Pb Isotope Analysis of Lead, Silver and Copper Artifacts from Dholavira

R.S. Bisht[1], **Randall Law**[2], **Emily Peterman**[3] **and Virginie Renson**[4]

1. Dholavira Section, Purana Qila, Mathura Road, New Delhi – 110003, India (*Email: rsbishtarch@gmail.com*)
2. Department of Anthropology, University of Wisconsin-Madison, 1180 Observatory Drive, Madison, WI 53705, USA (*Email: rwlaw@wisc.edu*)
3. Earth and Oceanographic Science, Bowdoin College, 120A Druckenmiller Hall, Brunswick, ME 04011, USA
4. University of Missouri, Research Reactor Center, 1513 Research Park Drive, Columbia, MO 65211, USA

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***Abstract**: Thousands of metal artifacts have been recovered during excavations at the Indus Civilization city of Dholavira. For this study, 35 lead objects or lead ores, 14 silver items, and 16 copper objects or copper ores were selected from contexts representing all major areas of the site and most of its chronological stages. These were non-destructively sampled for lead atoms using an EDTA solution. The solutions were later subjected to lead isotope analysis. Using the results of those analyses, we can now begin to provisionally trace the networks through which the ancient residents of Dholavira acquired lead, silver and copper. The Ambaji-Deri area polymetallic deposits on the Gujarat-Rajasthan border and the Kanrach Valley deposits in southern Balochistan were found to be significant source areas. The results also suggest that some copper from the extensive occurrences in both northern Rajasthan and Oman was also utilized to some extent at Dholavira. Some lead may have come from distant deposits in western Balochistan and there are indications that minor sources like Khera Mawal in southern Rajasthan and Tosham Hill in Haryana may have been exploited for silver and/or lead.*

Keywords: Dholavira, Indus Civilization, Pb Isotope Analysis, Geologic Provenience, Lead, Copper, Silver

Introduction

Unlike the Indus Civilization urban centers of Mohenjo-daro, Ganweriwala, Harappa and Rakhigarhi – all of which are located on the stone and metal resource-deficient alluvial plains – the city of Dholavira was established in an area where rocks and minerals are abundant and varied. Sources of agate, carnelian, chalcedony, limestone, sandstone, basalt, gabbro, gypsum, calcite, amazonite and many other types of raw materials identified at the site (Law 2015) are found locally in Kachchh and/or in directly adjacent parts of Gujarat (Law 2013). Significantly, however, deposits of lead, silver and copper are lacking across the region. To obtain these metals the residents of Dholavira would have needed to look to the distant margins of Gujarat and beyond. Objects made from them are, therefore, among the best categories of artifacts with which to trace the city's long-distance resource acquisition networks. In this paper, we attempt to do just that by using lead isotope analysis to identify the geologic sources of lead, silver and copper objects from Dholavira.

Lead Isotope Analysis

Archaeologists have long employed lead isotope analysis in their efforts to identify the ore sources from which the processed metal used to create finished artifacts was derived (Gale 1989). There are four stable isotopes of the element lead (Pb) that vary in absolute amounts, depending on the geologic age of the deposit from which it comes and the conditions in which it mineralizes. These isotopes do not undergo physiochemical fractionation when a metal ore is smelted, re-melted and fashioned into a finished object. Thus, an artifact composed of metal derived from a single deposit will retain the original lead isotope composition of that deposit. In this way, a metal artifact can be matched to its raw material source. Although it is a problematic possibility that artifacts may contain lead derived from multiple sources, lead isotope data are, nonetheless, extremely useful for archaeological studies attempting artifact-to-ore source correlation. The key to success for such studies is having a reasonably comprehensive database of the Pb isotope characteristics of potential sources against which the isotopic values of metal artifacts can be compared. For northwestern South Asia, such a database has been compiled and published in Law 2011.

Non-destructive Sampling and Analysis of 65 Metal Artifacts from Dholavira Using EDTA

Thousands of metal artifacts have been recovered during excavations at Dholavira, the vast majority of which are composed of copper. From among these, 65 were selected for lead isotope analysis. Thirty-five are lead objects or lead ores, 14 are silver items, and 16 are copper objects or copper ores. The artifacts sampled came from all major areas of the site (Fig. 1) and from most of the chronological stages that have been defined there (Table 1).

The artifacts were sampled using a non-destructive method for extracting lead atoms from archaeological metals composed of lead (Law and Burton 2006), silver (Law and Burton 2008) or copper (Law 2011). This method involves briefly immersing artifacts in a solution composed of 99.95% ultra-pure water and 0.05% dissolved ethylene diamine tetra acetic acid (or EDTA), which is a safe, non-toxic substance that forms a chemical bond with lead atoms. The Dholavira artifacts were placed into a plastic sampling tray containing the EDTA solution for approximately five minutes, after which time they were removed, rinsed in distilled water, allowed to completely dry, and then returned to their place of storage. This short immersion time, which was enough to extract a minute amount of lead atoms (on the order of parts per billion) into the sampling solution, did no visible or microscopic harm to the artifacts whatsoever. The sample solutions were poured into polyethylene vials and returned to the United States for analysis on either a multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) or thermal ionization mass spectrometer (TIMS) – instruments that are sensitive enough to detect and quantify the extremely minute amount of lead extracted by the EDTA.

