

Exchange and interaction between early state-level societies in Mesopotamia and the Indus Valley during the 3rd millennium BC has been documented for some time. The study of this interaction has been dominated by the analysis of artifacts such as carnelian beads and marine shell, along with limited textual evidence. With the aid of strontium, carbon, and oxygen isotopes, it is now possible to develop more direct means for determining the presence of non-local people in both regions. This preliminary study of tooth enamel from individuals buried at Harappa and at the Royal Cemetery of Ur, indicates that it should be feasible to identify Harappans in Mesopotamia. It is also possible to examine the mobility of individuals from communities within the greater Indus Valley region.

1. Introduction

Trade connections between the Indus Valley and Mesopotamia have been recognized since the discovery of the Indus civilization in the 1920s, along with the probable corollary that people were moving back and forth from one or both regions (Mackay, 1928-29; Marshall, 1931) (Fig. 1). The primary evidence for interaction between these two distant regions has been distinctive artifacts of Indus origin found in Mesopotamia (Ratnagar, 2004), and Mesopotamian texts that refer to the presence of traders from the land of Meluhha (Parpola et al., 1977; Possehl, 1997). Indus seals with distinctive iconography and script have been found in Mesopotamian cities and artifacts such as carnelian beads have been recovered in the royal cemeteries at Ur and Kish (Mackay, 1943; Reade, 1972; Chakrabarti, 1982).

Various objects found at other sites in Mesopotamia and western Iran include Indus-style cubical stone weights, shell bangles and figurines of monkeys that appear to have been produced in and traded from the Indus Valley (Moorey, 1994; Kenoyer, 2008a). Preliminary studies of the actual beads from Ur and the sites of Mohenjo-daro and Harappa, indicate that many of the long carnelian beads at Ur were made either in the Indus region or by craftsmen living in Mesopotamia using Indus raw materials and technology (Kenoyer, 1997, 2008a). Specific objects in Mesopotamia made from shells of marine species found only in the Indus waters, such as *Turbinella pyrum* (L.), or *Lambis truncata sebae* which can be found in the Indus as well as off the Gulf of Oman, also provide evidence for the movement of specific goods and presumably traders moving between the Indus, Oman, and the major Mesopotamian cities (Gensheimer, 1984; Kenoyer, 2008a). The goods sent in return from Mesopotamia have not been recovered

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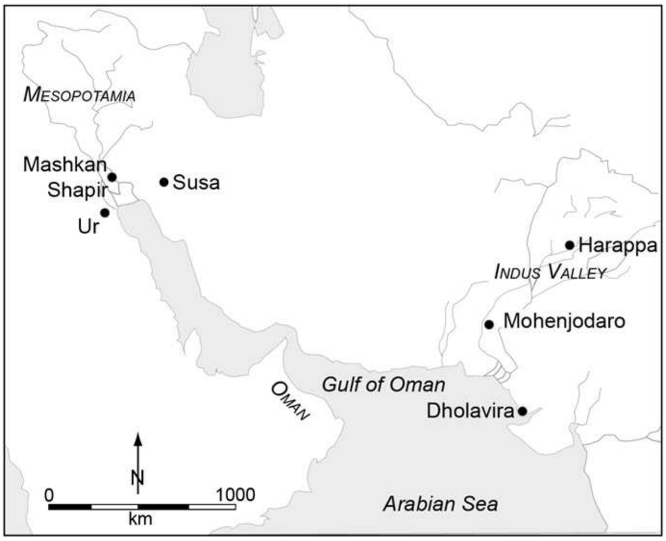

Fig. 1. The location of sites mentioned in the text.

archaeologically but – according to Mesopotamian texts – gold along with wool, incense and other perishable items that are not preserved in the archaeological record were exported to the Indus (Crawford, 1973; Possehl, 1997). However, it is possible that gold or silver used in the Indus, may have been brought from Mesopotamia and melted down to make Indus-style ornaments (Kenoyer, 1998; Law, 2008).

Various models of exchange have been proposed for the movement of goods between the Indus and Mesopotamia – a distance of 2500 km – that include indirect overland trade through Baluchistan and Iran, direct trade between the major cities in both regions via the Persian/Arabian Gulf, as well as the possibility of sea trade with middlemen in the Gulf region as the main traders (Lamberg-Karlovsky, 1972; Dales, 1976; Shaffer, 1980; Chakrabarti, 1990; Potts, 1994; Ratnagar, 2004). Although the sourcing of artifacts provides direct evidence for trade, these artifacts cannot confirm the movement of people between the Indus and Mesopotamia.

If direct exchange was taking place and if people were moving from one region to the other, it is not unlikely that trading colonies were established at different locations along the trade route. We do not know if traders were predominantly male or female, but it is not unlikely that both men and women were involved in long distance trade journeys. Furthermore, marriage exchange may have been arranged to finalize trade agreements as documented in later historical periods. If these types of activities were ongoing during the third millennium BC, then it would not be unlikely to find evidence of both men and women from the Indus region in Mesopotamia and vice versa. If people from one region died and were buried in the other region, it should be possible to identify them using strontium isotope analysis.

Isotopic proveniencing has become an important part of the study of ancient human remains in the last 20 years (e.g., Price et al., 1994, 2008, 2010; Müller et al., 2003; Benson et al., 2009; Sjögren et al., 2009). The basic principle for the isotopic proveniencing of human remains essentially involves the comparison of isotope ratios in human tooth enamel with local, or baseline, levels in bone or other materials (Price et al., 2002). Because isotopic ratios of strontium, oxygen, and lead vary geographically, values in human teeth (marking place of birth) that differ from the local ratio (place of death) indicate mobility. The method is discussed in more detail in a subsequent section of this article.

This project began as a feasibility study to compare human remains from sites in Mesopotamia and the Indus Valley in order to determine if it would be possible to differentiate people who were born in one region and died and were buried in the other. Two sites were chosen based on the possibility that some individuals might derive from the other region. The site of Harappa, Pakistan, is one of the largest cities of the Indus Civilization and has a well-studied cemetery with a large number of individuals that could be analyzed. Being a large city and a trade center, it would not be surprising to find that people from distant regions such as Mesopotamia were living in the city and may have eventually died and been buried there. The site of Ur in Mesopotamia also has an important Royal Cemetery with individuals who were buried with objects from the Indus region. It is possible that some of these individuals may have been from the Indus and married into or were serving in the royal household of Mesopotamian elites.

Human tooth enamel from Harappa and Ur was analyzed for strontium, oxygen, and carbon isotopes. Teeth from animals, such as pig and sheep from both regions, dating to the same general time period, were also sampled in order to obtain a local strontium isotope signature for comparison. The results are very encouraging because the isotope ratios between the two regions show significant differences that can be used to distinguish local and non-local individuals. In addition there is substantial variability among the human remains at the site of Harappa, suggesting significant immigration to the site. More samples are needed from Ur to assess the presence of non-local individuals and to determine if individuals from the Harappan civilization (or elsewhere) are present in the Royal Tomb. The results of this study indicate that non-local individuals will be highly visible in the tombs and cemeteries at Ur and also at the site of Harappa.

This report on our study first presents the archaeological background with an introduction to the Harappan civilization and the site of Harappa itself. Detailed information on the cemetery at Harappa provides context for the burials samples for this study. Ur and its Royal Cemetery, where samples were taken, are also described as the other end of the interaction we are examining in this study. The basic principles of isotopic proveniencing of human tooth enamel are introduced, followed by a discussion of the geology and strontium isotope landscape of the Harappa and Ur regions. Results of the isotopic analyses are presented in some detail and evaluated in terms of the question of human movement between Ur and Harappa.

