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Late Bronze and Early Iron Age copper smelting technologies in the South Caucasus: the view from ancient Colchis c. 1500–600 BC

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ABSTRACT

Many of the arguments for how and why people began to use iron in Southwest Asia rely on assumptions about the technology and relative organization of copper and iron smelting. However, research on the technological transformations of the Late Bronze Age and Early Iron Age suffers from a lack of investigation of primary metal production contexts, especially in regions outside the Levant. The current research examines metal production debris from a large number of smelting sites in western Georgia, and addresses questions of technology and resource utilization through detailed examination of few select sites. Through the chemical and mineralogical analysis of slag samples, we demonstrate the existence of an extensive copper-production industry and reconstruct several key aspects of the smelting technology during the Late Bronze Age and Early Iron Age. Combining a statistical analysis of slag mineralogy with other lines of evidence, we argue that copper was extracted from sulfide ores through a process of roasting and smelting in deep pit furnaces. The data also suggest that metalworkers at different sites exploited different ore sources within the same ore body. These results form a fundamental basis for further examination of spatial and chronological patterns of technological variation, with implications for models of Near Eastern copper production in this crucial period. Intriguing evidence of bloomery iron smelting, though currently undated, reinforces the region's potential to provide data on a key technological transformation.

1. Introduction

The organization of metal production and the processes of technological change are key areas of interest for archaeologists studying the Eastern Mediterranean and the Southwest Asia. Yet despite a number of theories about the reasons for the rise of iron production, many significant questions remain about technological and social changes occurring during this period.

Perhaps the single most significant reason for the lack of resolution on many of these issues is the absence of data on the technology and organization of metal production activities in the Late Bronze Age (LBA) and Early Iron Age (EIA). Investigations of LBA–EIA copper smelting are rare in Southwest Asia outside of a few well-studied regions such as Cyprus (Kassianidou, 2012; Knapp, 2012) and the Southern Levant (Barker et al., 2007; Hauptmann, 2007; Levy et al., 2012). For iron, the picture is even more sparse. There is only one well-studied example of primary iron smelting (Tell Hammeh, Jordan), and only a few secondary iron smithing workshops have been found dating to before about 500 BC (Eliyahu-Behar et al., 2008; Eliyahu-Behar et al., 2012; Veldhuijzen, 2012; Veldhuijzen and Rehren, 2007).

Without evidence from primary production contexts for both iron and copper alloys, it is very difficult to test theories about how iron production emerged. Many argue that the organization and distribution of copper/bronze and iron production differed in significant ways, making iron more attractive than bronze for certain types of objects. Iron's geological ubiquity, contrasted with copper and tin's geological rarity, remains a significant feature of many explanations (Mirau, 1997:110–111), even if the hypothesis of a tin shortage driving the spread of iron has lost popularity (Muhly, 2003:180, Waldbaum, 1999:39). The assumption that the distribution of early iron production matched the geological distribution

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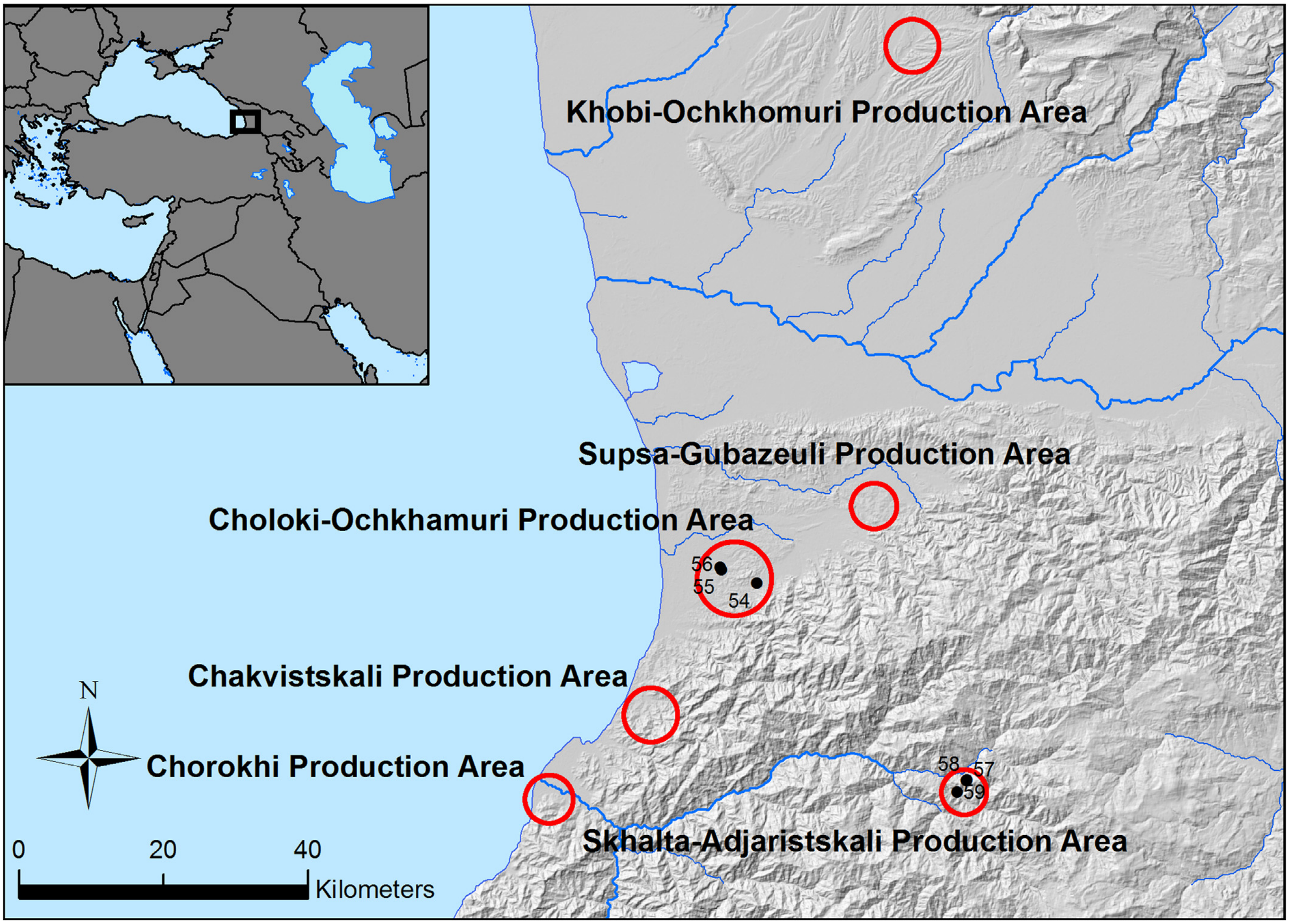

Fig. 1. Map of Colchis showing key metal producing areas. Smelting sites outside of the Supsa–Gubazeuli production area are marked on the map. Elevation data: SRTM.

of ore deposits ignores the human element of production. The landscape of technical knowledge and socio-technic practices likely had a huge influence on where and how iron production developed.

The western part of the Republic of Georgia, known in ancient times as Colchis, is an ideal place to investigate the relationship between copper and iron production (Fig. 1). Archaeological excavations and chance finds have yielded huge numbers of both copper-base and iron artifacts, and the region is extremely rich in copper and iron ores (Gambashidze et al., 2001; Mikeladze and Baramidze, 1977; Nazarov, 1966; Papuashvili, 2011; Tvalchrelidze, 2001). Evidence of metal production occurs both in settlement sites (casting molds and tuyères) (Mikeladze, 1990:26), and at dedicated smelting sites. Previous analyses of slags from Colchian metal production sites offer contradictory interpretations about whether iron or copper was produced (Inanishvili, 2007; Nieling, 2009:257–259, Tavadze et al., 1984).

In order to examine the organization and technology of LBA–EIA metal production, we have started a new field project to locate, map, and investigate new and previously-identified smelting sites. This paper focuses on the identification of metal smelting debris and the technologies of metal smelting. The clarification of these production processes is fundamental to further research for two reasons. First, by establishing the various activities which occurred at each site, we can gain a clearer picture of the organization of craft production. Spatial variations in resource acquisition and production practices may suggest varying practices across different communities, and may hint at the participation of distinct social groups in the production process.