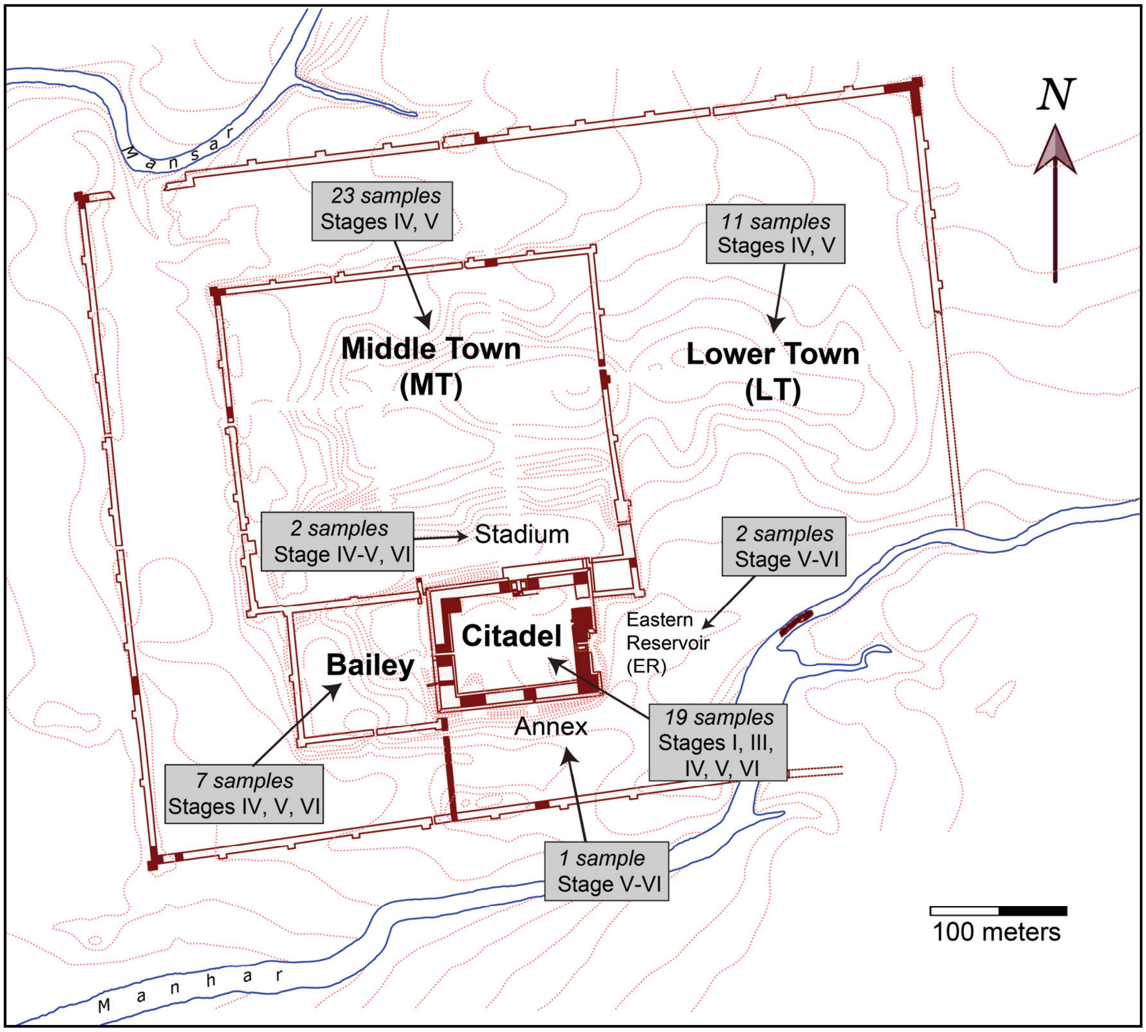

Figure 1: Dholavira site plan and area sampled for this study

Table 1: The Chronological Stages of Dholavira (after Bisht 2015: 104)

Stage I	Early Harappan (Dholavira culture)	c. 3000 – 2900 BCE
Stage II	Early Harappan (Dholavira culture)	c. 2900 – 2800 BCE
Stage III	Early Harappan (Dholavira culture)	c. 2800 – 2500 BCE
Stage IV	Mature Harappan	c. 2500 – 2100 BCE
Stage V	Mature Harappan	c. 2100 – 2000 BCE
Stage VI	Late Harappan	c. 1950 – 1800 BCE
Stage VII	Post-Harappan	c. 1500 – 1450 BCE

Lead isotope analyses were conducted on the Dholavira samples at multiple facilities. Forty-three of the samples were sent to the W.M. Keck Isotope Laboratory (UCSC). After being filtered, the EDTA samples were dried completely down, brought up again in 2% nitric acid and then analyzed on a ThermoFinnigan MC-ICP-MS. All analyses were corrected for mercury interferences and spiked with thallium to correct for mass bias. Twelve samples went to the Archaeometry Laboratory at the University of Missouri Research Reactor (MURR). Lead was extracted from the EDTA solution using column chromatography and Pb isotope analyses were realized on a Nu Plasma II (Nu Instrument) MC-ICP-MS. Ten samples went to the Geochronology and Isotope Geochemistry Lab at the University of North Carolina-Chapel Hill (UNC-CH). Column chromatography was also used to extract lead from the EDTA solutions where upon the samples were isotopically assayed on a VG-Sector 54 TIMS.

The results of the Pb isotope analysis, along with descriptive and contextual information for each artifact are presented in Table 2 (lead artifacts), Table 3 (silver) and Table 4 (copper). The lead data are listed as three ratios of the absolute amount of one of the four measured isotopes (^{208}Pb, ^{207}Pb, ^{206}Pb and ^{204}Pb) against the amount of another. On a series of figures for each type of metal (figures 3, 5 and 7), the Pb isotope data for the various Dholavira artifacts are graphically represented by red symbols on a bivariate plot of the values of two of the ratios (with ^{208}Pb/^{207}Pb for the y axis and ^{207}Pb/^{206}Pb for the x axis). They are presented in relation to the spreads of isotopic values (or "fields") of select geologic sources in the South Asia Pb isotope database (Law 2011). The individual datapoints making up the fields have been outlined and then labeled on the figures to aid in interpretation.

Lead Artifacts

Lead artifacts, as compared to those composed of copper, are not particularly common at Dholavira or, for that matter, at Indus Civilization sites in general. Only around 30 in total have been recovered at Harappa since excavation re-commenced there in 1986 (Law 2011). The thirty-five lead artifacts analyzed (Table 2 and Fig. 2) from Dholavira represent most items in this sub-assemblage at the site. The only ones not analyzed were several small spherical pieces from surface or near surface contexts that are probably musket shot from relatively recent times.

Analyzed artifacts include items such as ingots, rings, rods, a cube (that might have been a weight), a flat sheet and assorted fragments and lumps. However, in terms of positively identifying the geologic sources from which artifacts of this kind were derived, the most important objects in the group are nine lead ore fragments. These include examples of the lead minerals galena (lead sulfide), massicot (lead oxide) and cerrusite (lead carbonate). Objects composed of processed metal may potentially contain lead from multiple geologic deposits, which would act to mix and, thus, obscure the isotopic characteristics of those sources. With unadulterated ores one can be certain that the measured isotopic values are precisely those of the geologic deposit from which they originally came.