2. Harappa and the Indus Civilization

The site of Harappa is located along the Ravi River, in Punjab Pakistan, and is one of the largest cities of the Indus Civilization (Fig. 2). Numerous excavations have been undertaken to document its chronology and character (Vats, 1940; Dales and Kenoyer, 1993; Meadow and Kenoyer, 1993, 1994, 2001, 2005, 2008; Kenoyer and Meadow, 1999). The chronology for the site is outlined in Table 1. Around 3700 BC a small agro-pastoral settlement with craft workshops for stone bead making and other crafts was established on high ground at the edge of the Ravi floodplain (Kenoyer and Meadow, 2000). For the next 1000 years this settlement gradually expanded and was eventually reorganized into an urban center with two walled sectors that covered ca. 27 ha (Kenoyer, 1991). From 2600 to 1900 BC the city of Harappa flourished as one of the major urban centers of the Indus Tradition (Kenoyer, 2008b).

During the Harappa Phase, the city reached its largest extent of more than 150 ha, with multiple walled sectors, gateways, drains, wells, fired brick buildings and an extensive cemetery located to the south of one of the major mounds. The final phase of the prehistoric occupation dates from 1900 to 1700 BC at Harappa, and a second

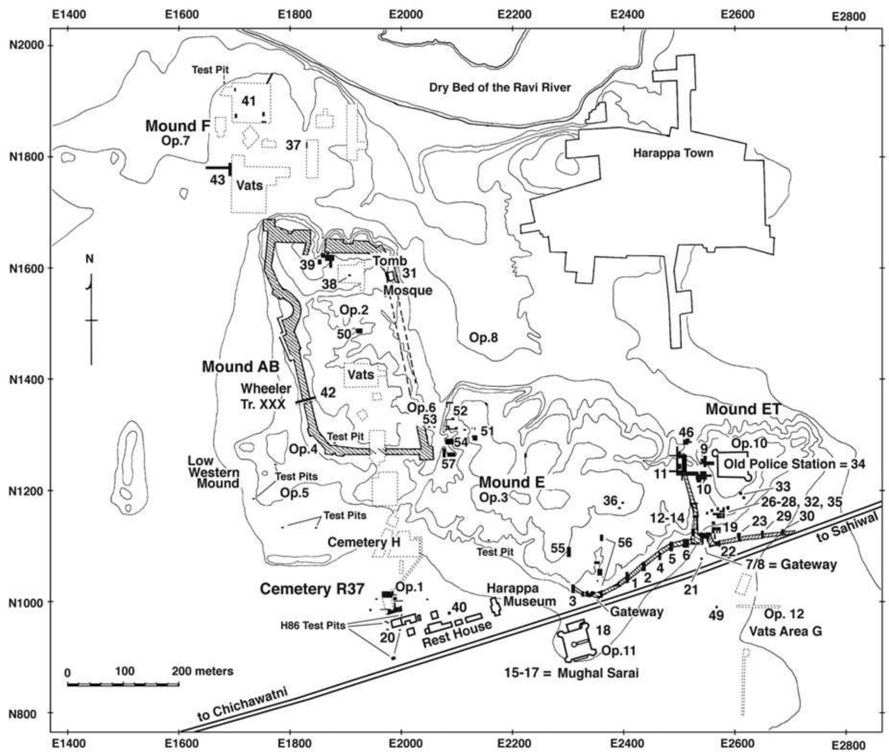

Fig. 2. Plan of the ancient city of Harappa.

major cemetery associated with this time period overlapped parts of the earlier cemetery. The site continued to be occupied in later historical periods and one-third of the ancient mound is still covered by the modern city of Harappa.

Harappa was connected to distant resource areas for the procurement of a variety of raw materials including marine resources, wood, stone, and metal raw materials throughout its prehistoric period. These materials were brought to the site and processed into various utilitarian and prestige objects for local use, as well as for regional and extra-regional trade. Beginning as early as the Ravi Phase, circa 3700 BC, there is evidence for trade with the coastal regions some 800–900 km to the south, as well as parts of Afghanistan, Baluchistan, and the Himalayas, some 300–1000 km to the west and north (Kenoyer, 1998; Law, 2006). Other trade networks for rocks and minerals extended to the east and southeast (Law, 2008). The majority of rocks and metals were procured from the northern and western regions, but as the city grew, and particularly during the height of the Indus civilization, more materials were procured from the south and southeast (Law, 2008). Throughout its long history, there must have been movements of traders to and from Harappa, bringing to the city not only raw materials, but also people from different geographical regions.

During the height of urbanism (2600–1900 BC), Harappa would have included many different classes of people, some with local roots and others with links to nearby towns as well as distant cities and resource areas. In terms of overall population the cities such as Harappa and Mohenjo-daro may have held between 40,000 and 80,000 people (Fairservis, 1979; Kenoyer, 1998). So far, no cemetery has been discovered at Mohenjo-daro and the Harappa cemetery dating to the Harappa Phase is relatively small and probably represents only one of the communities living in the city. Analysis of the pottery and other artifacts suggests that this cemetery represents one of the elite groups of Harappa, and does not represent the overall population of the site (Kenoyer, 1998). Most inhabitants of the city were probably not buried and their bodies were disposed of in other ways, i.e., water burial, exposure, or cremation (Kenoyer, 2006).

Table 1
Indus tradition chronology at Harappa.

Localization Era	
Late Harappan Phase	ca. 1900–1300 BC.
Harappa: periods 4 and 5	1900–1700 BC.
Integration Era	
Harappan Phase	2600–1900 BC.
Harappa: period 3C, final	2200–1900 BC.
Harappa: period 3B, middle	2450–2200 BC.
Harappa: period 3A, initial	2600–2450 BC.
Regionalization Era	
Early Harappan (several Phases)	ca. 5500–2600 BC.
Harappa: period 2, Kot Diji Phase	2800–2600 BC.
Harappa: period 1, A & B, Ravi/Hakra Phase	>3700–2800 BC.

3. Harappa Cemetery

The cemetery at Harappa is one of the most extensively excavated cemeteries of the Harappa Phase. It was discovered by K. N. Sastri in 1937 (Vats, 1940; Sastri, 1965). Subsequent excavations by Sir Mortimer Wheeler (Wheeler, 1947) and Dr. M. Rafique Mughal (Mughal, 1968) sorted out some of the chronological aspects of the cemetery. The most extensive excavations were carried out by the Harappa Project in 1986–1988 (Dales and Kenoyer, 1989, 1991), and 1994 (Meadow and Kenoyer, 1994). The comprehensive analysis of the stratigraphy, artifacts and human remains has now been completed and the final publication of the excavations is in progress. For the purposes of this paper, only a brief summary of the cemetery will be presented to provide a context for the specific focus of this study.