Second, through a reconstruction of smelting technologies, we can begin to understand how metalworkers adapted or preserved traditions of copper production during the emergence of iron smelting technology. A number of scholars have argued that iron was invented by the accidental production of iron in the process of copper or lead smelting (Charles, 1980:165–166, Gale et al., 1990; Pigott, 1982:21, Wertime, 1964:1262), though direct evidence for this is lacking (Merkel and Barrett, 2000). Regardless of whether the invention of iron occurred in this way, it is reasonable to hypothesize that experience in manipulating ores at high temperatures, gained through the smelting of copper, would have impacted the adoption and spread of iron technology. One perspective might argue that early iron technologies would flourish in regions that also had long-standing traditions of copper production. A contrary view might propose that an elaborate and conservative tradition of bronze production would slow the social acceptance and adoption of iron and iron-making technologies (Japaridze, 1999:65). Testing these models requires accurate reconstructions of technical practices and clear evidence for the contexts of different production activities. The goal of the present study is to determine what kinds of metal were produced at smelting sites in western Georgia, identify the types of ores used, and reconstruct the practices used in the smelting process. This is a fundamental first step in the investigation of questions of economic organization, resource acquisition, and the social context of technological change.

2. Metal smelting in western Georgia

Hundreds of smelting furnaces have been reported in the region, some of which have been excavated (Gzelishvili, 1964; Khakhutaishvili, 1976, Khakhutaishvili, 2009 [1987], Khakhutaishvili, 2006; Khakhutaishvili, 2008). Most of the previous radiocarbon and paleomagnetic dates for these sites fall between c. 1500–600 BC, with one or two sites attributed to the period of Greek colonization and influence (beginning in the mid 1st millennium BC), and a few to the first half of the 2nd millennium BC (Khakhutaishvili, 2009 [1987]:105–106). Limited ceramic evidence also suggests that most sites belong to the Late Bronze and Early Iron Age.

In two seasons of fieldwork, we have mapped over 50 smelting sites in the region. The main focus in these two seasons was the region of the Supsa and Gubazeuli rivers (Fig. 2), which yielded the oldest dates in earlier fieldwork (Khakhutaishvili, 2009 [1987]:105–106). From a regional perspective, metallurgical activity seems to have been clustered in several production areas, probably due to the location of the necessary resources: ore, fuel,

Fig. 3. Copper smelting furnace excavated at site 46, showing a ring of reddish burned clay surrounding the pit. The length of the scale bar is 1 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

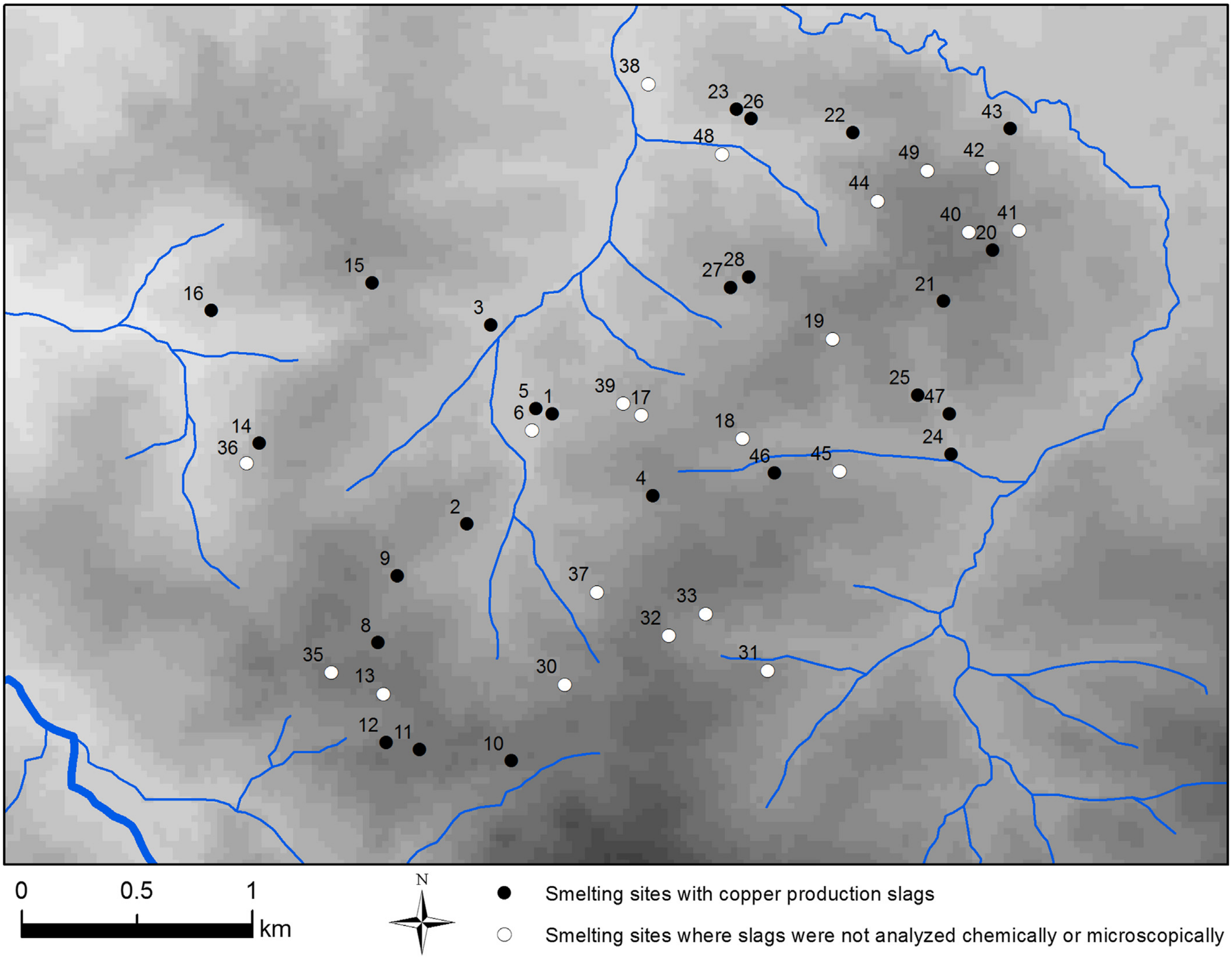

Fig. 2. Map of smelting sites discovered in the Supsa–Gubazeuli production area. Elevation data: ASTER GDEM (a product of METI and NASA).

and clay (Fig. 1). However, within these areas, metal production sites are quite dispersed. Previous excavations have shown that they generally consist of the one or two furnaces, a scatter of slag, and sometimes a small platform with signs of burning. Furnaces take the form of pits dug into the natural clay substrate, usually to a depth of a little over 1 m (Khakhutaishvili, 2009 [1987]) (Fig. 3). Large amounts of partially vitrified and slagged ceramic material strongly suggest that these pits were lined with a layer of clay. The presence of tuyère fragments, some which are slagged, indicate the method of delivering air to the furnace, but the exact geometry of tuyère positioning is not clear. A large proportion of tuyère fragments are not slagged, and larger fragments show unusual curvature, flared interlocking sections, and occasional side holes, suggesting a rather complex air delivery system that probably used a forced draft (see Khakhutaishvili, 2009 [1987]:43, 67, 73, 88, 100).

Buildings or other habitation evidence have not been found in close proximity to these sites, and non-metallurgical pottery is often present in only small amounts, even in fully excavated sites (e.g. Khakhutaishvili, 2009 [1987]:55, 58). While the size of each individual slag heap does not approach the massive scale seen elsewhere in the Near East (Levy et al., 2004), in aggregate the sites represent an extensive landscape of production. Considering the extremely dense vegetation and the small size of the slag heaps, it is likely that the rough count of 400 sites mentioned by David Khakhutaishvili (2009 [1987]:17), represents a lower limit for the actual number of sites in the LBA–EIA.

As the primary form of material culture found at smelting sites in Colchis, slags are crucial for reconstructing the kinds of activities that occurred there. Detailed analysis of these materials can reveal the type of metal produced, the kinds of ores used, and can differentiate between secondary shaping (casting and forging) and primary smelting. Moreover, the examination of the mineral phases present in the slag can reveal the atmospheric conditions in the smelt, and help to reconstruct the smelting process.