Table 2: Context and Pb isotope data for lead artifacts from Dholavira

Artifact #	Object	Area	Stage	207Pb/ 206Pb	208Pb/ 207Pb	206Pb/ 204Pb	Lab
3118	ore (galena)	MT	IV	0.86436	2.4439	18.137	UNC-CH
5229	ore (massicot)	Citadel	IV	0.84596	2.4689	18.548	UCSC
25738	ore (galena)	LT	IV	0.84844	2.4649	18.496	UNC-CH
Temp_Pb_B	ore (cerrusite)	Citadel	IV	0.90366	2.3890	17.362	UNC-CH
1385	ore (galena)	Citadel	n/a	0.85288	2.4609	18.412	UCSC
19266	ore (galena)	Bailey	V	0.84743	2.4676	18.506	UCSC
Temp_Pb_L	ore (galena)	LT	V	0.84759	2.4685	18.505	UCSC
21124	ore (galena)	Annexe	V-VI	0.84262	2.4691	18.617	UCSC
Temp_Pb_C	ore (galena)	ER	V-VI	0.84562	2.4684	18.633	UNC-CH
8622	cube / weight?	Citadel	I	0.90574	2.3944	17.408	UNC-CH
8178	piece	LT	IV	0.84796	2.4663	18.491	UCSC
5131	ring	Citadel	IV	0.84707	2.4669	18.513	UCSC
24766	rod	Bailey	IV	0.84726	2.4677	18.516	UCSC
Temp_Pb_J	bent rod	MT	IV	0.90004	2.3906	17.360	UCSC
Temp_Pb_G	mass	Citadel	IV-V	0.85949	2.4488	18.243	UCSC
Temp_Pb_D	sheet	Stadium	IV-V	0.84224	2.4703	18.625	UCSC
197	lump fragments	Citadel	n/a	0.84613	2.4686	18.542	UCSC
756	ring fragments	Citadel	V	0.84634	2.4686	18.537	UCSC
312	sheet	Citadel	n/a	0.88282	2.4145	17.720	UCSC
3752 (2002)	ingot	MT	V	0.84772	2.4661	18.522	UNC-CH
9671	lump	MT	V	0.84748	2.4666	18.505	UCSC
Temp_Pb_F	lump	MT	V	0.90224	2.3869	17.316	UCSC
19427	piece	MT	V	0.84688	2.4680	18.521	UCSC
21430	piece	Bailey	V	0.84814	2.4667	18.491	UCSC
23205	piece	LT	V	0.84736	2.4667	18.504	UCSC
4032	rod	Citadel	V	0.86789	2.4481	18.147	UNC-CH
Temp_Pb_E	rod	Stadium	V	0.84742	2.4670	18.499	UCSC
Temp_Pb_I	rod/ring fragment	LT	V	0.89449	2.3982	17.456	UCSC
Temp_Pb_H	sheet fragment	Citadel	V	0.90263	2.3872	17.305	UCSC
21918	button?	LT	V	0.84699	2.4675	18.517	UCSC
Temp_Pb_K	folded piece	Bailey	V	0.84749	2.4677	18.508	UCSC
2670 (2000) A	lump	MT	V	0.84605	2.4689	18.547	UCSC
2670 (2000) B	sheet	MT	V	0.84594	2.4688	18.547	UCSC
18680	ring fragment	Bailey	VI	0.84898	2.4653	18.472	UCSC
18921	rod	Bailey	VI	0.84762	2.4661	18.497	UCSC

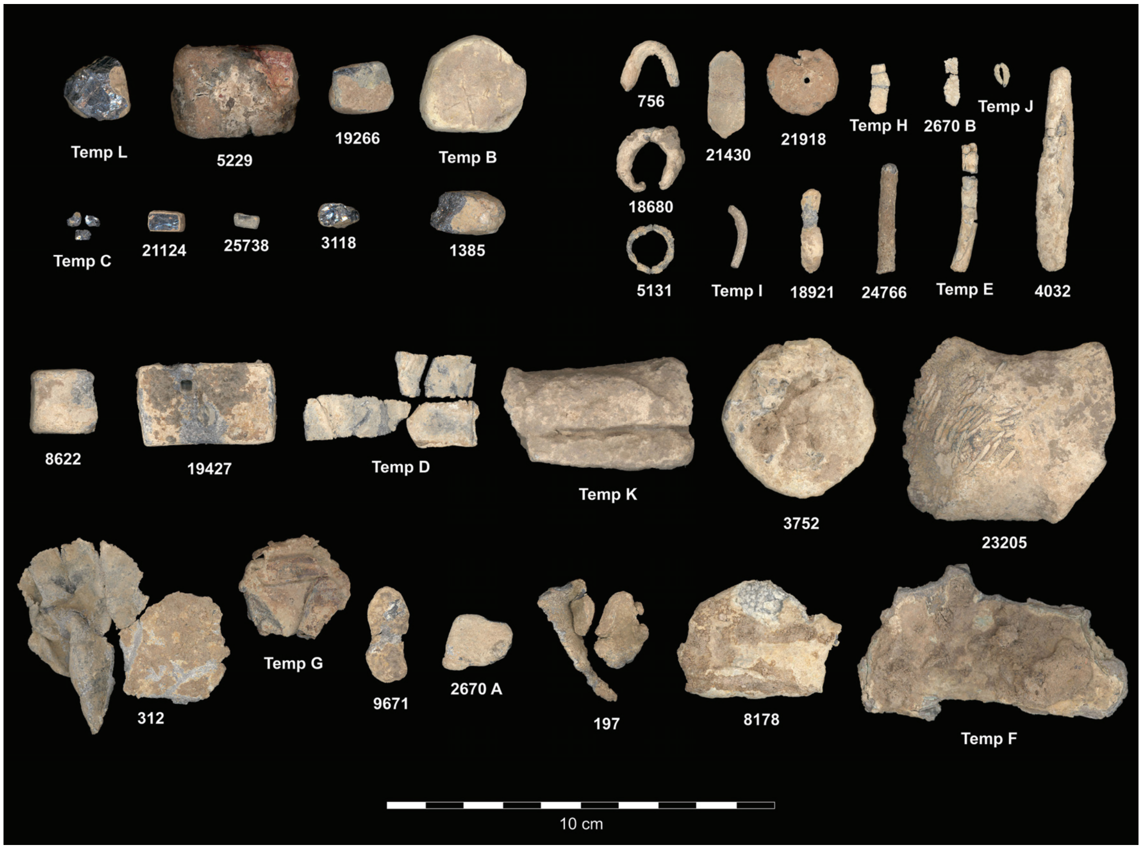

Figure 2: Analyzed lead artifacts from Dholavira

The isotopic values of the nine lead ores are plotted as red circles on Fig. 3. They fall in three distinct areas. Seven ores (six galenas and one massicot) group with lead deposits located in what today is the southern part of Balochistan Province, Pakistan. A single galena fragment plots with the metal smelting area/source adjacent to the ancient site of Ganeshwar in the Sikar District of northern Rajasthan. Lastly, a cerrusite fragments plots with the polymetallic sulphide deposit straddling the Gujarat-Rajasthan border at Ambaji-Deri (which is southern end of the Ambaji-Sendra sulphide belt).

Most of the 26 lead metal artifacts, which are represented by red triangles, plot closely with or in the vicinity of one of the three sources indicated by the lead ores. Nineteen of those 26, groups in the southern Balochistan source area. In fact, they group so closely (with one another and the ores) that it is difficult to make out their individual datapoints at the resolution of the bivariate plot. Two of the lead artifacts fall adjacent to the ore that plots with the Ganeshwar source and four fall together near the ore plotting with the Amabji-Deri deposit. Finally, a single artifact plots away from the three groups near the datapoint for the small polymetallic deposit at Tosham Hill, Haryana.