The Harappa Phase cemetery extends over an area of 0.8–1.2 ha, located to the south of Mound AB and southwest of Mound E

(Fig. 3a and b). The area is between 100 and 150 m east–west and around 80 m north–south, but the highest concentration of burials is located in on a natural ridge in the center of this area that is approximately 60 × 80 m (0.48 ha). The total number of individuals in the cemetery is difficult to calculate due to disturbances and the different methods of recording used over the many years of excavation. However, based on the published reports and the current studies conducted by the Harappa Project (Lovell and Kennedy,

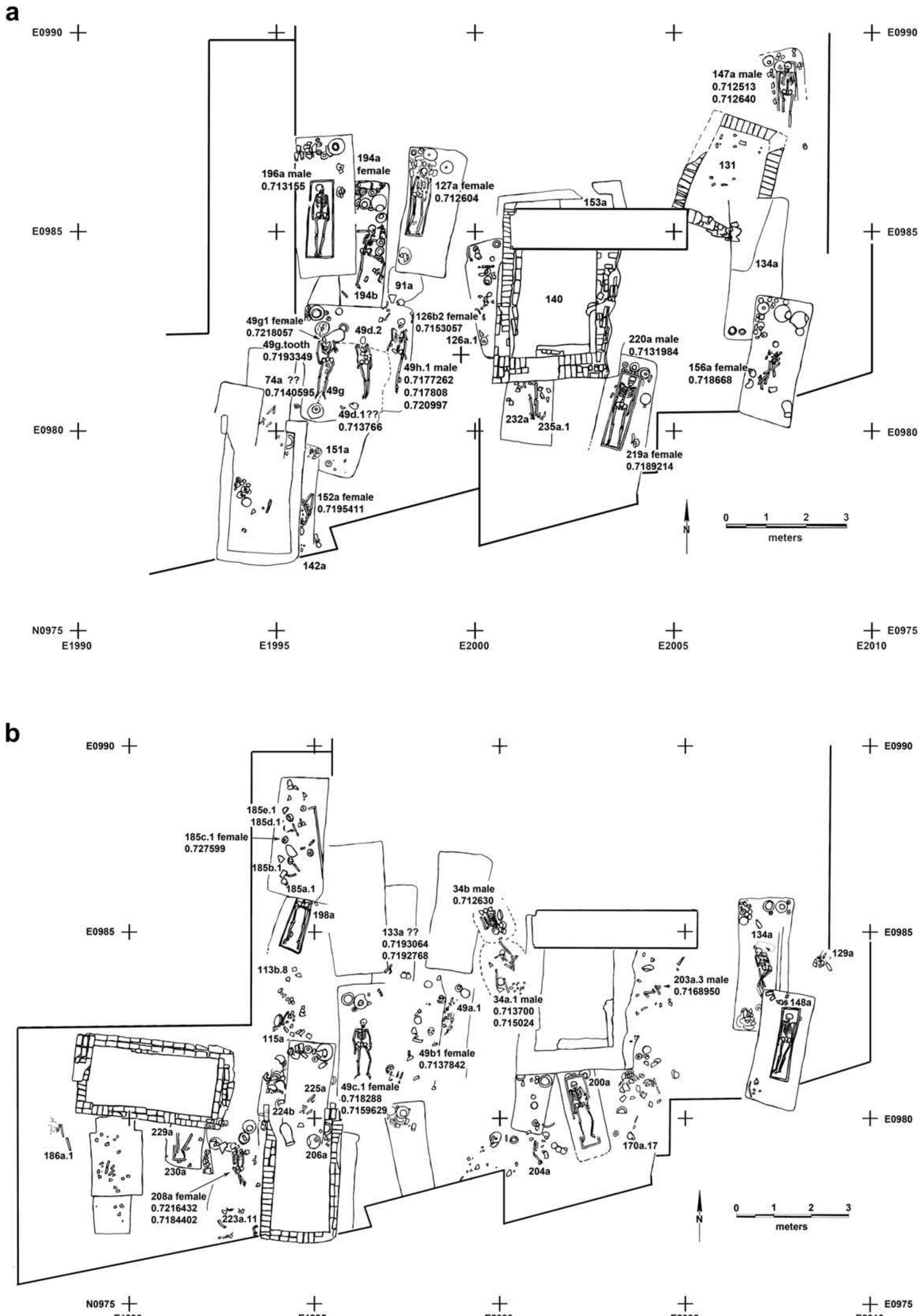

Fig. 3. a). Harappa Cemetery – Upper Levels. b). Harappa Cemetery – Lower Levels.

1989; Hemphill et al., 1991; Kennedy, 2002) there are around 145 complete/partial burials, including individual isolated crania (Fig.). But other concentrations of bone and unexcavated burials would bring the total to around 260. This number of burials can only reflect a very small proportion of the overall population of the ancient city and since no other cemeteries have been found, we can assume that most of the dead were disposed using other methods (Kenoyer, 1998: 122). The chronology of the cemetery is based on a combination of artifact studies and radiocarbon dates of charcoal found in undisturbed contexts. No dates could be obtained from the bones due to the absence of collagen, but indirect relative dating has been possible using charcoal found beneath specific burials. The earliest burials date to around 2550 cal BC and the final burials took place around 2030 cal BC (Meadow and Kenoyer, 1994).

4. Ur and the Royal Cemetery

The ancient city of Ur, also known as Tell al-Muqayyar, is located in southern Mesopotamia. The site has been the focus of numerous excavations, but the most extensive and systematic work was carried out for thirteen years by Sir Leonard Woolley in the 1920–30s (Woolley, 1934). This large site covers around 96 ha, with multiple mounded areas reaching 20 m above the surrounding plain. The city is made up of different sectors, including several ritual centers with temples and ziggurats, palaces, and residential quarters. A massive wall was built around the site with harbors located to the north and west, connecting the city to the Euphrates (Woolley, 1955). Although this was not the largest city of southern Mesopotamia, it would have been an important center of trade, politically dominating the surrounding region (Stone, 1997).

The chronology of the city is based primarily on the relative dating of pottery and other artifact styles in conjunction with Mesopotamian list of Kings. The lowest levels of the site date from the Ubaid Period (5900–3500 BC). Burials dating to the Jemdet Nasr Period (3100–2900 BC) were found in the lowest levels of the Royal Cemetery (Zettler, 1998a). The city continued to flourish throughout the Early Dynastic period (2900–2334 BC), the Akkadian period (2334–2150 BC), Third Dynasty of Ur (2112–2047 BC), the Isin-Larsa Dynasties (2000–1792 BC) and into later periods that are not relevant for this paper (Zettler, 1998b).

The Royal Cemetery was excavated by Woolley between 1926 and 1931 (Woolley, 1934; Zettler and Horne, 1998). Around 2100 burials were recovered in an area of approximately 70 × 55 m (Fig. 4), although Woolley estimated that there may have been up to three times as many burials originally (Zettler, 1998d: 21). Woolley reported 660 burials associated with what he termed the Early

