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On the Exploitation of Copper Ores at Shahr-i Sokhta (Sistan, Iran) in the 3rd Millennium BC

Introduction

25 years are a long time between the closing of a major field project such as Shahr-i Sokhta and the systematic publication of its materials. In such a long period, while the bulk of the excavated artefacts was left in Iran and is not currently available for study, samples brought to Rome with official permission were moved within and between the main storage facilities (the Centro Scavi e Ricerche archeologiche in Asia of IsIAO and the National Museum of Oriental Art in Rome or MNAOR). Some labels fell off; some of the samples were given to specialists for analysis in different labs and in different countries; some other objects are being actively searched for. As usual, some samples from these small analytical collections were correctly processed and, finally, others were not.

We present in this paper some preliminary results and reflections emerging from a new set of studies and analyses that we began at the Istituto per le Tecnologie Applicate ai Beni Culturali – CNR, and at the Istituto Centrale per il Restauro (ICR) in collaboration with IsIAO, Rome.

The Rome collections (Centro Scavi IsIAO and MNAOR) are currently the subject of a major effort at data organizing and further archaeometric analysis (including mineralogical identification of rock samples, paleotechnological studies of various classes of slag and semi-processed copper artefacts), paleotechnological studies, and a typological evaluation of finished goods such as pins, tools, knives, seals, vessels, and figurine fragments. Obviously, we are not materially dealing with the artefacts (or the sampled parts) given to other institutions for analysis or kept in Iran.

So far, we have built a major database (about 800 entries), inventorying each item, and collecting drawings, pictures and any analytical information relevant to every single piece. Of some important pieces – for example, some rare copper melting crucibles – we have good photographs and drawings, but not the actual items. Furthermore, about 500 items belonging to different technical steps were analysed at ICR by means of qualitative X-ray fluorescence (ED-XRF), including 30 samples of rocks or minerals containing copper or other metals; the same 30 samples were also processed by X-rays diffraction (XRD). This paper takes into account, as a first step, the question of the type of copper-bearing ores processed at Shahr-i Sokhta and their possible source areas.

One of the present writers (Vidale, in press) has given to print a volume with the final publication of the lapis lazuli industries of Shahr-i Sokhta. We now move to another ambitious project: recollecting in a single volume and a final catalogue the collection of copper-related artefacts and metallurgical residues stored in Rome, piecing together the history of the research carried out so far, incorporating what has been published on the metallurgy of the site (mainly cared by our colleagues in Bochum), and placing the results in the more general frame of the development of protohistoric metallurgy in the Turanian area. The study, in the next stage, will include a systematic drafting and photographing of a substantial selection of artefacts, more (quantitative) ED-XRF analyses on a selected series of samples, SEM observations and metallography of semi-finished and finished copper artefacts with a preserved metal core.

Context and chronology of the finds

The copper-based artefacts we are studying may be generically dated to Periods II and III of the general sequence, i. e. between 2800 and 2400 BC. It is well known that the stratigraphical contexts in the early urban context of Shahr-i Sokhta are largely formed by artificial fillings, packed between superimposed floors of private dwellings.

Most of the copper-based artefacts from Period II (about 2800–2550 BC) come from such deposits, and it has probably no relationships to the surrounding architectural context. Possibly, the fillings were made by removing, transporting and piling up in new locations heaps of refuse or

10	Fe Cu Ca Sr Zr Mo As
3	Fe Pb Sr Zr Ca Rb
2	Fe Ca Ti Mn Cu Sr Zr
122	Cu Fe Ca
99	Fe Sr Ca Cu Zr Rb K Ti? Ni?
287	Cu Fe Ca Sr Zr Rb S Mo Bi?
321	Fe Ca Cu Mo Zn Zr
94	Cu Fe Ca Sr Zr Bi?
67	Cu Fe Ca
73	Cu Fe Ca Mo Mn Sr
92	Cu Fe Mo Bi Se?
115	Cu Fe Ca
80	Fe Cu Ca Sr Mo Rb Zr Bi K Pb tr. As tr.
108	As Cu Fe tr.
1	Cu Fe Sr Ca
272	Cu Fe As
72	Cu Fe Sr K
195	Cu Fe As Sr Ca tr.
316	Fe Cu Sr Mo Rb Bi? Ca tr.
225a	As Fe Cu Sn tr.
225b	Cu Fe As Ca
203	Cu Fe As Mo
85a	Cu Ca Fe Mo
85b	Ca Cu Fe Mo Ni Sr Zr
72	Cu Fe Sr K
290	Cu Fe Mo Ca Sr tr. Pb tr. Cl? K? Zn? tr.
288	Cu Fe Sr Ca Zr Cl
317	Ag Br Cu Ca Pb Fe Sr
151	Pb Fe tr.