Overall, the results indicate that at least three distinct geologic sources (possibly more) are represented among the 35 lead artifact analyzed. Twenty-six cluster together among the southern Balochistan ore fields. Closer examination of the isotopic characteristics of the different geologic occurrences making up that source area (not shown here but available in Law 2011) suggests that it is deposits in the Kanrach Valley of the Las Bela District that are most analogous to this group of artifacts. Four artifacts appear to have derived from the Ambaji-Deri deposit on the Gujarat-Rajasthan border, which, at almost 275 km due west of Dholavira, is the lead source nearest to the site. Three artifacts including an ore sample plot with the Ganeshwar area source. It should be noted, however, that no evidence of lead mineralization is noted in the geologic literature pertaining to this area (the Nim-Ka-Thana copper belt of northern Rajasthan). This could mean that such evidence remains to be discovered in that area or, perhaps more likely, a lead source with these same isotopic characteristics exists in a different region and is not yet included in the database. A small degree of lead mineralization (galena) does occur at Tosham Hill (Murao et al. 2008: 497). However, it is possible that the isotopic characteristic of the single lead artifact that plots with this distant occurrence is a product of the mixing of metal from multiple sources.

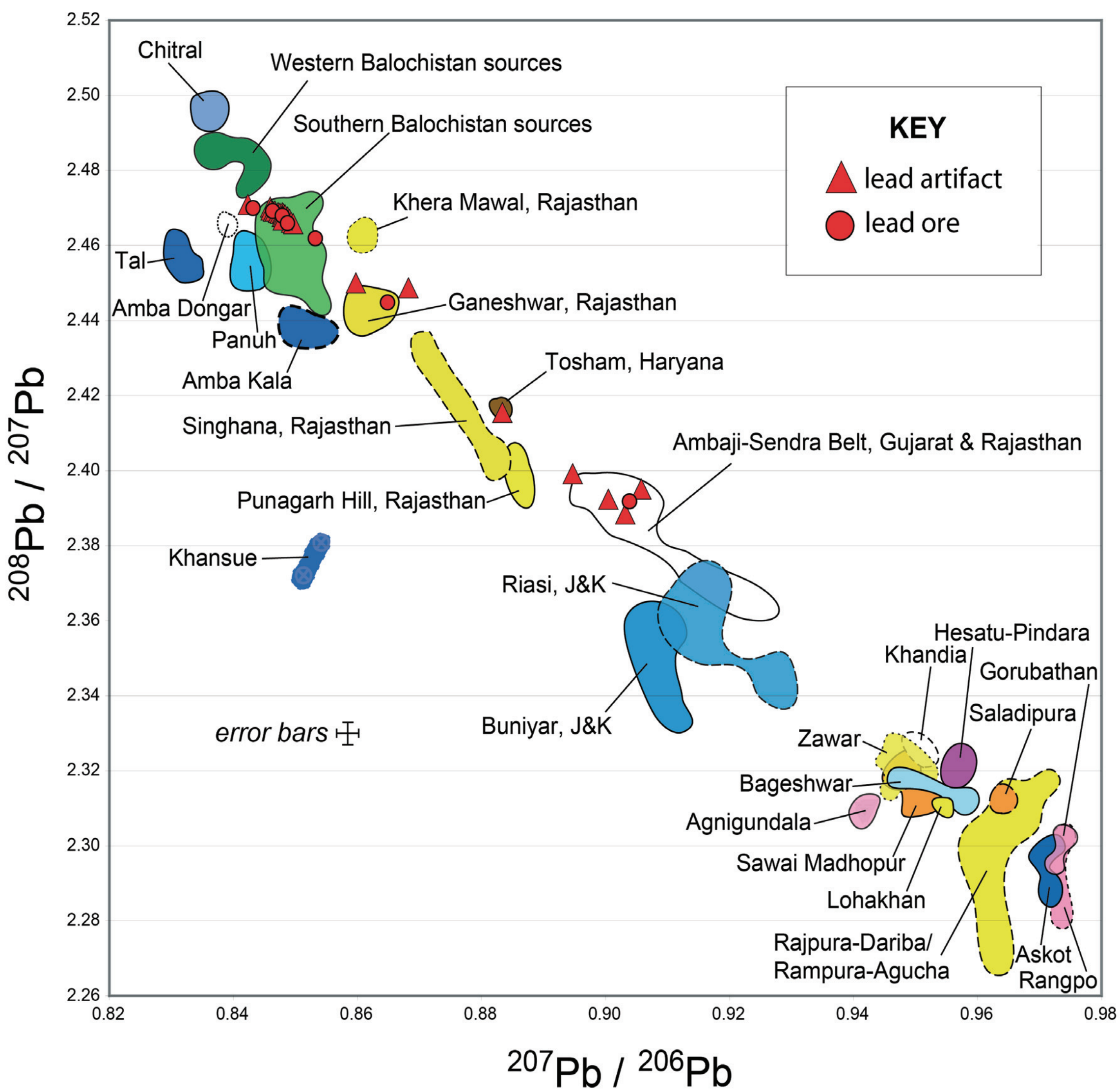

Figure 3: Lead artifacts from Dholavira compared to South Asian Metal Sources

Silver Artifacts

Outside of jewelry hoards, silver objects are, on the whole, rare at Indus Civilization sites. Dholavira is no different in this regard. Only 15 objects made from the precious metal have been recovered there. Rather than being indicative of its limited of use, however, this scarcity may largely be due to factors relating to its preservation (or rather lack of) in the often saline, moisture-laden soil of archaeological sites. Silver, unlike gold, is oxidizable and water-soluble (Guilbert and Park 1986: 744). Under certain burial conditions it is subject to "complete disintegration through several internal corrosion and embrittlement" (Drayman-Weisser 1992: 192). Thus, many of the silver objects that escaped recycling four millennia or so ago in the past may have since degraded to the point that little or no trace of them has been left behind (especially small ornaments and tiny fragments). Still, we have been able to glean from the discovery of jewelry hoards (such the ones at Mohenjo-daro, Allahdino, Kunal and Mandi) and individual finds at numerous other settlements, both large and small, across the Greater Indus region that silver was an important and widely traded metal during the Harappan Period (for more details see Ratnagar 2004: 197 or Lahiri 1992).

Fourteen of the silver artifacts recovered from Dholavira were sampled and analyzed (Table 3 and Fig. 4). The Pb isotope data for each is plotted on Figure 5 using red triangles. The largest group of artifacts (5 or 6 of the 14), plot with or near the southern Balochistan source area. The remaining ones fall in several different areas, either in alone or in pairs. One artifact plots among the data points for lead occurrences in western Balochistan, another groups with the lead source at Khera Mawal in southern Rajasthan, another falls on the Ganeshwar copper source and another plots in the vicinity of the Ambaji-Deri area deposits. Two artifacts plot at the upper margin of the Singhana isotope field while two others isotopically match the Tosham Hill data point.