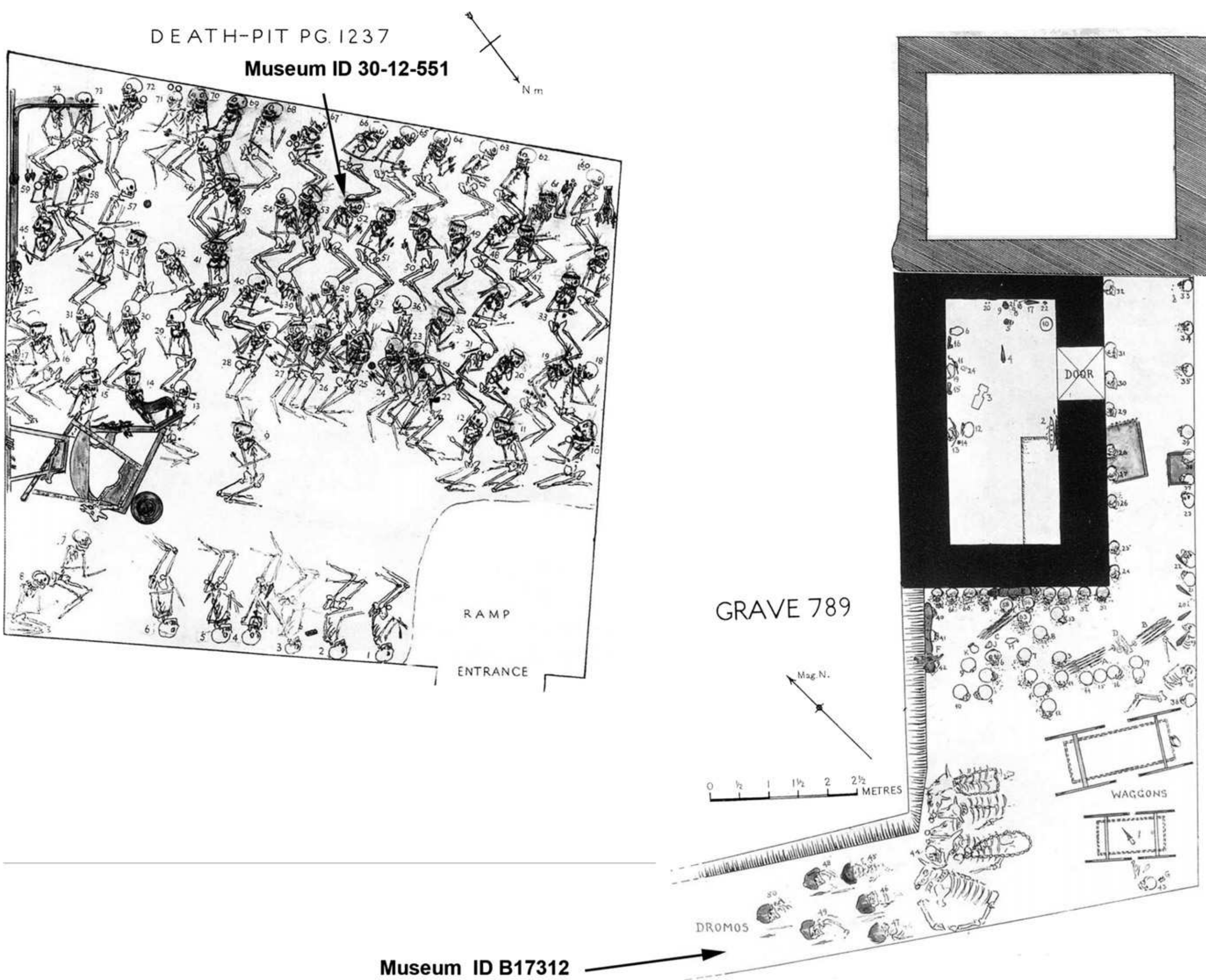

Fig. 4. Ur Cemetery and Burials.

Dynastic period, and 16 of these were much more elaborate in terms of burial goods and architecture (Zettler, 1998b). This cemetery included burials of both ruling elites and other individuals who were scattered among the larger royal tombs (Zettler, 1998a, 1998b). There were 16 elite burials, usually with rooms for the royal individuals and associated grave pits with large numbers of sacrificed retainers. Analysis of these sacrificial burials suggests that they were killed by blunt force and that their bodies were treated by heating or the application of mercury to preserved them before they were placed in the grave pit (Baadsgaard et al., 2011).

The burial goods are of great interest. Although most of the objects and the nature of the burials are distinctively Mesopotamian, there are many non-local objects found in the cemetery that indicate contact with the Indus valley and the Gulf region to the east. These include a circular Gulf style stamp seal with Indus style script, carnelian beads and shell cylinder seals that appear to have been made from the Indus shell species *Turbinella pyrum* (Potts, 1997; Kenoyer, 2008a). Later burials from the Akkadian period were also recovered and many of these burials also included long carnelian biconical beads and some green and red spotted bloodstone beads that were probably from the Indus valley region as well.

A comprehensive study of the buried objects and associated burials from the Royal Cemetery is needed to better understand the materials present with the burials, as well as to determine if people from regions other than southern Mesopotamia were buried in the cemetery. Unfortunately, out of all the skeletons uncovered, only "four of the better-preserved skulls well provided with ornaments were waxed together with all the beads, hair-ribbons, etc." (Woolley, 1934: 121). Of these four examples, two appear to have only contained jewelry (Irving and Ambers, 2002: 110–111). One is preserved at the University of Pennsylvania Museum (Zettler, 1998c). Another waxed skull from Body 53 is currently on display at the British Museum (Museum no. 122294 and 1929, 1017.106) (Molleson and Hodgson, 2003: 93, Fig. 16). It is presumed that the other two waxed skulls (from bodies 19 and 48) are in the Baghdad Museum. Additional fragmentary skeletal remains were collected, but how many is not known, nor where they are curated.

For this preliminary study, two individuals from the Ur collections at the University of Pennsylvania Museum were sampled to see if it would be possible to distinguish these individuals from persons from the Indus valley (Fig. 5). Although we would have liked to sample more individuals, it was only possible to obtain two samples from Ur for this preliminary study. The description of each sample is given below. Eventually a long-term collaborative project could be undertaken to collect data on skeletons that are still preserved and properly documented.

4.1. Penn museum object ID 30-12-551 (field no. U 12380)

This object is the skull of a female found in the grave PG 1237, known as the "Great Death Pit", a large pit containing 74 sacrificial victims, mostly elaborately dressed young women. This skull together with the ornaments found on it was removed as a whole, according to Woolley so as to "preserve the remains of the skull and all the visible ornaments in their position as found," for purposes of further study and museum display (Letter of Correspondence, December 25, 1928).

Found on the skull was a silver comb with three inlaid flowers (only one preserved), gold ribbon, two gold rosettes, a wreath of gold foil poplar leaves and lapis and carnelian beads, large, double lunate gold earrings, and two necklaces of gold and lapis beads.

Her third molars (wisdom teeth) are fully erupted, but not worn, suggesting the woman was perhaps in her late teens or early twenties at death. Based on comparisons between the ornaments found on the skull and descriptions in the field notes, this head appears to belong to Body 52 from the Great Death Pit, one of four heads that were preserved using wax to hold the many fragmentary bones, tiny beads, and other artifacts in place.

4.2. Penn museum object ID B17312 (no field number)

This object consists of a skull of a male smashed flat and waxed together with the remains of a copper helmet that was placed on the head (backwards) after the death of the individual. This skull is from the death pit attached to the King's Grave (PG 789) and is presumed to be one of six soldiers whose bodies were placed at the entrance of the death pit.

It was not possible to obtain animal teeth from the excavations at Ur for baseline isotope information. Animal teeth from the site of Maskhan Shapir were used to obtain an example of the local strontium signature. Maskhan Shapir is located on the Tigris River, some 35 km north of the ancient city of Nippur and around 180 km northwest of the site of Ur (Stone and Zimansky, 1994; Stone, 2008). This ancient settlement is roughly contemporary with the Royal Cemetery of Ur. Due to the fact that both the Tigris and the Euphrates Rivers derive from similar hinterlands and the geological sediments that the rivers flow through are homogenous, the strontium signature of the animal teeth from Mashkan Shapir should provide a comparable value for local people living in the alluvial plains of southern Mesopotamia.