Fig. 1. Shahr-i Sokhta, EDXRF analysis of rock and ore samples (elements empirically listed in order of peak intensity).

collapsed architectural material found nearby in abandoned lots (Tosi 1983, 164). At the same time, the wide distribution of copper working indicators, although in secondary or tertiary contexts, suggested that this craft activity was not concentrated or segregated in a single part of the town, but that it was commonly performed within the private dwellings, in their courtyards, or in external open spaces accessible or controlled by the dwellings themselves.

As far as we presently know, there is no evidence of furnaces, ovens or firing areas bearing crucibles, slag or other metallurgical residues *in situ* at Shahr-i Sokhta. The only meaningful association is provided by rare finds of clusters of small drops or prills in slag. One of the most distinctive indicators, a truncated-cone shaped slag cake, may be formed by pouring the slag into a mould-like cavity in the ground, but such cavities have so far escaped the archaeologists' search. In some cases, small-scale copper metallurgy was clearly carried out together with a varied range of other technologies: for example, in sqq. EWK-EWP, together with lapis lazuli and turquoise bead making, carnelian, agate and aragonite bead making, and recycling of broken alabaster vessels (Vidale, in press).

Tosi (1984) evaluated the general evolution in time of the three-dimensional distribution of craft indicators across the compound, suggesting that metallurgical indicators were relatively common in the fillings of Period II, together with craft indicators of the other industries. In Period III (about 2550–2400 BC) these craft indicators became more frequent in surface contexts, particularly in the western and southern extensions of the city, where metallurgists concentrated their dumping grounds or possibly may have erected their workshop areas. This evidence was interpreted by Tosi as the output of a major change in the organization and management of craft production by the urban elites.

One of the aims of our project is to reconsider the spatial and stratigraphical distribution of the copper-based finds from Shahr-i Sokhta, both in terms of relative and absolute chronology, and of manufacturing steps. Although we expect that, besides the trends identified by Tosi, the search for meaningful correlations will hardly provide clear-cut results, only a distributional study based upon careful statistics will allow us to substantiate or modify the presently accepted theory of a small-scale craft industry loosely performed in the urban network.

Previous research

The history of archaeometallurgical research at Shahr-i Sokhta is long, and so is the list of the scholars involved in the study. In 1973, not less than 270 samples (both slag fragments and finished objects) were given to the Laboratory for Metallurgy of the Leningrad section of the Institute of Archaeology of Sciences Academy of SSSR. The samples underwent a quantitative spectro-chemical analysis. The results, still unpublished, were presented in 1997 by the present Institute of the History of Material Culture of Russian Academy of Science (St. Petersburg): they provide a wide spectrum of substantial analytical information that will be a part, in the next future, of our current general study. The processed samples are still in St. Petersburg. In 1975, another set of 150 samples (including artefacts and by-products at every stage of processing) were given to Maurizio Salmi (Italy) to be analysed by the means of X-ray fluorescence (hereafter XRF: the elements counted were only Cu, Fe, Pb, Sn); we have the results, which are still unpublished and present same interpretational problems.

In 1974, David Heskel came to Rome and carried out a thorough examination of the collections, both in the MNAOR and in the Centro Scavi; he selected 51 artefacts for spectrographic analysis (XRF) and X-rays diffraction (XRD). He used the data for his PhD thesis on the development of prehistoric pyrotechnology in Iran, submitted at the Harvard University, Cambridge MA