Table 3: Context and Pb isotope data for silver artifacts from Dholavira

Artifact #	Object	Area	Stage	207Pb/ 206Pb	208Pb/ 207Pb	206Pb/ 204Pb	Lab
12254	piece	MT	IV	0.86058	2.4612	18.442	UNC-CH
15372	bead	MT	IV	0.85396	2.4692	18.389	UCSC
25408	sheet	LT	IV	0.87015	2.4319	17.994	UCSC
2732 (2002)	silver coil	MT	IV	0.85644	2.4536	18.304	UCSC
Temp_Ag_B	sheet fragments	MT	IV	0.83914	2.4809	18.712	UCSC
Temp_Ag_C	wire fragments	Citadel	IV	0.84437	2.4732	18.586	UCSC
23239	bead	LT	n/a	0.90107	2.3779	17.352	UCSC
23604	bead	LT	V	0.88302	2.4128	17.718	UCSC
27406	wire fragments	Citadel	V	0.84597	2.4718	18.600	UNC-CH
2670 (2000) C	sheet	MT	V	0.84594	2.4688	18.548	UCSC
521 (2000)	bead	MT	V	0.85383	2.4604	18.430	UNC-CH
Temp_Ag_A	bead	MT	V	0.88256	2.4149	17.728	UCSC
9700	piece	ER	V-VI	0.86431	2.4389	18.122	UCSC
16092	bead	Bailey	VI	0.86961	2.4326	18.007	UCSC