5. Oxygen isotope analysis

Oxygen has three isotopes – ^{16}O (99.762%), ^{17}O (0.038%), ^{18}O (0.2%) – all of which are stable and non-radiogenic. The oxygen isotope ratio in the skeleton reflects that of body water, and ultimately of drinking water (Kohn, 1996; Luz et al., 1984; Luz and Kolodny, 1985). Isotopes in rainfall vary primarily with temperature and latitude. Rain that falls in warm areas close to the sea has a high oxygen isotope ratio, while rain that falls more inland and at higher elevations and latitudes has a lower ratio. The hydroxyapatite mineral contains oxygen in both phosphate groups (PO_4) and carbonates (CO_3). Phosphate and carbonate produce similar results, but less sample is needed for carbonate, preparation is less demanding, and results between laboratories are more comparable. Oxygen isotope measurements are reported as a ratio of ^{18}O to ^{16}O. This ratio ($\delta^{18}O$) is reported relative to a standard, and expressed in parts per thousand (per mil, ‰). Oxygen isotopes are commonly reported as the per mil difference (‰ or parts per thousand) in $^{18}O/^{16}O$ between a sample and a standard.

Oxygen isotopes enter the body in drinking water, which comes primarily from rainfall. Oxygen isotopes in ancient human skeletal remains are found in both tooth enamel and bone. Oxygen is incorporated into dental enamel during the early life of an individual and the $\delta^{18}O$ ratio remains unchanged through adulthood. Samples for the analysis of human skeletal remains are normally taken from dental enamel due to better preservation and resistance to diagenesis. Oxygen isotopes are also present in bone apatite and are exchanged through the life of the individual during bone turnover, thus reflecting place of residence in the later years of life. Thus, oxygen isotopes have the potential to be used to investigate human mobility and provenience (Bowen et al., 2005).

Oxygen, in this application, will likely be of little utility compared to strontium. Both Ur and Harappa are at similar latitude and elevation and have similar estimates for their annually averaged rainfall. Oxygen isotopes in precipitation are being determined at

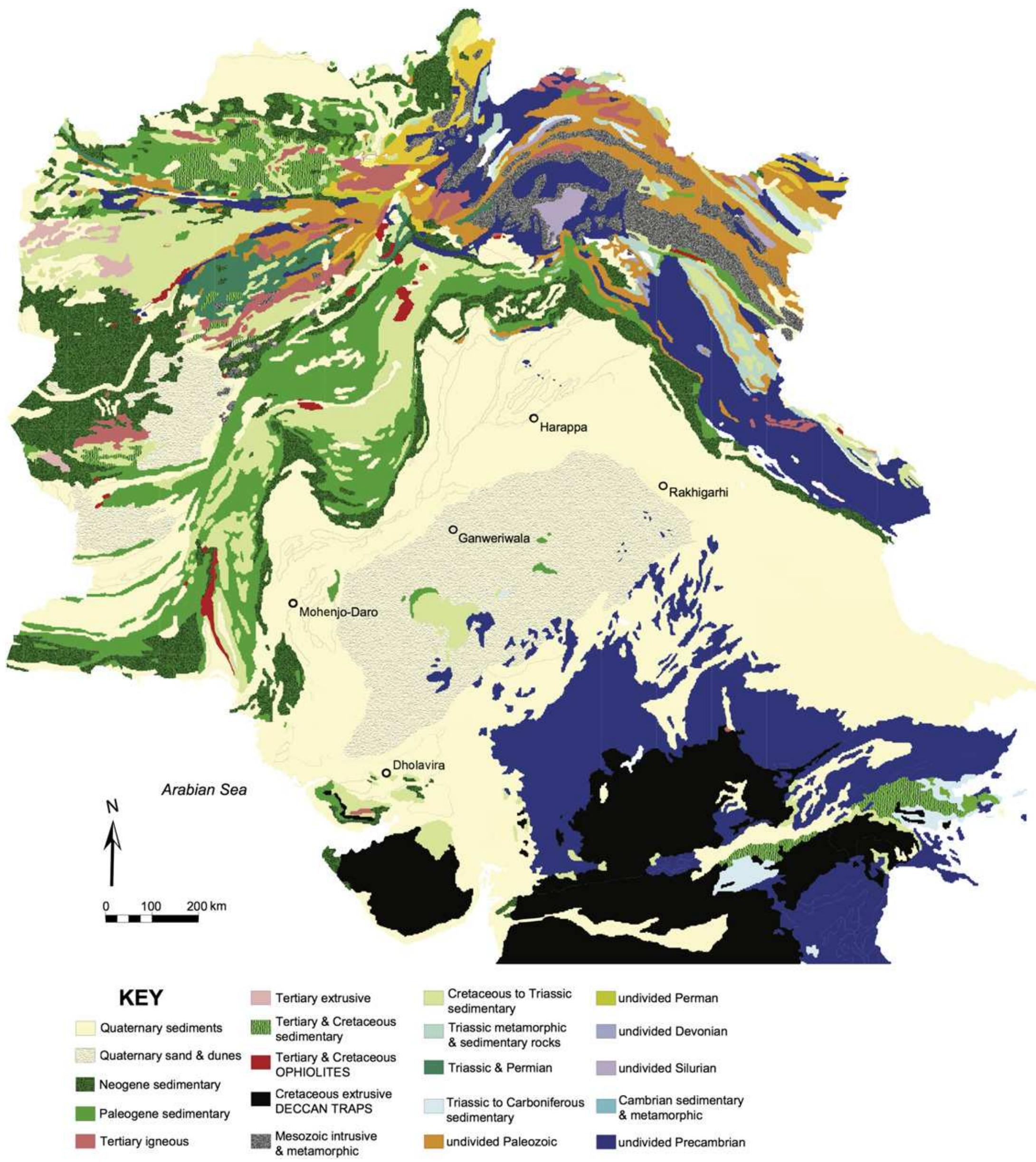

Fig. 5. Geological map of the Indus River Valley and surrounding regions. (Law, 2011: Fig. 2.2).

a large number of stations worldwide so that it is now possible to assess by extrapolation from these stations the annually averaged $\delta^{18}O_{VSMOW}$ for most locations (Bowen and Revenaugh, 2003; Bowen, 2012), yielding $\delta^{18}O$ ratios of -3.9 ± 1.0 for Ur and -4.6 ± 0.5 for Harappa. Using the relationship established by Chenery et al. (2012) between drinking water $\delta^{18}O$ and apatite carbonate $\delta^{18}O$ of $\delta^{18}O_{Carbonate} = (\delta^{18}O_{DW} + 48.634)/1.59$ SMOW and converting between the PDB and SMOW standards: $\delta^{18}O_{C(VPDB)} = (0.97 \times \delta^{18}O_{C(SMOW)}) - 29.98$, estimated precipitation values would produce enamel $\delta^{18}O_{Carbonate(PDB)}$ values of -2.7‰ at Ur and -3.1 at Harappa – a difference too small to detect given a typical 2‰ range for local populations.

6. Carbon isotope analysis

Measurement of the stable isotopes of carbon in bone collagen is standard archaeological practice in the study of past human diet. This analysis provides a direct index of long-term average diet and of certain dietary patterns. Values are reported as $\delta^{13}C$, the ratio of carbon 13 to carbon 12, standardized to a reference material. Collagen carbon is largely produced from ingested protein so that a somewhat biased view of diet is provided. Carbohydrates are not well represented in the collagen.

We have measured carbon isotope ratios ($\delta^{13}C_{en}$) in tooth enamel. This tissue provides different information on diet than bone collagen. First, tooth enamel – and the carbonate and phosphate minerals where carbon is bound – forms during childhood. Bone collagen provides a record of adult diet; tooth enamel is a record of the diet of early childhood. Second, the carbon in enamel apatite (the carbonate mineral that makes up dental enamel) appears to come from dietary energy sources (Krueger and Sullivan, 1984). Experimental studies have shown that apatite carbon more accurately reflected the isotopic composition of the total diet (e.g., Ambrose and Norr, 1993). Although there are potential problems with contamination in apatite, this carbon isotope ratio can provide substantial insight on past diet.