Nr.	Quartz	Feldspars	Micas	Other silicates	Iron oxides	Copper oxides	Acatamite	Paraca-tamite	Other chlorides	Digenite	Galena
10	×	.	.	.	.	.	.	.	.	.	.
3	.	×?	.	.	.	.	.	.	.	.	.
2	.	×?	.	.	.	.	.	.	.	.	.
122	.	.	.	Wollastonite.	.	.	.	.	.	.	.
99	.	Albite	Illite	Clinochlore.	.	.	.	.	.	.	.
287	.	Anorthite	Muscovite	Diopside.	.	.	.	.	.	.	.
321	×	.	.	Grossular	Magnetite	.	.	.	.	.	.
94	.	.	.	Grossular	.	.	×	.	.	.	.
67	×	.	.	Diopside	.	.	×	.	.	.	.
73	×	.	.	.	.	.	×	.	.	.	.
92	×	.	.	Goldmanite	.	.	×?	.	.	.	.
115	.	.	.	Goldmanite	.	.	×	.	.	.	.
80	×	.	.	Sanidine	.	.	×	.	.	.	.
108	.	.	.	.	.	.	×	.	.	.	.
1	×	.	.	.	.	.	×	.	.	.	.
272	.	.	.	.	.	Cuprite	×	.	.	.	.
72	.	.	.	.	.	Cuprite	×	.	.	.	.
195	.	.	.	.	.	Cuprite	×	.	.	.	.
316	×	.	.	.	.	Cuprospinel	×	.	.	.	.
225	.	.	.	.	.	.	×	.	.	×	.
203	.	.	.	.	.	.	×	.	.	×	.
85	.	.	.	Goldmanite?	.	.	×	.	.	×	.
72a	×	.	.	.	.	.	.	×	.	.	.
290	×	.	.	.	Hematite	.	.	×	.	.	.
288	.	.	.	Diopside, Augite	.	.	.	×	.	.	.
317	×	.	.	.	.	.	.	.	Chlorargyrite*	.	.
151	.	.	.	.	.	.	.	.	.	.	×

*More properly, a silver chloride-bromide

Fig. 2. Shahr-i Sokhta, XRD identification of the same rock and ore samples.

(1981). The problem with Heskel's data is that his text does not provide the information to establish the identity and the provenance of the analysed samples.

In 1977, further 25 samples were given to Thierry Berthoud and Juliette Liszak-Hours (Laboratoire de Recherche des Musées de France at the Louvre). Evidently, the mid-seventies were a period of great interest in Shahr-i Sokhta materials. These objects were analysed by the means of UV spectroscopy: the results were included in Berthoud's PhD thesis at the Pierre et Marie Curie University – Paris VI, a general overview of protohistoric copper exploitation in terms of mineral sources in the Near East. In 1980, Gerd Weisgerber and his collaborators of the Deutsches Bergbau Museum, Bochum, started their study of the materials on a series of 35 samples, mostly unfinished items and manufacturing residues. The analytical techniques included XRF and atomic absorption spectrometry (AAS). The results ended in some papers (Hauptmann 1980; Hauptmann/Weisgerber 1980; Helmig et al. 1991; Hauptmann et al. 2003) as well as in the PhD thesis of Detlev Helmig (1986).

Nr.	Arsenical ores and minerals
10	Quartz with Fe, Cu, Mo, As
108	Atacamite with As (main peak), Cu, Fe
272	Cuprite and Atacamite with Fe, As
195	Cuprite and Atacamite with Fe, As
225a	Atacamite and Digenite with As (main peak), Fe, Sn
203	Atacamite and Digenite with Fe, As, Mo

Fig. 3. Shahr-i Sokhta, arsenical ores.

In 1997, our team started to face the difficult task of tracking the whole process and identifying precisely which objects (or which parts of the same objects) were analysed by whom and, perhaps more crucial, assessing the comparability (or, as we rather expect, not) of the analytical results (Giardino/Lazzari 1997; 1998). At the same time, we shall try to understand such wide and diversified analytical effort in the wider frame of a holistic reconstruction of the copper working cycle and, possibly, its evolution in time.

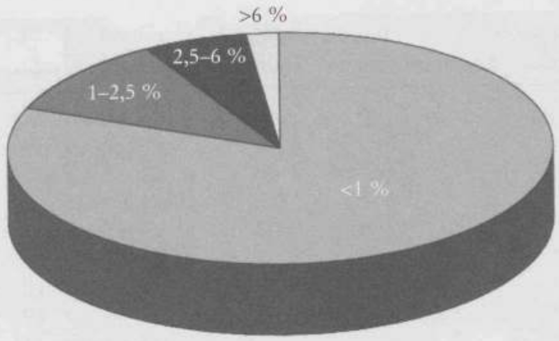

Fig. 4. Shahr-i Sokhta, arsenic % in copper objects.