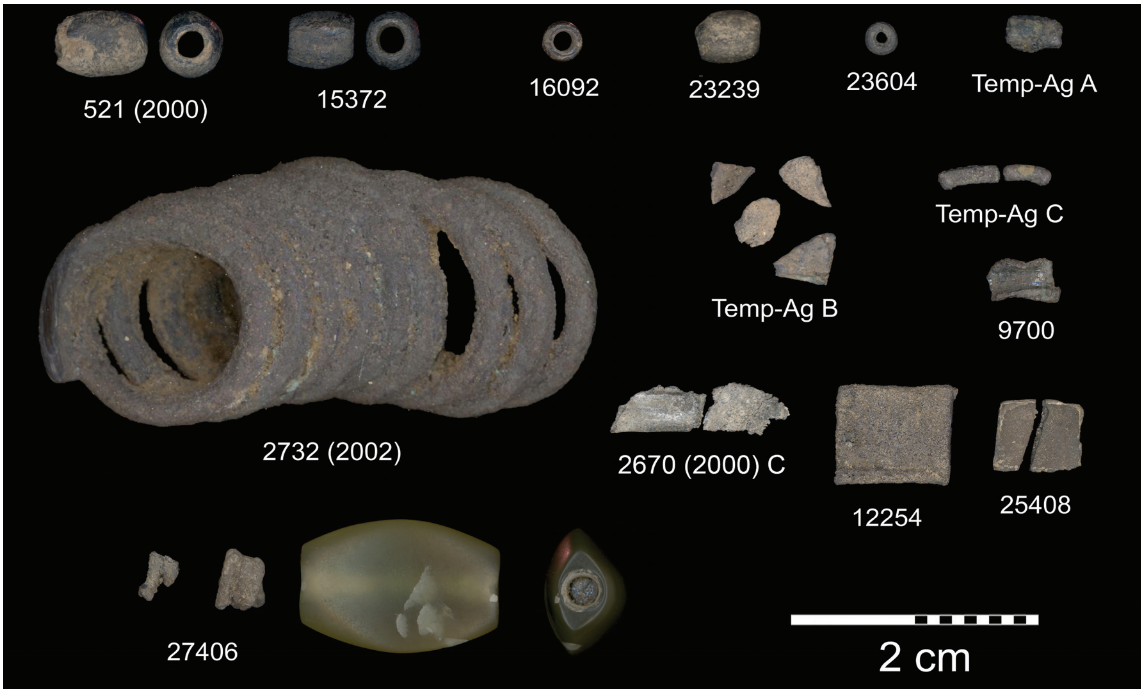

Figure 4: Analyzed silver artifacts from Dholavira

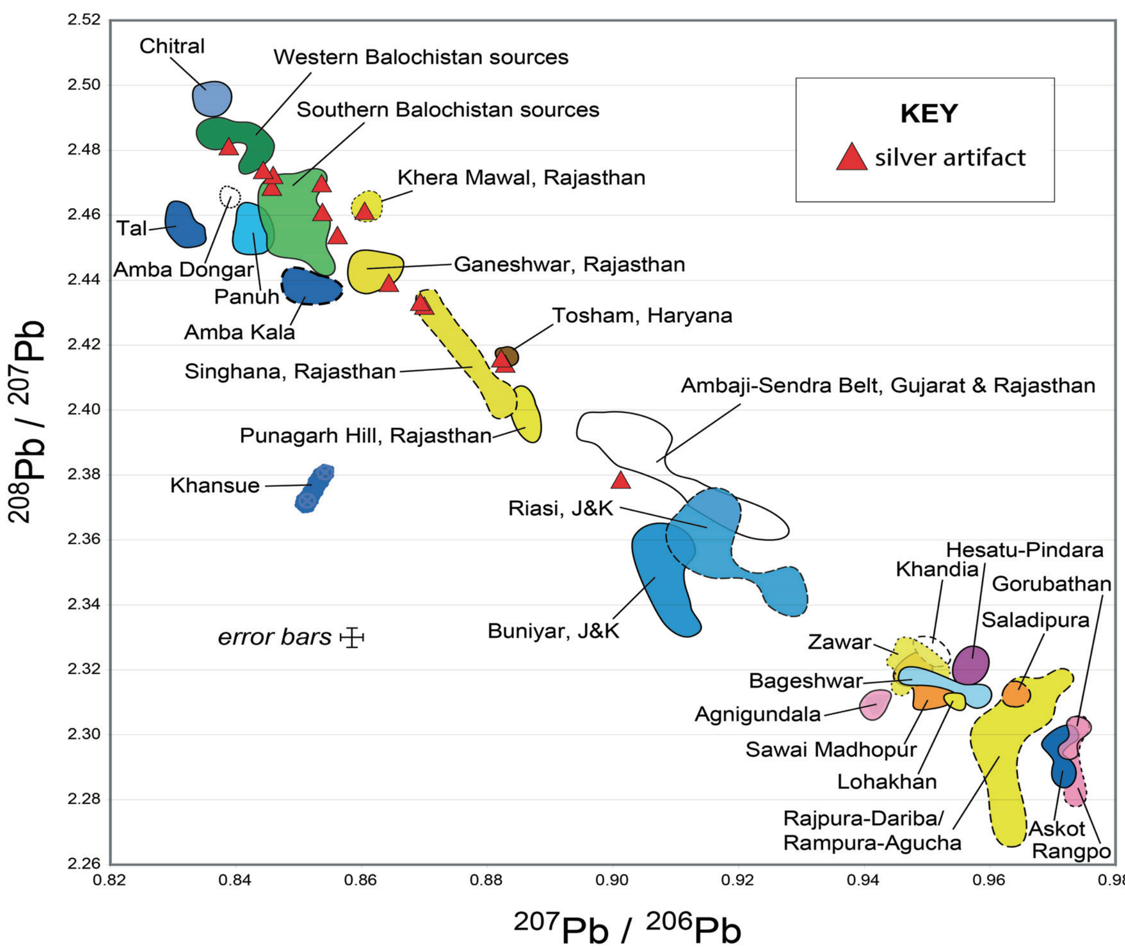

Figure 5: Silver artifacts from Dholavira compared to South Asian Metal Sources

Scholars have long suggested that Harappan silver was likely obtained through the *cupellation* (refinement through the oxidation of base metals) of *argentiferous* (silver-rich) lead ores (Asthana 1993: 276; Biwas 1996: 329; Mackay 1931: 524; Ratnagar 2004: 193). A number of lead sources in southern and western Rajasthan have been shown to be rich in silver (Kazmi and Jan 1997: 454-455) and the Ambaji-Deri area deposits, which are primarily lead, zinc and copper "are known to contain recoverable quantities" of the precious metal (Radhakrishna and Curtis 1999: 148). The silver content of the galena at Khera Mawal is unknown but that small deposit is located only some 15 km from the Ambaji-Deri. The polymetallic deposit at Tosham Hill in Haryana contains a component of silver but it seems to be an extremely minor one (Murao et al. 1996).

Copper ores (such as chalcopyrite and chalcocite) may also be argentiferous (Craddock 1995: 232). Although it is unknown if this is the case with the Ganeshwar area deposits, those near Singhana – the extensive metal processing site adjacent to the massive Khetri copper deposit – are known to be rich in silver (Rao et al. 1997). If this area was one of the major sources for the copper used by Indus Civilization peoples as has been proposed (Agrawala 1984), then the possibility exists that at least some of the silver found at Harappan sites like Dholavira may have been the byproduct of the intensive copper production that took place in that part of northern Rajasthan.

Copper Artifacts

Sixteen copper artifacts from Dholavira were analyzed for this study (Table 4 and Fig. 6). Ten additional artifacts were to have been analyzed but the concentrations of lead in the EDTA solutions for those samples were found to be so low that they would have negatively affected the accuracy of the isotopic measurements. The artifacts that did contain sufficient lead for analysis included six copper ores (five examples of the mineral *cuprite* and one piece of *chalcocite*) and four objects that appear to be fragments of bun-shaped ingots.

The Pb isotope data for the 16 copper artifacts from Dholavira are plotted on Figure 7 – copper ores are represented using red circles, ingots with red squares and all remaining artifacts using red triangles. Added to the figure/plot are black triangles representing datapoints for copper deposits in the eastern Arabian country of Oman. The isotopic data for these come from various studies and have been compiled in Appendix 12.8 of Law 2011. They are included here because there is strong evidence for a Harappan presence in Oman (Cleuziou 1992) and it is believed that the rich copper deposits of the region may have been the impetus for that contact (Kenoyer and Miller 1999). Owing to the geographic location of their city near the coast, the Harappans of Dholavira would have been especially well-positioned to take acquire resources coming to ancient South Asia via oceanic trade routes across the Arabian Sea. Data for Oman was not included on the previous plots as there are no significant occurrences of lead ore in that region and the copper deposits there are not known to be argentiferous.

Table 4: Context and Pb isotope data for copper artifacts from Dholavira

Artifact #	Object	Area	Stage	207Pb/ 206Pb	208Pb/ 207Pb	206Pb/ 204Pb	Lab
1287(2002)	ore (cuprite)	MT	n/a	0.9024	2.3871	17.314	UCSC
2095(2002)	ore (cuprite)	MT	n/a	0.9022	2.3870	17.317	UCSC
URC-19	ore (chalcocite)	MT	V	0.9019	2.3868	17.3342	MURR
URC-34	ore (cuprite)	Citadel	V	0.9024	2.3869	17.3211	MURR
URC-39	ore (cuprite)	Citadel	III	0.9025	2.3870	17.3200	MURR
URC-45	ore (cuprite)	Citadel	I	0.9022	2.3872	17.3264	MURR
496 (2003)	ingot fragment	Citadel	VI	0.8786	2.4161	17.7980	MURR
URC-11	ingot fragment	MT	V	0.8857	2.4103	17.6712	MURR
URC-10	ingot fragment	MT	V	0.8928	2.4009	17.5230	MURR
1328	ingot fragment	MT	V	0.8643	2.4308	18.1486	MURR
4052	large bowl	Citadel	IV	0.8841	2.4078	17.6590	MURR
8468	pin	MT	IV	0.8581	2.4499	18.2865	MURR
877/05	spear	LT	V	0.8447	2.4683	18.5783	MURR
9621	curved blade	LT	V	0.8558	2.4539	18.3234	MURR
RM-126	bangle fragment	MT	V	0.8776	2.4211	17.832	UCSC
RM-96	bangle fragment	Citadel	VI	0.9007	2.3889	17.349	UCSC

On Figure 7, the data points for all six of the Dholavira copper ores and one of the artifacts (a bangle fragment) cluster tightly together in the Ambaji-Deri isotope field. The ingots fragments and remaining artifacts plot in a much more dispersed fashion. Two of the ingots and two of the artifacts plot closest to the isotope field for the Singhana/Khetri source in Rajasthan. It is important to note, however, that an outlier of the Oman copper sources also plots in this location. The other two ingots fall in areas of the plot that are not well defined isotopically. One falls between the Ambaji-Deri and Punagarh Hill deposits while the other plots between but apart from the Rajasthan sources. The isotopic characteristics of these particular ingots could be due to them being a mixture of metal from multiple sources or they might be indicative of a source not yet in the database.

Two of the three copper artifacts that remain plot between the Ganeshwar and southern Balochistan fields and one falls within the southern Balochistan field. Interestingly, however, those three artifacts also fall squarely within the two clusters of data points representing the Oman copper deposits. There are good reasons to think that these objects may indeed be composed of copper from Oman rather than from one of the South Asian sources. The isotopically undefined area between the South Asian sources where the two Dholavira artifacts plot actually becomes well-defined when the Oman cluster of data points is added. As for the other Oman cluster that overlaps the southern Balochistan source area while encompassing the single Dholavira artifact, although copper mineralization does also occur within the southern Balochistan sulfide deposits it is generally very minor. Still, we have shown that lead and silver was exploited from that region so it is not unreasonable to think that at least some copper may have been as well.