7. Strontium isotope analysis

Isotope ratios of several different elements have been investigated as possible indicators of movement of prehistoric peoples (Katzenberg and Krause, 1989). Of these strontium appears to be the most reliable. Numerous studies have documented its utility in various time periods and places (Price et al., 1994; Sealy et al., 1995; Budd et al., 1999; Price et al., 2000).

The principles are straightforward and involve the passage of strontium from the earth into plants and animals and human tissue. The method uses the ratio of the isotopes of strontium 87 to strontium 86. Radiogenic ^{87}Sr is formed in rock over time by the decay of rubidium (^{87}Rb, half-life $\sim 4.7 \times 10^{10}$ years) and comprises approximately 7.0% of total natural strontium. The other naturally occurring isotopes of strontium are nonradiogenic and include ^{84}Sr ($\sim$0.56%), ^{86}Sr ($\sim$9.87%), and ^{88}Sr ($\sim$82.5%). Strontium isotope ratios in the earth's crust vary with the age and type of rock. Geologists have employed this principle for some time in measuring the strontium isotope composition of bedrock and determine the age of various formations through the proportion of ^{87}Rb that has decayed.

Strontium isotope composition in natural materials is conventionally expressed as a ratio ($^{87}Sr/^{86}Sr$), which varies among geologic terrains as a function of relative abundances of rubidium and strontium and the age of the rocks. Ratios of $^{87}Sr/^{86}Sr$ generally range between 0.700 and 0.750. Geologic units that are very old (>100 mya) and had very high original Rb/Sr ratios will have very high $^{87}Sr/^{86}Sr$ ratios. In contrast, rocks that are geologically young (<1–10 mya) and that have low Rb/Sr ratios, such as late-Cenozoic volcanic fields, generally have $^{87}Sr/^{86}Sr$ ratios less than 0.706 (e.g., Rogers and Hawkesworth, 1989). Rocks that had very low initial Rb/Sr ratios, such as basalt, can have $^{87}Sr/^{86}Sr$ ratios ca. 0.704. These variations may seem small, but they are exceptionally large from an instrumental standpoint and far in excess of analytical error.

Measured in human bones and teeth, these ratios can serve as tracers of the geology of the areas where individuals grew up and where they died, respectively, because consumed strontium is incorporated into the skeleton during bone formation and remodeling. Strontium in bedrock moves into soil and ground water and into the food chain. The strontium isotope compositions of plant tissues and the bones and teeth of animals and humans thus match those of the nutritional intake of the individuals, which in turn reflect the strontium isotope composition of the local geology.

Bone undergoes continual replacement of its inorganic phase, so that measurements of bone strontium reflect the later years of the life of the individual. Tooth enamel, on the other hand, forms during childhood and undergoes little change. Differences in strontium isotope ratios between bone and tooth enamel in a single individual thus reflect changes in the residence history of that person.

Our methods require one tooth from each individual (preferably a premolar, either upper or lower but any tooth except the third molar will do if a premolar is not available). The analysis is destructive, but only a very small amount of material is required. For the tooth, we remove a small portion of the enamel from a molar, ca. 5 mg. In addition, we need samples of modern or archaeological fauna from the place of interest in order to establish the local strontium isotope ratio to compare to the enamel values.

Tooth samples are mechanically abraded with a Patterson dental drill fitted with a fine burr bit to remove any visible dirt, contamination, and/or preservative and then drilled to remove the enamel layer from the underlying dentine. Tooth enamel powder is then digested in ultrapure 3-M nitric acid. Strontium is isolated using cation exchange chromatography with Eichrom Sr-specific resin and nitric acid as the mobile phase. The sample $^{87}Sr/^{86}Sr$ ratios were measured on a Nu Plasma HR, which is a high-resolution multi-collector, double-focusing, plasma-source mass spectrometer (MC-ICP-MS) at the University of Illinois-Urbana-Champaign. Adjustments are made for isobaric Rb and Kr. Standard deviation for each analysis is normally less than $\pm$0.00001.

8. Geology and strontium isotope ratios in the Indus and Mesopotamian regions

In order to evaluate variation in strontium isotope ratios in the Indus and Mesopotamian regions it is necessary to review the geology of the areas and assess the potential for isotopic differences both between and within these regions.

8.1. Indus Basin

The Indus River Basin spans approximately three thousand km between the Salt Range in the Punjab of Pakistan and the coast of the Arabian Sea. Ranging from 50 to 300 km in width, it encompasses much of modern Pakistan. The basin consists of Tertiary and Quaternary alluvium deposited by the Indus River and its tributaries (Fig. 5). Harappa is located on the Ravi River, one of the four Punjab tributaries. The geology of the surrounding regions is highly complex and spans a large range of $^{87}Sr/^{86}Sr$ values (0.708–0.822). The strontium isotope systematics for the Indus River Basin have been extensively detailed by Karim (1998) and Karim and Veizer (2000). Karim was able to differentiate alluvial sources into three isotopically distinct terranes: (1) to the north/northeast, the highly radiogenic crystalline rocks of the Higher Himalayas (0.82–0.89), (2) to the north/northwest, young volcanic and ultramafic rocks of the Kohistan-Ladakh arc (0.7037–0.7068), and (3) to the west, the high strontium, but less radiogenic sedimentary rocks of the West Pakistan Fold Belt (0.710–0.712).

The main Indus channel varies from relatively low $^{87}Sr/^{86}Sr$ sediments in the north (0.709), reflecting proximity to the Kohistan-Ladakh arc, to 0.711–0.712 in the Middle and Lower Indus, reflecting the large strontium input from the western carbonate rocks (Palmer and Edmond, 1992). At the mouth of the Indus, Karim provides a weighted average of 0.7118 – quite close to earlier assessments of Indus sediments (0.7112, Goldstein and Jacobsen, 1987; 0.7111, Pande et al., 1994). The four Punjab tributaries, lying east of the main Indus channel, are more influenced by proximity to the Himalayas and accordingly have higher $^{87}Sr/^{86}Sr$ ratios, with the Ravi channel, where Harappa is sited, being the most radiogenic (0.7291) and the Jhelum, the westernmost of the four, being the least (0.7127). Although the geologic data allow neither geographic nor isotopic precision, we can surmise $^{87}Sr/^{86}Sr$ ratios of approximately 0.72 in the vicinity of Harappa and 0.71+ for most of the rest of the Indus River Basin, with higher ratios to the northeast than the south.

8.2. Mesopotamia

Ur and Maskhan Shapir are also located in the huge, broad alluvial basin of the Tigris–Euphrates rivers. The Tigris receives sediments from the Zagros and the load of the Euphrates comes from the sediments of the Arabian Shield. No $^{87}Sr/^{86}Sr$ data is available from these source regions. Both Ur and Maskhan Shapir are located in the lower portion of the Mesopotamian basin which was earlier a zone of shallow, saline lakes, and which is probably highly homogeneous isotopically, although there are no known published geologic data regarding local isotopic values. We do however have a few clues as to the approximate $^{87}Sr/^{86}Sr$ ratio. Cullen et al. (2000) assessed a general ratio for Mesopotamia from measurements of Iraqi dust at 0.708–0.709. A better assessment of biologically available, but non-provenienced, strontium ratios can be gleaned from studies of early Mesopotamian glass. Chemical studies of these glasses from the Mesopotamian sites of Nuzi and Brak (Henderson et al., 2010; Degryse et al., 2010) reveal the use of low-strontium quartz-rich sands fluxed with high-strontium plant ashes, with the $^{87}Sr/^{86}Sr$ ratio of the glass reflecting that of the plant ash. We use this as a proxy for biologically available "Mesopotamian" $^{87}Sr/^{86}Sr$. This may be fraught with error, but the ratios are in agreement with those deduced by Cullen and others, i.e., 0.7081–0.7082 (Brak) and 0.7084 to 0.7085 (Nuzi), and in agreement with our own faunal measurements, all of which are quite distinct from the much higher Indus Basin ratios.