Sources of copper in the Sistan basin and the neighbouring regions

According to Hauptmann et al. (2003), the analytical study of 15 samples of ores fragments, which are described as green metamorphic rocks, siliceous rocks coloured green by impregnated copper salts, and massive dark blue lumps of copper sulphides, was concentrated on the sulphidic parts of the ores; it revealed the following minerals: chalcocite/digenite (Cu_2S) and bornite (Cu_5FeS_4), with covellite (CuS) present as a weathering product of the first two. Minor phases in the same aggregates included magnetite (Fe_3O_4), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), graphite (C) and more rarely molibdenite (MoS_2). These mineral associations would be typical of skarn ores, produced by the intrusion of igneous fluids rich in ores into calcareous or siliceous host rocks in the upper crust. Besides sulphides and associated phases, Hauptmann and his colleagues report the presence of oxidic ores such as malachite intergrown with iron hydroxides. The analysed ores were, as a rule, very poor in As. Sulphidic and oxidic copper minerals were found in association. Always quoting Hauptmann et al. (2003, 199–200): "There was remarkably little deviation from this pattern of ore paragenesis among the studied samples, indicating a rather stable source of ore supply over the period of copper production at Shahr-i Sokhta." Such skarn formations, conclude the authors, are frequent in the mountain ranges surrounding Shahr-i Sokhta, and the nearest possible similar geological context is no more than 100 km far away from the city, to the northwest.

In a following statement (Hauptmann et al. 2003, 210), while commenting the results of a lead isotope analysis of a series of samples of prills, matte fragments, ingots and finished objects, as compared to some mineral samples gathered in contemporary mining areas, the authors provide additional hints. They analysed 2 fragments of ores excavated at Qaleh Zari, in the copper ore-bearing formation of the Kuh-i Malik Siah as well as 2 other ore samples coming from Chehel Kureh (about 100 km to the south-west of Shahr-i Sokhta). The ores were identified respectively as atacamite (copper chloride hydroxide, $Cu_2Cl(OH)_3$) atacamite and malachite, and atacamite (2 samples).

While lead isotope analysis, in general, suggested that the ore pieces found at Shahr-i Sokhta and analysed by the Bochum colleagues show little match with the metallurgical products, four finished artefacts match with the isotope abundance ratios of the Chehel Kureh, and one ore fragment matched with the two ore samples from Qaleh Zari. In the same context, the authors somehow tempered the previous statement on the homogeneity of the ore sources exploited at Shahr-i Sokhta, and affirm "... It would appear that there was a complex, multistage ore deposit (such as it might be the case with skarn deposit), or a multiplicity of ore sources that served the needs of Shahr-i Sokhta ..." (Hauptmann et al. 2003, 210).

According to Bazin and Hubner (1969) copper mineralization in the region Sistan-Balochistan is generally poor (after contemporary standards) with the exception of some sites on the south and south-western border of the Sistan basin: Shoveh, 25 km south-east of Nosratabad; the quoted Chehel Kureh mines, 45 km north-east of Nosratabad; Siah Jekul, 25 km east of the same town. The mining area of Chah Doust, is found 90 km south-southeast of Zahedan, and is somehow far from the southern margin of the Sistan flatlands. Other copper mines in the same general area are Haji Koshteh (17 km north of Zahedan) and Shor Kuh, geographically representing the extension of the mountains in the Chagai district. The copper mineralizations reported by Bazin and Hubner are the following: Shoveh: malachite, azurite and chrysocolla; Chehel Kureh mines: chalcocite, malachite (old workings with small pits filled with debris, dumps, 100 hectares of slag coverings produced by ore smelting in situ); Siah Jekul: malachite (old workings); Chah Doust: malachite, chalcantite; Haji Koshteh: malachite, azurite (old workings); Shohr-Kuh and Chagai districts: copper sulphides oxidized on surface. Copper chlorides are never mentioned.

These southern mining areas are one of the most likely sources of copper for the early urban centres of Sistan. On the southern border of Sistan, presently within the Afghan territory, rose the prehistoric city (reportedly strongly deflated by wind) of Gardan Reg, near the banks of the Rud-i Biyaban. Gardan Reg, in the beginning of the second half of the 3rd millennium BC, was probably as large as Shahr-i Sokhta and the major political centre of the southern part of the Sistan basin. The two cities were most probably connected through close economical and trade ties. A survey carried out by George Dales led to the discovery of wide areas littered with copper smelting slag, sometimes apparently found in huge dumps (see Fairservis 1952, 1961; Dales 1992). There is no mention of the presence of ore fragments in this dumping area, nor we know which types of metalliferous ores could have been mined in the immediate surroundings. According to Dales, some of the slag contained substantial amount of copper (14%) and traces of gold, but no further details were reported. If these extra-urban specialized smelting areas were contemporary with the great centre of Gardan Reg, they should be dated to Period III of Shahr-i Sokhta, around 2500–2400 BC (see also Kenoyer/Miller 1999, 116).