The discussion about whether sites in western Georgia represent the remains of copper or iron production has centered around a limited number of chemical and microstructural analyses. Wüstite (FeO) and metallic iron are characteristic features of bloomery iron slags. Although copper smelting slags contain various iron oxides and occasionally metallic iron, they are clearly distinguished by the presence of copper-bearing phases, visible in polished sections under the microscope.

Previous analyses of slags from smelting sites in western Georgia offer contradictory interpretations. Early studies of these slags (Tavadze et al., 1984) argue that they represent the remains of iron production, pointing to the presence of wüstite and metallic iron in the slags. Published photomicrographs show abundant dendritic minerals, and metallic iron was reported. Neither copper metal nor copper-bearing mineral phases are mentioned (Inanishvili, 2007; Tavadze et al., 1984). On the other hand, the discovery of copper sulfides in a more recent analysis of a few slags led Nieling to interpret them as the result of a matte smelting operation, which produces a consolidated mass of copper sulfides, known as matte, as an intermediate stage of production (2009:257–259). However, not all slags with sulfides in them are the result of a true matte smelting process, in which the matte is produced in an initial stage before being crushed, roasted in an oxidizing atmosphere, and then smelted again.

Unfortunately, only a small number of photomicrographs, which are crucial for determining the type of slag, have been published. Bulk chemical analysis is reported for a larger number of samples (Inanishvili, 2007:12–13), but copper and iron smelting slags can be very close in bulk chemical composition, with the only distinction being the presence in the former of roughly 0.5–3.0 wt.% copper (Pleiner, 2000:254). Iron smelting slags typically have copper values under 200 ppm (0.02 wt.%) (Humphris et al., 2009:364, Veldhuijzen and Rehren, 2007:194). However, published bulk chemical analyses of slags from Colchis do not report the copper content.

3. Analytical methods of slag analysis

Slag was collected from surface scatters, previously excavated material remaining at the sites, and new excavated contexts. 134 samples of slag and 1 sample of matte from 34 sites were mounted and analyzed by the author (NES) via optical microscopy, while a subset of these (102 slag samples from 24 sites) has also been analyzed using scanning electron microscopy in order to determine the mineralogy and chemistry of the sample. The samples come from sites in the Supsa–Gubazeuli, Choloki–Ochkhamuri, and the Skhalta–Adjaristskali production areas (Fig. 1). For each sample, mineral phases and inclusions (e.g. charcoal, partially reacted gangue fragments, pieces of partially melted technical ceramic) were coded as being present in a significant number of instances (coded as “2”), present in rare isolated instances (coded as “1”), or not identified in the sample (coded as “0”). Mineralogical identifications were carried out by reflected-light optical microscopy cross-checked with energy dispersive X-ray microanalysis (EDS). Morphology, optical properties, elemental composition, and paragenetic associations were used to make identifications.

In order to obtain major element chemical compositions, EDS area analyses were carried out on fully melted regions of the sample, avoiding unmelted inclusions, corroded areas, and large voids. Analyses of at least four different areas were averaged together. In nearly all cases, intra-sample variation was minor. All SEM analyses were carried out by the author (NES), using an Oxford Instruments INCA X-Sight EDS system at the Museum of Fine Arts in Boston.

4. Analytical results of slag analysis

4.1. Macroscopic analysis of copper smelting slags

The surfaces of most slags are covered with buff to reddish-orange corrosion. Tell-tale copper-green corrosion was only rarely observed. Slags from the Supsa–Gubazeuli and Choloki–Ochkhamuri production areas can be categorized into several macroscopic groupings.

The most distinct and easily recognizable type of slag consists of fragments of dense cakes with few voids. The slag matrix is very homogeneous, and there are usually very few partially reacted inclusions. Larger, more complete examples show that these slags are parts of large cakes, with variable diameters typically about 20–30 cm, and thicknesses around 10 cm. The rarity of complete cakes is most likely a result of the ancient metalworkers breaking them apart to free material that pooled underneath, probably copper matte (sulfides) or copper metal. While the upper surface of these slag cakes is more common, one example (Fig. 4, right) has a particularly well preserved bottom surface, which shows the formation of a meniscus at the interface between the slag and the metal or matte below it. Slags of this type probably formed at the bottom of the deep pit furnaces.

A second category of slag consists of amorphous, sponge-like masses, often with charcoal fragments encased within the slag matrix. Slags of this type often contain numerous partially reacted minerals and rock fragments (Fig. 4, left). Small amorphous drips, splashes, and lumps of slag were also assigned to this category. A rare third type of slag, sometimes difficult to distinguish from the amorphous spongy slag, was designated tap slag. These glassier slags show evidence of rapid cooling and flow patterns. However,

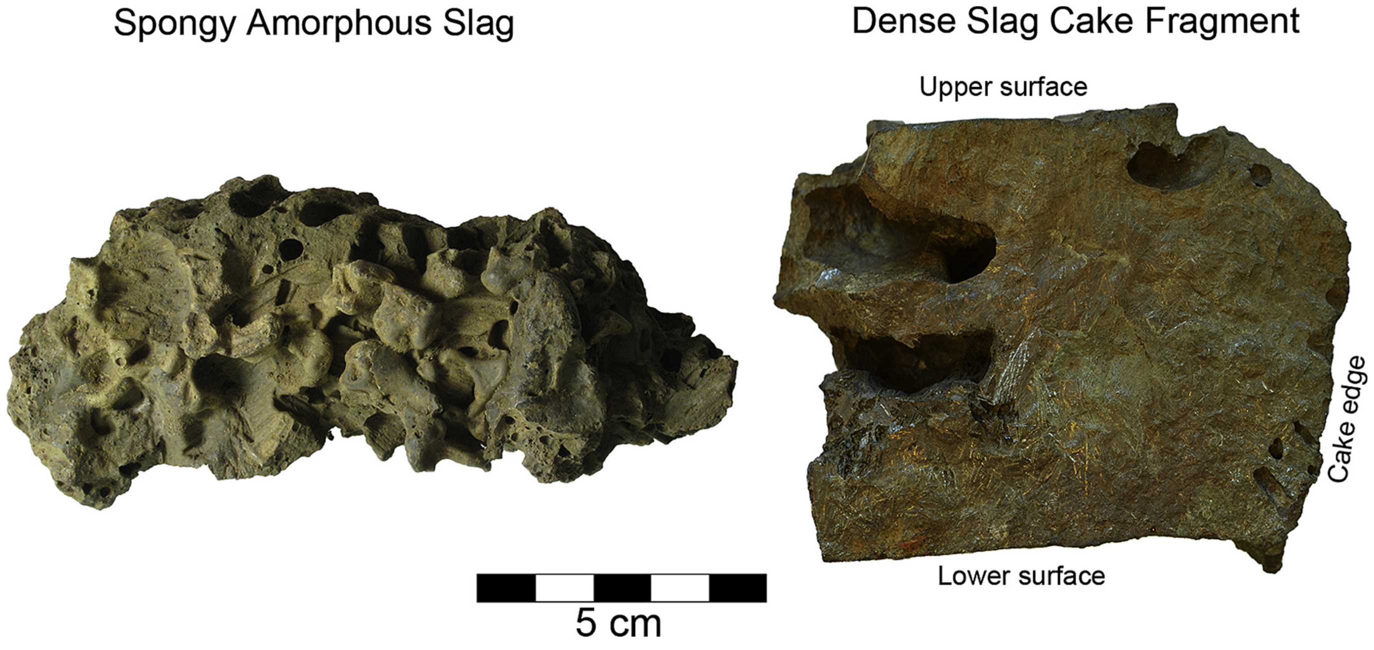

Fig. 4. Examples of a spongy amorphous copper smelting slag (sample 301) and a copper smelting slag cake fragment (sample 4301).

this type of slag is rare at sites in the Supsa–Gubazeuli and Choloki–Ochkhamuri areas.