Samples of both human tooth enamel and archaeological fauna were measured for this study (Table 2). Three sheep teeth from the site of Mashkan-Shapir, approximately 180 km NNW of the site of Ur, were used to estimate the local strontium isotope ratio for this part of Mesopotamia (Stone and Zimansky, 1994, 2004). An average value of 0.7080 ± 0.0001 provides this estimate.

Nine teeth from three cows, three ovi/caprids, and three pigs from the site of Harappa were used to obtain the local signal for the site itself. The average value of these teeth was 0.7178 ± 0.0011, with a minimum of 0.7158 and a maximum value of 0.7189. This range will be used as the baseline bioavailable values for Harappa. Some of these animals may have been imported, but the relatively narrow range of values will be used to estimate the strontium isotope ratios around the site itself.

Each of these faunal sets has very low variability as can be seen in the graph below (Fig. 6). Both regions, Mesopotamia and the

Table 2
Human and faunal samples from Harappa and Ur.

Lab no.	Site	Species	Context	Tooth	$^{87}Sr/^{86}Sr$	$\delta^{13}C$	$\delta^{18}O$
F3926	Harappa	Bos	H2000/9441 #1		0.7158		
F3924	Harappa	Bos	H2000/8988 #1		0.7167		
F3918	Harappa	o/c	H2000/8990 #1		0.7168		
F3920	Harappa	o/c	H2000/9445 #1		0.7175		
F3925	Harappa	Bos	H2000/8997 #19		0.7183		
F3919	Harappa	o/c	H2000/9439 #1		0.7183		
F3923	Harappa	Sus	H2000/8990 #2		0.7187		
F3921	Harappa	Sus	H2000/8990 #3		0.7187		
F3922	Harappa	Sus	H2000/9451 #1		0.7189		
F4928	Harappa	Human	H94/253 18	LLM2	0.7124	−14.0	−7.8
F4912	Harappa	Human	H88/439 4b	LLM2	0.7124	−12.3	−5.9
F4915	Harappa	Human	H88/130 147a	LLM2	0.7125	−12.3	−6.0
F4914	Harappa	Human	H88/114 127a	LLM1	0.7126	−12.3	−5.2
F4899	Harappa	Human	H87/40-89 34b.1	LRM1	0.7126	−11.2	−2.8
F3930	Harappa	Human	H87/136 147a	LM3	0.7126		
F4927	Harappa	Human	H94/253 18	LLM1	0.7127	−12.5	−4.0
F4913	Harappa	Human	H88/439 4a	LRM1	0.7131	−13.0	−4.9
F4922	Harappa	Human	H88/194 196a	LLM2	0.7132	−11.4	−4.9
F4926	Harappa	Human	H88/217 220a	LLM2	0.7132	−11.7	−6.1
F4909	Harappa	Human	H87/116 128a	LLM1	0.7135		
F4907	Harappa	Human	H87/40 34a.2	LRM1	0.7137	−12.9	−3.5
F4906	Harappa	Human	H87/85 49d.1	LM	0.7138	−12.5	−4.6
F4898	Harappa	Human	H87/72 49b	URM1	0.7138	−12.7	−4.8
F4905	Harappa	Human	H87/85 74a	LRM2	0.7141	−12.6	−5.6
F4929	Harappa	Human	H94/250 17	LRM1	0.7147	−12.8	−4.6
F4896	Harappa	Human	H87/25 18A	LLM1	0.7148	−11.7	−5.4
F4897	Harappa	Human	H87/40 34A	LLM2	0.7150	−12.3	−5.1
F4930	Harappa	Human	H94/245 7	LLM1	0.7151	−12.6	−4.9
F4918	Harappa	Human	H88/174 126b.2	URM1	0.7153	−11.8	−5.3
F4901	Harappa	Human	H87/71 49c	LM1	0.7160	−11.8	−6.0
F4931	Harappa	Human	H94/243 27	LLM2	0.7161	−12.3	−3.8
F4908	Harappa	Human	H87/200 203a	LRM2	0.7169	−9.8	−4.5
F3927	Harappa	Human	H88/161 170	LM2	0.7169		
F4902	Harappa	Human	H87/85 49h	LRM2	0.7177	−11.4	−5.1
F3931	Harappa	Human	H87/72 49h	RM3	0.7178		
F4900	Harappa	Human	H87/71 49c	LM3	0.7183		
F4924	Harappa	Human	H88/206 208a	LM	0.7184	−11.3	−3.9
F3928	Harappa	Human	H88/185 186		0.7185		
F4911	Harappa	Human	H87/145 156a	LLM1	0.7187	−10.8	−4.2
F4925	Harappa	Human	H88/216 219a	ULM1	0.7189	−8.7	−4.1
F4916	Harappa	Human	H88/173 133a.10	LRm2	0.7193	−11.2	−4.6
F4917	Harappa	Human	H88/173 133a.10	LLM2	0.7193	−11.1	−5.4
F4903	Harappa	Human	H87/85 49g	LLM2	0.7193	−10.9	−4.0
F4910	Harappa	Human	H87/141 152a	ULM1	0.7195	−12.5	−4.2
F3932	Harappa	Human	H87/72 49h		0.7210		
F3929	Harappa	Human	H88/162 121		0.7212		
F4923	Harappa	Human	H88/206 208a	UM	0.7216	−11.6	−4.7
F4904	Harappa	Human	H87/85 49g		0.7218	−12.1	−4.3
F4921	Harappa	Human	H88/191 185c.1	URM2	0.7276	−11.4	−4.0
F3075	Mashkan-Shapir	Ovid				0.7080	
F3076	Mashkan-Shapir	Ovid				0.7080	
F3077	Mashkan-Shapir	Ovid				0.7080	
F4894	Ur	Human	30-12-551		0.7080	−10.6	−4.0
F4895	Ur	Human	B17312		0.7081	−12.9	−2.7

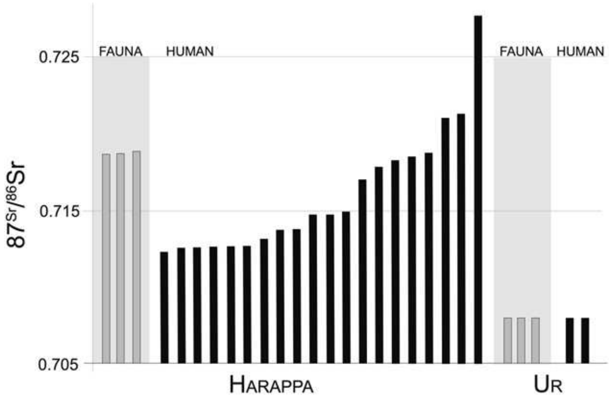

Fig. 6. Bar graph of Strontium Isotope Levels in ranked order for fauna and human tooth enamel from Harappa and Ur/Mesopotamia.