Mineralogical identification of 29 samples of metalliferous rocks

29 samples of rocks in the Rome collections were selected as possible ore fragments after visual inspection, and analysed both by Energy Dispersive X-rays Fluorescence (EDXRF) and X-rays diffraction (XRD) at the ICR labs in Rome. For qualitative XRF we used a specimen belonging to the new generation of movable spectrometers, employing miniaturized tubes and thermo-electrically cooled detectors (the tube was an EIS-XRG50, and we used multi-channel analyser Amptek MCA 8000, connected to a laptop). All selected samples showed variable amounts of copper, iron and, in one instance, lead; they were the subject of XRD. For XRD we used a RICH-Seifert ISO-DEBYEFLEX 3000. The results are reported in figs. 1 and 2.

Samples 10, 3, 2, 122, 99, and 287, although containing variable amounts of copper and iron, did not reveal, after XRD, detectable crystalline phases referable to metallic mineralizations (the detection limit is generally assumed to waver around 5% of the total). These samples might be interpreted as parts of silicatic rocks that are perhaps related to the ores gangue and were discarded before refining.

Sample 321 contains only magnetite in a silicatic matrix. All the other samples (but the last two) contain copper chlorides (atacamite and paratacamite) sometimes associated to copper oxides (mainly cuprite) and in three cases copper sulphide (digenite); in general these minerals appear associated to quartz and other silicates. Sample 317 contains a silver ore identified as chlorargirite or bromargirite (a silver chloride-bromide). This evidence might point to the smelting at Shahr-i Sokhta of silver minerals, perhaps without resorting to cupellation of lead-containing raw material. Finally, sample 151 was identified as lead sulphide or galena.

Conclusions

In general, these results confirm the conclusion offered by the colleagues in Bochum, namely that metallurgists of protohistoric Sistan exploited multistage ore deposits from skarn formations (the oxides possibly representing surface alteration of chlorides and sulphides). In contrast, we found little evidence of sulphidic raw material, while chlorides (atacamite and secondarily paratacamite) are well represented. This might be due to a biased sampling: previous investigators might have selected the most evident ore samples and pieces judged more suitable for mineralogical identification from the collections. On the other hand, as the conclusive report from Bochum (Hauptmann et al. 2003) presents mainly chemical and not mineralogical data on the 15 samples of ores, the new evidence might suggest the opportunity of reconsidering the role of chlorides in the exploitation strategies of the ancient metallurgists.

Although atacamite is not reported as a valuable copper mineral in the presently known mining areas on the southern mountain fringes of the Sistan basin, actually the identification of such a chloride as the main component in both of the four ore samples from the Kuh-i Malik Siah and Chehel Kureh mining areas (Hauptmann et al. 2003, Table 5), and in the archaeologically excavated ore samples from the city supports the impression that these mines were one of the main source areas for Bronze Age Sistan. They were also distinguished by extensive evidence of old workings. In this light, the southern urban pole of Gardan Reg must have obtained part of its welfare from the direct control and exploitation of these mining areas.

Another related question is the role of arsenic in the whole sequence. We enclose a table with the XRF-XRD identification of the six ore samples that showed significant traces of arsenic (fig. 3). Five samples were identified as atacamite, associated with cuprite or digenite. Thus, similar minerals, possibly coming from the southern fringe of Sistan, might be a source of the arsenic present in variable amounts in the copper artefacts from Shahr-i Sokhta.

It is still highly questionable whether arsenic was intentionally added to the molten copper; our preliminary observations (based upon an extensive XRF survey of the whole collection) confirm that the percentage of arsenic is very low in the slag cakes and in other slag forms, but it noticeably rises in the finished objects.

In a preliminary gross evaluation, taking into account the composite body of data so far available (fig. 4), we observed that about 81% of the samples contain arsenic in less than 1%; 11% of the samples fall between 1 and 2,5%; 6% have a medium arsenic content falling between 2,5% and 6%; while only 2% of the analysed samples contain more than 6% of arsenic (Giardino/Lazzari 1997; 1998). According to the experiments carried out by Tylecote (1976, 7–8) arsenic cannot pass from the ore to the refined metal in percentages higher than 7%; therefore, at least 2% of the total from the Shahr-i Sokhta collections should be considered an intentional product of an arsenic alloying technology.

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