There are strong similarities between the slag cake fragments and the copper smelting slags found at the LBA site of Politiko Phorades on Cyprus (Kassianidou, 1999; Knapp and Kassianidou, 2008). Knapp and Kassianidou (2008:144) argue, on the basis of experimental work (Bamberger and Wincierz, 1990:133) that slags of this type were formed by draining the whole contents of the furnace into a pit. In our case, however, this tapping process is highly unlikely, given the even pattern of burning encircling the pit furnaces we have excavated (Fig. 3). This pattern, along with the depth of the pit, suggests that the pits are the reaction chambers of the furnaces, not forehearths into which the furnace contents were drained. Moreover, there is no trace of any possible furnace structure off to the side of the pits we excavated. Earlier excavation reports reveal similar patterns for nearly all other furnaces, with two possible exceptions. In these cases, the excavator described unusual shallow depressions filled with burned clay and charcoal and adjoining the typical deeper stone-lined pit. However, these shallow depressions were interpreted as the location of the bellows (Khakhutaishvili, 2009 [1987]:69, 72). Because we have not found any of these shallow depressions in our current project, it is difficult to speculate further on their function.

4.2. Mineralogy and chemistry of copper smelting slags

The vast majority of the slags analyzed for the current study, including all samples from the Choloki–Ochkhamuri and Supsa–Gubazeuli production areas, are the remains of copper smelting. Most slags are characterized by the presence of olivine ($(Fe,Mg)_2SiO_4$), as well as variable amounts of magnetite (Fe_3O_4) and less commonly wüstite (FeO) (Fig. 5). Hematite (Fe_2O_3) was observed in a few samples, but may be either post-depositional alteration or a partially reacted addition to the furnace. A wide range of copper and iron sulfide phases were identified in the slags. Most common are chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), iron sulfide (probably originally pyrite (FeS_2), but transformed into pyrrhotite ($Fe_{1-x}S$) at high temperatures), sphalerite ((Fe,Zn)S), and covellite (CuS). Chalcocite (Cu_2S), and digenite (Cu_9S_5) also appear frequently. These mineral phases were identified microscopically in matte prills solidified from the melt, and, in the case of copper–iron sulfides, the iron sulfide, and sphalerite, in primary, partially-reacted ore and gangue fragments. Bornite and chalcopyrite are often finely interspersed in both matte prills and partially reacted ore inclusions. By contrast, copper oxides such as cuprite (Cu_2O) and malachite ($Cu_2CO_3(OH)_2$) were found only occasionally, and their morphology suggests that most are post-depositional corrosion of copper sulfides or copper metal. Fragments of partially reacted ore and gangue consist of various combinations of finely interspersed quartz, iron oxide, sphalerite, copper–iron sulfide, and iron sulfide (Fig. 6). Chalcopyrite and pyrite were probably the original copper and iron sulfides in the ore, but high temperatures has partially transformed chalcopyrite

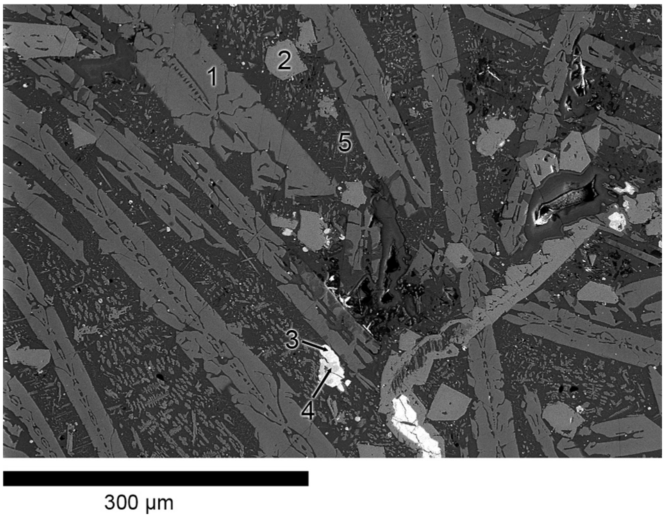

Fig. 5. SEM backscatter image of a typical copper smelting slag (sample 2702) showing fayalite (1), magnetite (2), copper–iron sulfide (ex-solution texture of chalcopyrite and bornite) (3) and iron sulfide (4) in a glassy matrix (5).

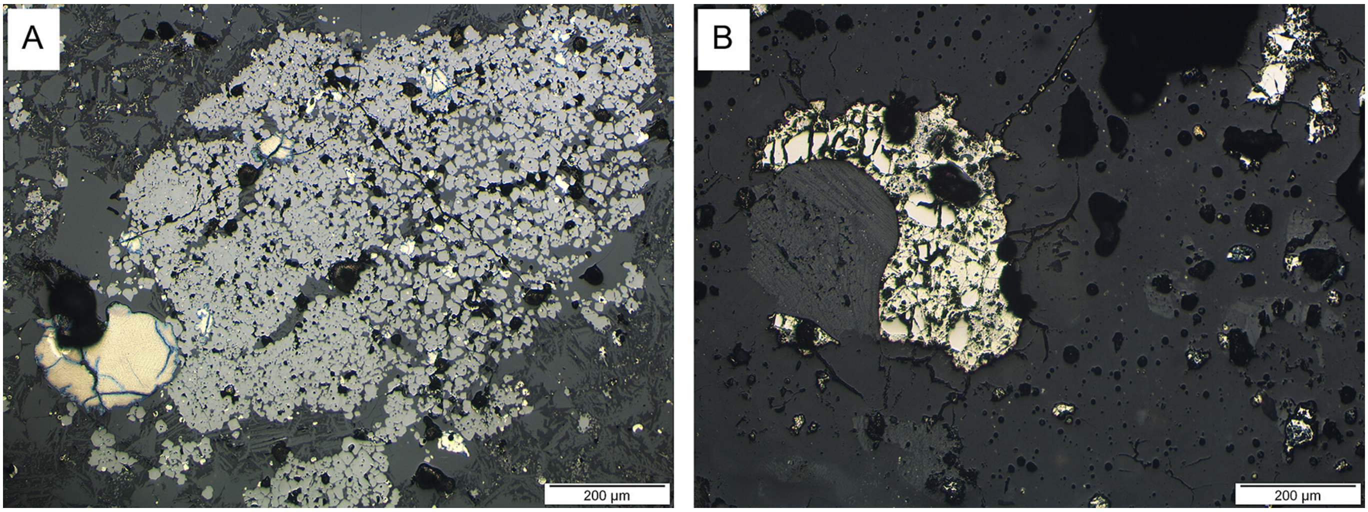

Fig. 6. A. Optical photomicrograph of sample 515 showing copper sulfides (a yellow ex-solution mixture of chalcopyrite and bornite rimmed with blue covellite) embedded in an iron oxide matrix (light gray). B. Optical photomicrograph of sample 1402, showing copper and iron sulfides (bright yellow) dispersed in a partially melted silica-rich matrix (dark gray), probably originally quartz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

into bornite, and the pyrite into pyrrhotite (Kullerud and Yoder, 1959; Yund and Kullerud, 1966:464–465). The single small fragment of matte, recovered from the surface of site 15, consists almost entirely of the phase covellite (CuS) with the minimal presence of other sulfides phases.

Despite broad similarities, the mineral content and chemistry of the slags show some important variations. First, copper metal was found in significant amounts (coded as 2) in only 19% of slags (24 of 129). Furthermore, there were statistically significant variations between the presence of metallic copper and the presence of certain sulfide minerals. 75% (18 of 24) of all slags with significant amounts of metallic copper in them have large amounts of iron-poor, copper-rich matte (either Cu_9S_5 or Cu_2S), while only 21% (22 of 105) of all slags with little or no metallic copper have iron-poor matte (Table 1). Chi-squared analysis demonstrated the statistical significance of this patterning ($\chi^2 = 26.67$, $p = 2.4 \times 10^{-7}$, df = 1). Furthermore, 90% (94 of 105) of all slags without significant copper metal in them have a significant copper–iron sulfides (mostly $CuFeS_2$ or Cu_5FeS_4), while only 54% (13 of 24) of slags with significant amounts of metallic copper have copper–iron sulfides (Table 2). Likewise, chi-squared analysis demonstrated the statistical significance ($\chi^2 = 17.26$, $p = 3.2 \times 10^{-5}$, df = 1). A similar pattern is visible when looking at purely iron sulfides—57% (60 of 105) of samples without abundant copper metal have iron sulfides, whereas only 21% (5 of 24) of samples with significant amount of metallic copper have them ($\chi^2 = 10.30$, $p = 0.0013$) (Table 3). Taken together, these analyses show a relationship between the presence of copper metal, the presence of iron-poor copper-enriched sulfides, and the *absence* of more iron-rich sulfide phases. Given that nearly all the sulfides observed in partially melted rock fragments were copper–iron sulfides (such as $CuFeS_2$ and Cu_5FeS_4), sphalerite, or iron sulfides, the Cu_2S and Cu_9S_5 phases are probably the result of the oxidation of iron out of the original ore consisting of chalcopyrite and possibly some bornite.