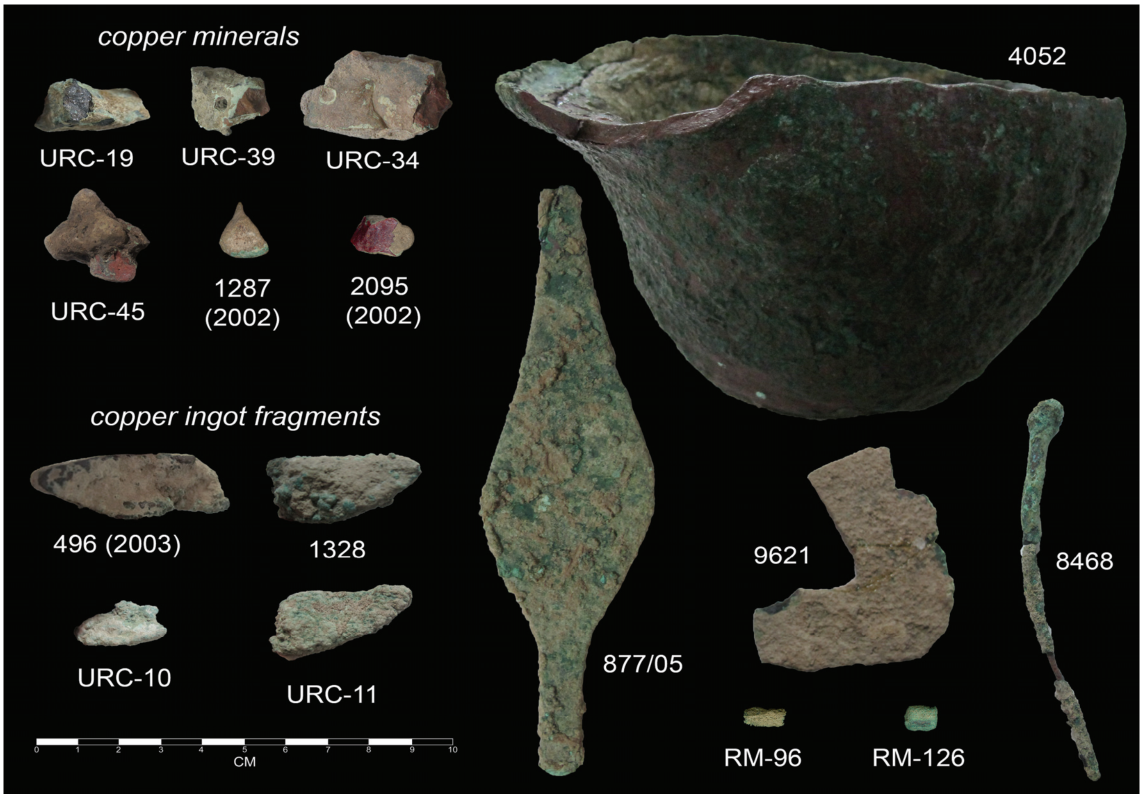

Figure 6: Analyzed copper artifacts from Dholavira

Discussion

Before discussing the results in detail it is necessary to acknowledge that any or all of the 65 lead, silver and copper artifacts in the dataset could well have come from sources other than those mentioned in this paper. The Pb isotope database for South Asia is far from complete. Thus, any artifact might actually be from uncharacterized but isotopically identical occurrences elsewhere South Asia or even from one in an entirely different region. It is also recognized that the isotopic characteristics of the processed metal objects might not reflect a single source at all but rather a mixture of lead derived from two (or more) different geologic deposits. Nevertheless, with these qualifications, it is possible to state that the results of this study indicate that the lead, silver and copper used by residents of Dholavira were derived from multiple geologic sources. Analyses of archaeological fragments of lead and copper ores have permitted us to identify some of those sources with a high degree of confidence. Although the geologic origin for the metal in other artifacts is less certain, the isotopic data obtained allow us to define certain deposits as potential sources while and excluding others altogether.