Indus Valley are very large, homogeneous alluvial plains. We expect that strontium isotope ratios will be similarly homogeneous across large parts of these regions.

9. Results of Harappa and Ur analyses

The measured $^{87}Sr/^{86}Sr$ values from Harappa and Ur are listed in Table 2 and presented in graphic form in Fig. 6. The values for each group of samples, fauna and human, Harappa and Ur, are presented in ranked order. The expected local value at Harappa is based the faunal samples as noted above, 0.7158–0.7189, and is indicated on the bar graph. The human remains from Harappa exhibit an unusual pattern of variability with values both above and below the expected local value. The mean value for enamel samples from 40 individuals buried at Harappa was 0.7164 ± 0.0035, with a minimum value of 0.7124 and a maximum value of 0.7276. The high standard deviation points to a variable population and suggests a number of non-local individuals.

The two samples of human remains from Ur have $^{87}Sr/^{86}Sr$ values very similar to the fauna from Mashkan Shapir and appear to be local to the area of southern Mesopotamia.

Another way to consider this data distribution is with a kernel density distribution plot that provides further information of the variation in the values (Fig. 7). Kernel density plots are a data smoothing technique for estimating the probability density function of a random variable (Wand and Jones, 1995). The most prominent mode in the kernel density plot is ca. 0.713. this mode contains the 12 lowest values in the Harappa dataset. There are three lesser modes in the graph to the right of the primary mode. The second node reflects the local inhabitants of the cemetery that fall within the local range of bioavailable $^{87}Sr/^{86}Sr$ as measured in the archaeological fauna. The third node represents the two high values above the local range and the last node in the plot is the single high value above 0.725.

Based on this distribution of values, it would appear from our preliminary analysis that almost half of the individuals sampled from the Harappa cemetery have isotope values outside the local baseline (0.7158–0.7189). Most of these individuals have values below the Harappa range. In addition, there are at least three non-local individuals with higher values, including one with an extremely isotope ratio that cannot be from the Harappa region. A more detailed discussion of the Harappa samples will be presented in a future publication on the Harappa cemetery, but it is clear that many of what appear to be local individuals at Harappa are females and they are associated in burial with nearby males who are clearly not local. These preliminary patterns require further testing before major conclusions can be proposed, but it does suggest that they represent a unique population of people from multiple regions of the Indus valley or beyond.

Carbon and oxygen isotopes provide a little more information. Carbon isotope ratios were measured on the apatite of 32 enamel samples and produced a mean value of $-11.9‰ \pm -4.8$ with a minimum value of $-14.0‰$ and a maximum value of $-8.7‰$. Oxygen isotope ratios were measured on the apatite of 32 enamel samples and produced a mean value of $-4.8‰ \pm -0.9$ with a minimum value of $-7.8‰$ and a maximum value of $-2.8‰$. The exact values are of less interest than the variation among the data.

A plot of oxygen isotope values versus strontium isotope ratios (Fig. 8) displays the two large groups of non-local and local individuals. The oxygen values among the lower $^{87}Sr/^{86}Sr$ value non-locals are more variable, reflecting their non-local origins. There are two outliers among the low non-locals that may have come from some significant distance to the site. The three individuals with values higher than the local strontium isotope range have rather average $\delta^{18}O$ values in the middle of the range.

A plot of $\delta^{18}O$ versus $\delta^{13}C$ is shown in Fig. 9 and in general terms appears as a rather random cluster of points, suggesting that rainfall isotope patterns and diet are not varying together. This generic scatter suggests that the parameters of diet and oxygen geography considered together are not particularly relevant for

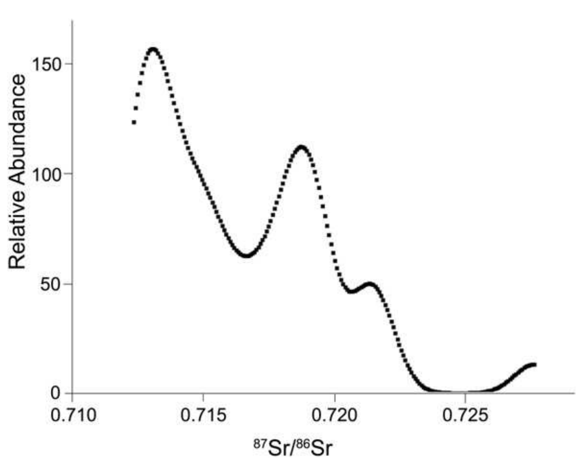

Fig. 7. Kernel density distribution plot of the $^{87}Sr/^{86}Sr$ values in human enamel at Harappa.

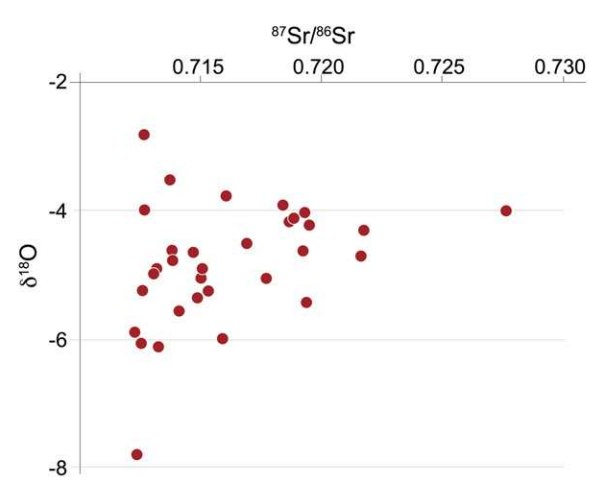

Fig. 8. Scatterplot of $^{87}Sr/^{86}Sr$ versus $\delta^{18}O$ in samples of human enamel from the Harappa cemetery.

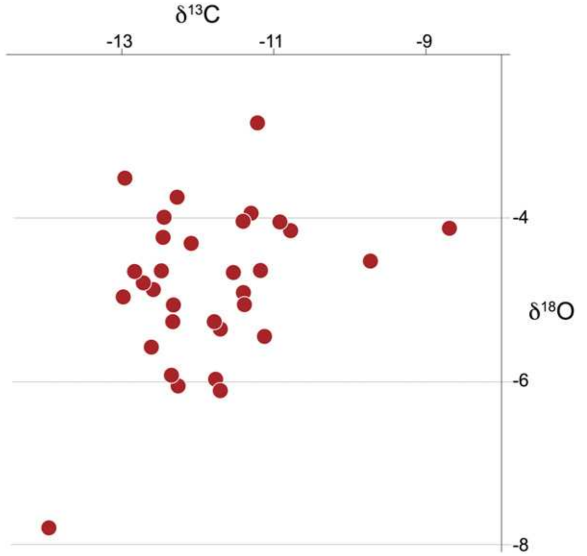

Fig. 9. Scatterplot of δ^{13}C versus δ^{18}O in samples of human enamel from the Harappa cemetery.

human proveniencing. There are several outliers in these plot that may prove to be individuals of interest on consideration of burial context, age, sex, or status.

10. Conclusions

Several insights are provided by the results of our preliminary study. 1. There is significant variation between Mesopotamia and the Indus Valley and non-local individuals from either area should be very visible in the enamel strontium isotope ratios. 2. There is substantial variation at the site of Harappa suggesting multiple homelands for the inhabitants of the city represented in the cemetery and the potential for a fascinating study of urban growth and development. 3. More samples are needed from the Royal Tomb at Ur to determine if Harappan-born individuals are present there. Our current sample of two human teeth from Ur is not sufficient to resolve this issue.

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