Finally, some chemical and mineralogical characteristics varied between sites. In the 14 samples analyzed from site 5, none were coded as 2 for copper metal. By contrast, 7 of the 11 samples from site 47 had significant quantities of copper metal in them (copper metal coded as 2). Secondly, slags from some sites have a significant amount of zinc (Table 4). Sphalerite ((Zn,Fe)S) was found both in partially reacted gangue inclusions, and as dendrites crystallizing out of the slag (Fig. 7). We found no zinc-containing slags at some sites (e.g. site 5), while at others (e.g. site 8) nearly every sample had an appreciable amount of zinc. Likewise, all but one sample

Table 1
Relationship between the presence of copper metal and the presence of iron-poor copper-rich sulfides (Cu_2S or Cu_9S_5) in copper smelting slags.

	No significant Cu_2S or Cu_9S_5 (both coded as 0 or 1)	Significant presence of Cu_2S or Cu_9S_5 (either or both coded as 2)	Total
No Significant Cu Metal (coded as 0 or 1)	83	22	105
Significant Cu Metal (coded as 2)	6	18	24
Total	89	40	129

Table 2
Relationship between the presence of copper metal and the presence of copper–iron sulfides ($CuFeS_2$ or Cu_5FeS_4) in copper smelting slags.

	No significant $CuFeS_2$ or Cu_5FeS_4 (both coded as 0 or 1)	Significant presence of $CuFeS_2$ or Cu_5FeS_4 (either or both coded as 2)	Total
No Significant Cu Metal (coded as 0 or 1)	11	94	105
Significant Cu Metal (coded as 2)	11	13	24
Total	22	107	129

Table 3
Relationship between the presence of copper metal and the presence of iron sulfides (FeS_2 or $Fe_{1-x}S$) in copper smelting slags.

	No significant FeS_2 (coded as 0 or 1)	Significant presence of FeS_2 (coded as 2)	Total
No Significant Cu Metal (coded as 0 or 1)	45	60	105
Significant Cu Metal (coded as 2)	19	5	24
Total	64	65	129

Table 4
Normalized EDS area analyses of slags in oxide wt.%. Compositions reflect the average value of at least four different area measurements of 60 s duration. By empirical examination of EDS spectra, the detection limit was conservatively determined to be about 0.25 wt.%. Compositions less than that were listed as below detection limit (bdl).