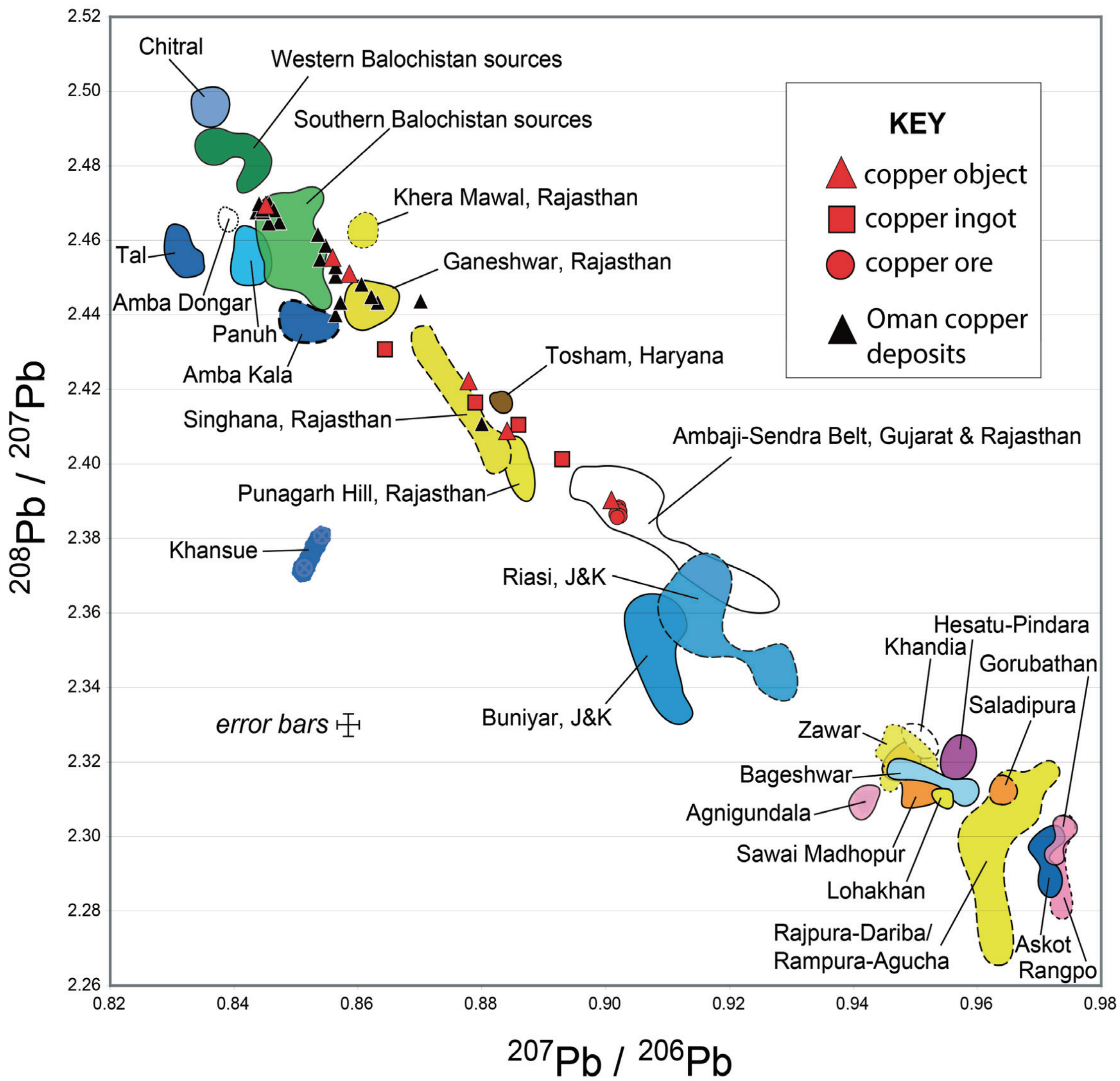

Figure 7: Copper artifacts compared to South Asian and Omani Metal Sources

It now appears that an important source area for lead, copper and, perhaps, some silver was located at Ambaji (sometimes called Ambamata) in the Banaskantha District of Gujarat and Deri around 10 kilometers away in the Sirohi District of Rajasthan. These are the southernmost deposits of an intermittent zone of sulphide mineralization – the Ambaji-Sendra Belt – that extends from the Gujarat border 240 km northeast into southern Rajasthan. The polymetallic Ambaji-Deri deposits are the richest occurrences in that zone and, as it happens, at 275 km from Dholavira the nearest sources of metal to that ancient city. Currently there are no known proto-historic sites in the vicinity of Ambaji-Deri and radiocarbon dating of roof supports and charcoal from the old mining and smelting areas there put the earliest date of exploitation as occurring during the 2nd century BC (Shekar 1983). Now, however, it is possible to the push its utilization back to approximately 3000 BC as copper ore (cuprite) and a cubical lead artifact from this source have been recovered from Stage I levels at Dholavira. Raw ore and processed metal from this source continued to be used at the site through at least Stage V.

Another important source area seems to have been the Kanrach Valley in the Las Bela District of southern Balochistan, Pakistan. Dozens of artifacts – galena fragments, lead objects and, possibly, ornaments made from silver extracted from the lead occurrences of this area – are found in Stage IV and V, which is Dholavira's Mature Harappan stage and the period of time when Indus Civilization trade networks were at their zenith. Harappans would have had direct access to the source during this period. The site of Bakkar Buthi, which contains both Kulli and "purely Harappan" occupation levels (Franke-Vogt et al. 2000: 196) lies within a few kilometers of several occurrences of lead (*personal observation*). Twenty kilometers north of the site Geologist A.H. Kidwai reported (in Heron and Crookshank 1954: 93) "weathered ore, slags of lead and copper and furnace clay" at a location noted as "ruins" near Thana Kanrach. Although no such items were found during the limited excavations at Bakkar Buthi (Ute Franke-Vogt *personal communication* 2003), it is by far the nearest of any Harappan settlement to a deposit of lead. So it is perhaps not surprising that lead and/or silver artifacts attributable to sources in southern Balochistan have also been identified at Indus sites as across northwestern South Asia including Harappa, Mohenjo-daro, Rakhigarhi, Gola Dhoro, Allahdino and Nausharo (Law 2011, Law and Burton 2006, Law and Burton 2008, Nath et al. 2014).

The location of a probable third discreet geologic source of lead – indicated by the analysis of a single galena fragment from Stage IV– is much less clear. It is not impossible that the fragment is an isotopic outlier of the southern Balochistan source area. Significantly, however, there are four or five archaeological lead ores (galena and massicot fragments) from the site of Harappa that also plot in this same general area (see Law 2011: Figure 12.23). This strengthens the case for there actually being a separate source with these isotopic characteristics out there. The galena fragment in question from Dholavira plots with the Ganeshwar area copper source in northern Rajasthan, as do two lead and one silver artifact from the site. However, no lead mineralization is reported from that source and, in fact, lead minerals are absent from most of the massive sulphide occurrences of northern Rajasthan. It would be prudent, therefore, to consider the geologic provenience of these particular artifacts from Dholavira as "presently unknown."

As for copper overall, it is clear that Ambaji-Deri was an important source area. Although their geologic provenience associations are somewhat more tenuous, the results of this study suggest that some metal used to make copper objects from Dholavira likely derived from deposits in northern Rajasthan and Oman. However, to get a clearer picture of the city's copper acquisition networks it will be necessary to analyze a substantially larger sample set and continue to build a more comprehensive Pb isotope database of potential copper sources.

Finally, a handful of lead and silver objects from Dholavira seem to be isotopically analogous to metal deposits that are either some distance away from the Indus heartland or are very minor in nature. Single lead object plots with deposits occurring

Figure 8: Provisional lead, silver and copper acquisition networks for the site of Dholavira

in the far western reaches of Balochistan while a silver ornament falls with the very small lead occurrence at Khera Mawal, which is actually not that far from Ambaji-Deri. It is certainly possible that the metal for both objects is genuinely from those sources. The two silver and one lead artifact that have isotopic characteristics very similar to the polymetallic deposit at Tosham Hill, Haryana are extremely interesting even though those metals are reported to be minor components of that already small deposit. Still, in this case (and in other instances too, like the apparently lead mineral-deficient copper deposits of northern Rajasthan and elsewhere) it should be noted that "the weathered outer parts of ore deposits and their deeper primary parts are completely different from each other, not only in the chemistries and occurrences of minerals but in the effects they exerted upon the development of metallurgy" (Patterson 1971: 286). In other words, in contrast to what is observed today, the Harappans and/or other ancient people that first exploited the sulphide ore deposits of South Asia may have encountered a very different set of minerals in the original gossan layers of those deposits.

Conclusion

Using Pb isotope analysis we can now begin to provisionally trace the networks through which the ancient residents of Dholavira acquired lead, silver and copper (Figure 8). Ambaji-Deri on the Gujarat-Rajasthan border and the Kanrach Valley of southern Balochistan were important source areas from which all three metals were obtained. The results of this study also suggest that some copper from the extensive occurrences in both northern Rajasthan and Oman was also utilized to some extent. A little lead may have come from distant deposits in western Balochistan and there are indications that minor sources like Khera Mawal in southern Rajasthan and Tosham Hill in Haryana may have been exploited for silver and/or lead.

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