Sample	Site #	Site name[a]	Date[b]	Prod. area[c]	Product[d]	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_2	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	BaO
101	1	Askana I	10th–9th c. BC	SG	C	2.1	6.6	12.5	45.4	0.6	bdl	1.4	6.6	0.6	bdl	23.5	0.6	bdl	bdl
201	2	Askana VI		SG	C	0.7	2.2	9.1	38.5	0.4	2.7	1.3	2.4	0.5	0.3	37.7	0.4	3.0	0.8
202	2	Askana VI		SG	C	1.3	1.4	8.2	32.9	bdl	3.6	1.1	2.6	0.3	0.3	42.5	0.4	4.3	1.1
301	3	Askana VII		SG	C	0.5	6.0	15.8	41.0	0.5	bdl	3.6	13.6	0.5	0.4	17.6	0.6	bdl	bdl
302	3	Askana VII		SG	C	0.4	5.9	11.7	40.9	0.5	0.5	2.0	9.0	0.4	0.3	27.6	0.5	bdl	0.4
303	3	Askana VII		SG	C	0.7	2.0	11.0	40.6	bdl	1.3	2.2	6.3	bdl	bdl	33.5	0.3	bdl	2.2
401	4	Askana XIV		SG	C	1.3	0.7	7.6	35.0	bdl	1.3	1.2	1.6	0.5	bdl	40.6	0.4	7.1	2.9
402	4	Askana XIV		SG	C	1.6	0.8	7.3	36.5	bdl	4.3	1.5	1.9	0.4	bdl	32.4	0.4	9.8	3.0
501	5	Askana V		SG	C	1.0	2.8	10.3	35.7	0.3	2.3	3.1	4.0	0.3	bdl	39.9	0.3	bdl	bdl
502	5	Askana V		SG	C	1.0	1.9	12.2	40.0	0.3	1.2	2.8	3.9	0.5	bdl	35.8	0.3	bdl	bdl
503	5	Askana V		SG	C	1.6	2.4	11.8	34.9	0.4	1.9	2.9	4.0	0.4	0.3	38.8	0.6	bdl	bdl
504	5	Askana V		SG	C	0.5	1.5	8.9	28.1	0.3	1.6	1.5	2.1	0.4	bdl	54.7	0.5	bdl	bdl
506	5	Askana V		SG	C	0.9	2.0	11.3	34.8	0.4	2.3	2.4	4.7	0.5	bdl	40.5	0.3	bdl	bdl
508	5	Askana V		SG	C	0.9	1.8	10.1	34.6	0.3	1.2	2.3	4.5	0.4	bdl	43.0	0.5	bdl	0.4
510	5	Askana V		SG	C	0.3	2.4	10.4	29.9	0.4	2.1	1.8	2.6	0.3	bdl	49.0	0.7	bdl	bdl
511	5	Askana V		SG	C	0.8	4.2	13.8	46.6	0.4	0.6	4.7	5.1	0.6	0.3	22.3	bdl	bdl	0.5
512	5	Askana V		SG	C	1.0	1.7	8.5	27.2	0.3	4.1	2.1	2.5	0.4	bdl	51.7	0.8	bdl	bdl
513	5	Askana V		SG	C	0.5	1.9	8.6	28.8	bdl	2.2	1.7	2.4	0.4	bdl	52.9	0.6	bdl	bdl
514	5	Askana V		SG	C	0.9	2.9	10.7	32.5	0.4	2.3	2.9	4.0	0.4	bdl	42.0	0.3	bdl	0.6
515	5	Askana V		SG	C	0.5	1.6	7.2	34.4	bdl	3.4	1.9	1.7	bdl	bdl	48.2	1.2	bdl	bdl
516	5	Askana V		SG	C	0.6	2.7	12.0	40.3	0.3	1.4	4.0	2.4	0.4	bdl	35.5	0.4	bdl	bdl
517	5	Askana V		SG	C	1.4	2.4	11.2	35.7	0.3	1.8	3.3	3.5	0.3	bdl	39.7	0.5	bdl	bdl
801	8	Askana II	15th–13th c. BC	SG	C	2.6	0.7	4.0	28.5	0.3	6.6	0.9	2.2	bdl	bdl	35.0	0.5	15.9	2.7
802	8	Askana II	15th–13th c. BC	SG	C	2.1	0.5	4.5	40.2	bdl	1.9	0.8	1.6	0.4	bdl	35.3	bdl	10.9	1.8
803	8	Askana II	15th–13th c. BC	SG	C	2.9	0.8	4.9	30.7	0.3	1.6	1.3	2.7	0.3	bdl	36.9	0.4	15.2	1.9
804	8	Askana II	15th–13th c. BC	SG	C	1.8	0.8	6.4	30.9	bdl	3.0	1.4	1.8	0.3	bdl	40.4	0.5	10.1	2.5
805	8	Askana II	15th–13th c. BC	SG	C	1.9	0.6	4.5	41.2	bdl	2.5	0.8	1.6	0.4	bdl	33.4	0.4	10.5	2.1
806	8	Askana II	15th–13th c. BC	SG	C	1.0	0.9	6.4	21.9	0.3	1.8	1.4	2.0	0.3	bdl	57.9	2.8	3.2	bdl
807	8	Askana II	15th–13th c. BC	SG	C	1.4	1.2	3.8	28.5	0.3	3.1	1.1	2.1	bdl	bdl	51.7	0.4	6.5	bdl
808	8	Askana II	15th–13th c. BC	SG	C	0.6	1.1	6.6	31.3	0.3	2.5	1.1	2.6	0.3	0.4	49.5	0.4	2.7	0.5
809	8	Askana II	15th–13th c. BC	SG	C	1.6	0.9	6.7	31.4	bdl	1.6	1.5	1.6	0.4	bdl	42.5	0.3	8.7	2.9
810	8	Askana II	15th–13th c. BC	SG	C	2.1	0.4	3.6	36.8	bdl	4.2	0.6	1.1	0.3	bdl	35.8	0.4	12.4	2.3
811	8	Askana II	15th–13th c. BC	SG	C	2.0	0.5	4.5	43.1	bdl	1.8	0.8	1.5	0.4	bdl	33.5	bdl	10.1	1.9
812	8	Askana II	15th–13th c. BC	SG	C	0.6	2.1	11.2	35.5	0.3	1.7	2.5	4.6	0.5	0.3	39.8	0.5	bdl	0.3
813	8	Askana II	15th–13th c. BC	SG	C	0.7	1.5	12.0	39.3	0.4	0.5	3.5	1.6	0.4	bdl	39.8	0.3	bdl	bdl
814	8	Askana II	15th–13th c. BC	SG	C	1.2	1.0	8.4	39.0	bdl	2.7	1.2	2.6	0.3	0.3	34.9	0.5	6.1	1.8
901	9	Askana IX		SG	C	0.4	3.2	7.1	26.2	0.4	1.6	1.3	4.1	bdl	0.3	54.4	0.9	0.3	bdl
1002	10	Askana XXI		SG	C	1.0	1.1	7.8	31.6	0.3	3.3	1.0	1.9	bdl	bdl	46.5	0.6	3.5	1.4
1201	12	Askana XXIII		SG	C	0.6	1.3	8.6	28.9	0.4	0.5	1.3	1.1	0.4	bdl	53.6	0.5	2.2	0.7
1202	12	Askana XXIII		SG	C	1.0	1.6	8.4	33.7	0.4	2.0	1.2	2.6	0.4	bdl	43.2	0.5	4.1	1.0
1402	14	Mshvidobauri I	10th–8th c. BC	SG	C	1.3	1.4	8.7	41.4	0.3	2.2	1.3	2.8	0.5	bdl	31.2	0.6	6.4	1.9
1501	15	Askana III(?)		SG	C	0.7	5.5	11.2	40.4	0.6	0.3	2.6	12.6	0.4	0.3	24.1	0.5	0.5	0.3
1601	16	Nagomari I	18th–17th c. BC; 10th–9th c. BC	SG	C	1.2	2.9	10.6	38.6	0.4	1.2	1.8	4.6	0.5	0.3	33.6	0.5	2.9	0.9
1602	16	Nagomari I	18th–17th c. BC; 10th–9th c. BC	SG	C	0.8	2.6	9.9	42.3	0.5	2.2	3.0	3.9	0.3	bdl	34.1	0.4	bdl	bdl
1603	16	Nagomari I	18th–17th c. BC; 10th–9th c. BC	SG	C	0.9	2.6	11.2	36.1	0.4	1.3	2.6	3.8	0.5	0.3	39.8	bdl	bdl	0.5
2401	24	Mziani XVII		SG	C	1.6	1.8	7.4	42.9	0.3	1.3	1.4	2.9	0.5	bdl	31.3	0.4	6.7	1.5
2403	24	Mziani XVII		SG	C	bdl	4.0	10.5	26.1	0.5	2.3	0.8	1.2	0.5	bdl	51.8	2.4	bdl	bdl
2501	25	Mziani XVI		SG	C	0.8	1.2	7.3	24.9	bdl	2.7	1.7	2.7	bdl	bdl	57.5	1.1	bdl	bdl
2502	25	Mziani XVI		SG	C	1.0	1.6	10.0	30.8	0.4	1.3	2.7	3.6	0.3	bdl	47.7	0.7	bdl	bdl
2701	27	Mziani XI		SG	C	0.3	3.5	15.0	36.2	0.5	0.8	1.5	13.8	0.3	0.3	27.5	0.3	bdl	bdl
2702	27	Mziani XI		SG	C	0.6	1.6	10.2	37.2	0.3	1.2	1.7	3.9	0.4	bdl	40.8	0.4	bdl	1.8
2704	27	Mziani XI		SG	C	0.7	1.4	15.2	57.0	bdl	bdl	6.6	1.2	0.3	bdl	16.9	0.5	bdl	bdl
2801	28	Mziani X		SG	C	0.5	2.3	8.6	34.2	0.3	0.8	2.2	0.7	0.3	bdl	49.4	0.3	bdl	0.4
2802	28	Mziani X		SG	C	1.4	0.5	6.4	33.1	0.3	4.4	1.0	2.0	0.3	bdl	40.9	0.5	7.1	2.0
4602	46	Askana XVII		SG	C	bdl	1.6	5.0	23.1	bdl	0.7	1.0	0.7	bdl	bdl	67.4	0.5	bdl	bdl
4603	46	Askana XVII		SG	C	0.6	2.4	11.0	36.3	0.3	0.4	2.4	3.6	0.3	bdl	39.3	bdl	bdl	3.3
4604	46	Askana XVII		SG	C	0.5	2.2	7.0	37.9	bdl	1.9	2.1	6.0	bdl	0.3	41.6	0.5	bdl	bdl
4605	46	Askana XVII		SG	C	0.4	3.9	10.1	37.6	0.4	1.8	1.3	2.9	0.5	bdl	40.5	0.3	0.4	bdl
4606	46	Askana XVII		SG	C	0.8	1.7	8.2	24.5	bdl	2.3	2.2	2.3	0.3	bdl	56.3	1.2	bdl	0.3
4607	46	Askana XVII		SG	C	1.0	1.4	7.6	30.7	0.4	1.6	1.9	2.4	bdl	bdl	51.4	1.6	bdl	bdl
4608	46	Askana XVII		SG	C	0.6	3.5	10.0	33.4	0.4	1.3	1.5	5.3	0.4	bdl	43.1	0.5	bdl	bdl
4609	46	Askana XVII		SG	C	0.9	1.3	8.3	30.4	0.3	2.0	2.0	2.6	0.3	bdl	51.5	0.5	bdl	bdl
4610	46	Askana XVII		SG	C	0.7	1.5	7.4	24.6	bdl	2.9	1.7	3.8	0.4	0.3	55.8	1.0	bdl	bdl
4611	46	Askana XVII		SG	C	0.8	1.8	8.2	31.0	bdl	2.4	2.1	2.4	0.3	bdl	50.6	0.4	bdl	bdl
4613	46	Askana XVII		SG	C	0.5	4.1	10.2	36.9	0.3	2.1	1.3	2.8	0.4	bdl	40.6	0.5	0.3	bdl
4615	46	Askana XVII		SG	C	0.7	1.7	9.4	30.4	bdl	2.1	2.9	1.4	0.3	bdl	49.9	0.4	bdl	0.8
4701	47	Mziani XXV		SG	C	0.3	1.1	6.5	18.3	0.3	1.3	1.2	2.2	0.3	bdl	66.1	2.5	bdl	bdl
4702	47	Mziani XXV		SG	C	0.5	1.0	6.7	21.1	0.4	1.2	1.1	2.1	bdl	bdl	65.0	0.9	bdl	bdl
4703	47	Mziani XXV		SG	C	0.5	3.8	9.9	35.6	0.5	1.0	1.7	8.5	0.4	0.3	36.6	0.5	0.3	0.6
4704	47	Mziani XXV		SG	C	0.5	1.7	12.0	35.6	0.3	1.0	2.1	3.4	0.5	bdl	41.8	0.7	bdl	0.3
4705	47	Mziani XXV		SG	C	0.5	3.1	9.1	34.0	0.4	1.7	1.6	5.3	0.4	bdl	42.2	0.3	0.5	0.8
4706	47	Mziani XXV		SG	C	0.9	8.6	11.6	38.5	bdl	0.5	3.0	17.8	0.3	0.3	17.7	0.9	bdl	bdl

(*continued on next page*)

Table 4 (*continued*)

Sample	Site #	Site name[a]	Date[b]	Prod. area[c]	Product[d]	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_2	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	BaO
4707	47	Mziani XXV		SG	C	0.6	3.8	10.4	34.9	0.5	bdl	2.0	6.0	0.5	bdl	39.9	1.1	bdl	0.4
4708	47	Mziani XXV		SG	C	0.9	4.8	11.9	40.2	0.4	0.7	1.8	4.5	0.4	bdl	33.5	0.6	bdl	0.3
4709	47	Mziani XXV		SG	C	bdl	3.0	6.5	40.2	0.5	0.6	0.9	1.5	0.3	0.3	45.0	1.3	bdl	bdl
4710	47	Mziani XXV		SG	C	bdl	2.0	10.3	29.0	0.3	1.7	0.7	5.8	0.4	bdl	49.2	0.6	bdl	bdl
4711	47	Mziani XXV		SG	C	bdl	1.3	5.2	33.6	0.3	2.9	1.5	2.7	0.4	bdl	51.4	0.5	0.3	bdl
5401	54	Leghva I	11th–9th c. BC	ChO	C	1.6	1.0	7.4	40.9	bdl	2.4	1.3	1.9	0.5	bdl	30.1	0.6	9.8	2.5
5403	54	Leghva I	11th–9th c. BC	ChO	C	1.6	0.7	6.7	30.5	0.3	2.3	2.0	2.6	0.3	0.3	42.8	0.4	8.2	1.2
5404	54	Leghva I	11th–9th c. BC	ChO	C	2.1	1.3	6.9	32.2	bdl	2.0	1.5	1.7	0.4	bdl	35.6	0.8	14.0	1.4
5405	54	Leghva I	11th–9th c. BC	ChO	C	1.6	0.7	7.8	41.4	bdl	2.2	1.4	1.3	0.4	bdl	29.9	0.4	9.6	3.2
5407	54	Leghva I	11th–9th c. BC	ChO	C	2.0	0.6	5.5	37.4	bdl	4.7	1.0	1.2	bdl	bdl	31.4	0.4	11.8	4.0
5408	54	Leghva I	11th–9th c. BC	ChO	C	2.4	0.4	6.7	34.1	bdl	5.0	1.2	1.5	bdl	bdl	32.3	0.3	13.8	2.3
5501	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.7	1.0	6.1	35.0	bdl	3.0	1.0	1.9	0.3	bdl	38.0	0.6	9.5	1.8
5502	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.8	0.8	5.7	28.5	0.3	4.0	1.2	2.2	0.3	0.3	43.6	0.5	8.8	1.9
5510	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.9	1.0	7.7	38.7	0.4	2.7	1.3	2.6	0.6	bdl	29.7	0.5	10.9	2.0
5511	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.4	0.9	6.4	38.5	bdl	2.7	1.1	2.5	0.3	0.3	35.5	0.5	7.9	2.0
5512	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.6	0.8	7.5	38.4	0.3	2.8	1.4	2.4	0.3	bdl	35.3	0.4	6.7	1.9
5513	55	Tsetskhlauri I	10th–8th c. BC	ChO	C	1.0	2.7	23.7	57.1	bdl	bdl	4.9	1.3	0.8	bdl	8.2	bdl	0.3	bdl
5601	56	uncertain		ChO	C	1.9	1.0	6.1	33.1	bdl	3.4	1.1	2.3	0.3	bdl	39.0	0.4	9.4	2.0
5602	56	uncertain		ChO	C	1.9	0.8	4.4	24.8	bdl	6.9	0.9	0.7	bdl	bdl	45.6	0.8	10.8	2.3
5603	56	uncertain		ChO	C	1.0	1.2	7.0	30.3	0.3	3.6	1.1	2.2	0.3	bdl	47.9	0.5	3.7	0.9
5604	56	uncertain		ChO	C	2.3	0.9	5.9	35.1	bdl	4.0	1.1	1.6	0.5	bdl	31.7	0.3	13.5	3.1
5605	56	uncertain		ChO	C	2.3	0.9	6.4	32.3	bdl	4.1	1.0	1.7	0.3	bdl	33.8	0.4	13.8	3.1
5607	56	uncertain		ChO	C	1.0	0.5	7.8	26.6	bdl	2.2	0.9	0.5	0.3	bdl	45.7	0.6	5.6	8.1
5613	56	uncertain		ChO	C	1.4	1.1	6.9	41.7	0.3	2.8	1.2	1.8	0.4	bdl	32.2	0.4	7.6	2.3
5701	57	Tago I		SA	I	0.8	1.8	14.2	28.2	1.6	0.3	1.4	2.3	0.6	bdl	48.8	bdl	bdl	bdl
5702	57	Tago I		SA	I	0.8	1.6	16.1	35.3	1.3	bdl	1.9	4.4	0.7	bdl	37.9	bdl	bdl	bdl
5801	58	Tago II		SA	I	0.5	1.1	8.1	19.4	1.6	0.4	1.6	2.3	bdl	bdl	65.0	bdl	bdl	bdl
5802	58	Tago II		SA	I	0.8	1.1	9.5	25.8	1.1	0.5	1.6	3.8	0.5	bdl	55.2	bdl	bdl	bdl
5901	59	Dzmagula I		SA	I	0.4	0.6	7.4	17.9	0.4	0.7	1.1	2.1	bdl	bdl	69.5	bdl	bdl	bdl
5902	59	Dzmagula I		SA	I	0.5	1.0	10.8	30.3	1.1	0.5	3.1	5.0	0.6	bdl	47.1	bdl	bdl	bdl

[a] Site name indicates the name of the site used in earlier Georgian publications (e.g. Khakhutaishvili, 2009 [1987]) and field notebooks.

[b] Approximate dates, where available, are reported from Khakhutaishvili (2009), and are based on pottery chronologies, radiocarbon dates, and paleomagnetic dating carried out in earlier field projects. Some sites (e.g. site 16, Nagomari I) yielded different dates for different furnaces.

[c] Production area abbreviations: SG-Supsa–Gubazeuli area, ChO-Choloki–Ochkhamuri area, SA-Skhalta–Adjaristskhali area.

[d] Indicates the product of the smelt: C-copper, I-iron.

from the three sites in the Choloki–Ochkhamuri region has a ZnO content greater than 3 wt.%. Other chemical variations are apparent in many of the samples. Some samples have significantly elevated magnesium and calcium contents (Fig. 8). As one might expect, there seems to be greater chemical variation in spongy amorphous slags, but there are several slag cake fragments with exceptional compositions (e.g. 4706).

4.3. Undated iron smelting slags

All slag samples from the Supsa–Gubazeuli and Choloki–Ochkhamuri regions analyzed thus far by the current project are copper smelting slags. This differs from the interpretation of several earlier studies of slags from these regions, which argued that they were sites of iron smelting (Tavadze et al., 1984). At this stage, we could

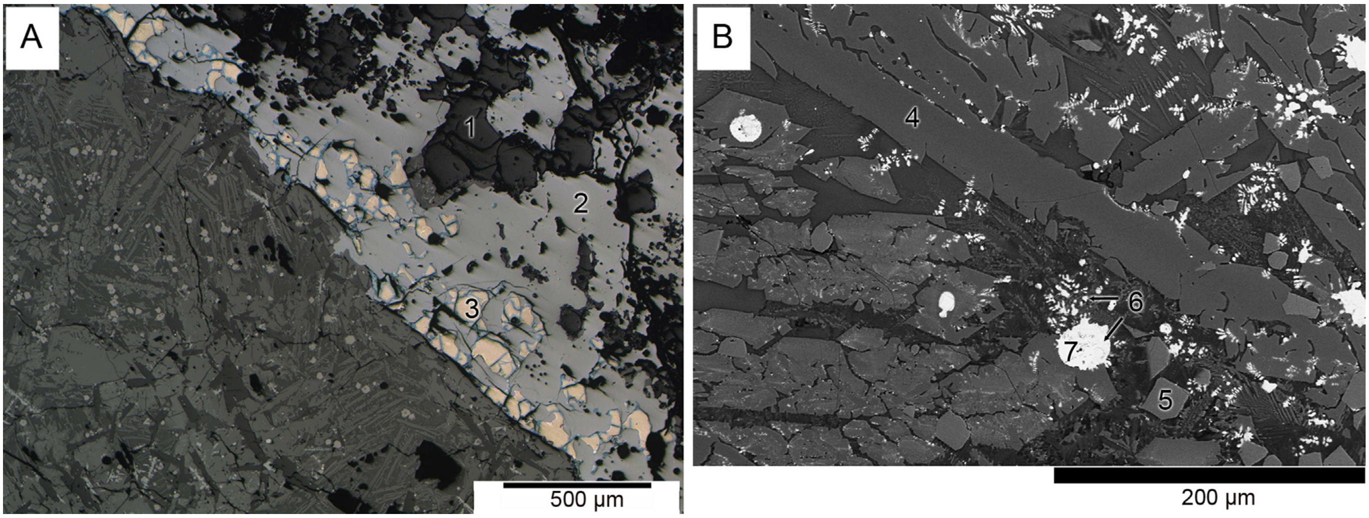

Fig. 7. Copper smelting slags containing sphalerite. A. Optical photomicrograph of sample 5408 showing a large fragment of ore and gangue reacting with slag. The ore-gangue fragment consists of quartz (1), sphalerite (2), and a partly reacted mixture of chalcopyrite and bornite edged with blue covellite (3). B. SEM backscatter electron image of sample 801 showing fayalite (4), magnetite (5), sphalerite in dendrites and in prills (6), and chalcocite (7). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

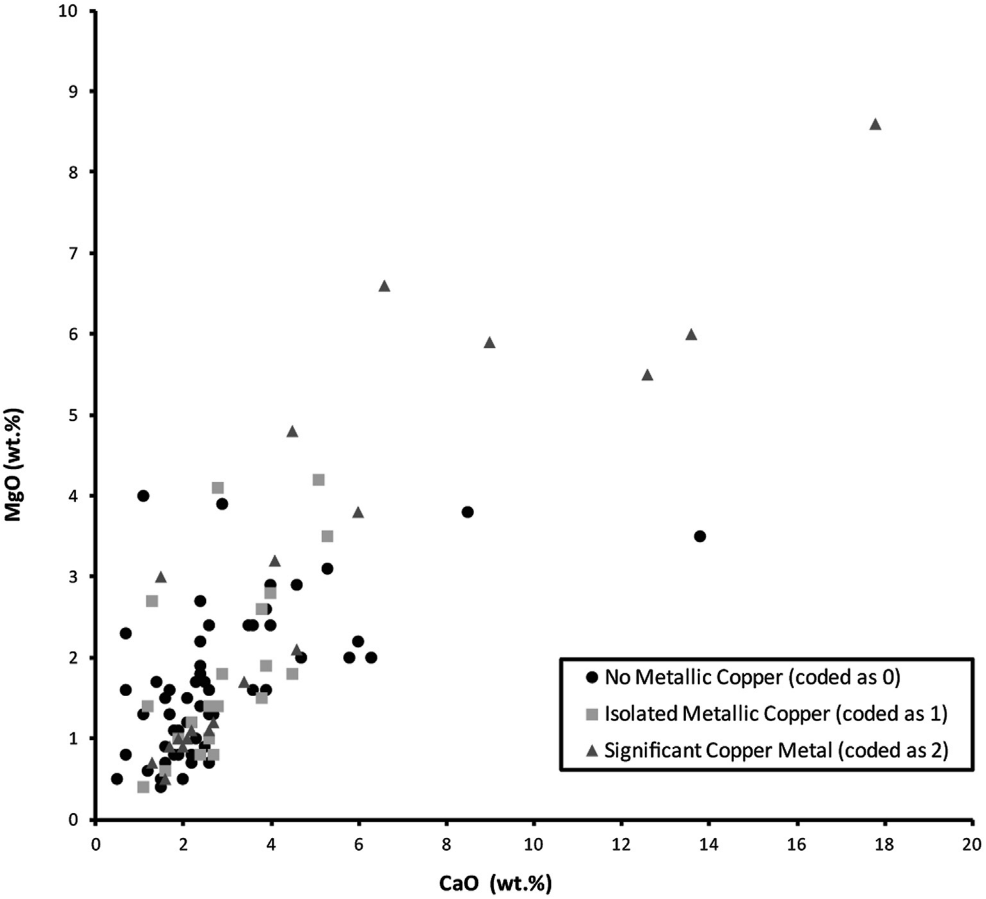

Fig. 8. Plot of MgO vs. CaO in copper smelting slag samples.

not reproduce their results, and the previously published data do not offer detailed enough information to fully evaluate the claims. However, a set of six slags analyzed from three different sites in the mountainous Adjara region (Skhalta–Adjaristskali production area in Fig. 1) are undoubtedly bloomery iron smelting slags. They are characterized by presence of abundant metallic iron and wüstite, coupled with the total absence of copper bearing phases (Fig. 9).

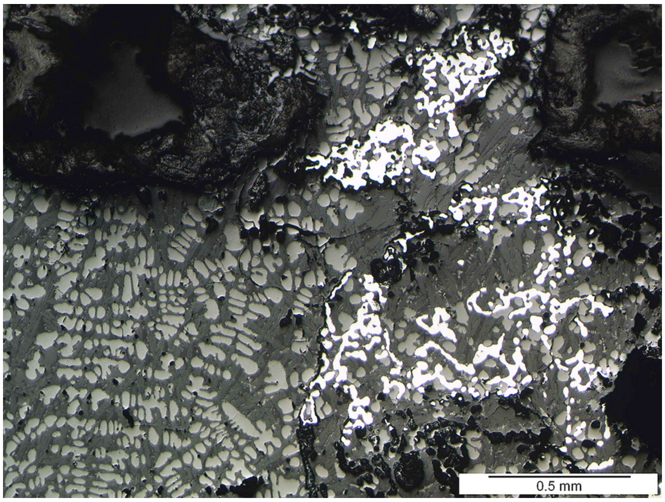

Fig. 9. Optical photomicrograph of an iron smelting slag (sample 5901) showing abundant wüstite (light gray), laths of fayalite (dark gray), and metallic iron (white).

Unlike the Supsa–Gubazeuli and Choloki–Ochkhamuri copper smelting areas, where extensive previous work suggests most sites date roughly to the LBA–EIA, there has been no earlier work on smelting sites from the Skhalta–Adjaristskali production area. Thus, at this stage, it is impossible to assign even approximate dates to these sites. Further work is planned to provide high quality dates from these sites.

5. Discussion

We can draw two types of conclusions from the results of slag analyses. First, and most fundamentally, it is clear from these data that copper was produced at a large number of sites dating to the Late Bronze and Early Iron Age in western Georgia. Iron was also produced, but the dating of those sites remains unclear at present. Second, the large body of data allows us to address questions concerning the nature of ore sources, the smelting technology used, and the possible linkages between copper smelting and iron smelting technologies.

5.1. Ore sources

Microscopic evidence strongly suggests that ancient metalworkers were exploiting copper ore from the polymetallic sulfide deposits of the Adjaro-Trialeti folded zone, where chalcopyrite is the dominant copper-bearing mineral (Ghambashidze, 1919:81, Gugushvili et al., 2010; Nazarov, 1966:117–132). This is aptly demonstrated by the discovery of partially reacted ore and gangue fragments in the slags (Figs. 6 and 7A). In some cases, the gangue appears to be quartz, while in other cases, the copper–iron sulfide is embedded in an iron oxide matrix. While it is possible that copper oxides and/or carbonates formed part of the original ore charge, it is clear that they would have derived from the partially oxidized zone of one of the sulfide deposits.

The inter-site variability and intra-site consistency in the zinc content also relate to the question of ore sources. Given the geological association between copper and zinc sulfides and the presence of unreacted sphalerite in the slags, the zinc undoubtedly originated in ore/gangue additions to the furnace. There are three possible explanations for the variations seen in the zinc content. First, they might be due solely to variability within the furnace. However, this is highly unlikely because of the magnitude of variation (cf. Humphris et al., 2009:364), as well as the consistent inter-site patterning. A second possibility is that the two types of slag are the result of different stages of smelting, and the zinc was completely volatilized by the later stage. However, experiments show that zinc is not volatilized during ore roasting and smelting. Instead, it is preferentially incorporated into the slag (Tylecote et al., 1977). While one would expect some variation in the zinc content, the nature of the variation suggests that it is not due to technological parameters. The third, most likely explanation is that natural ore body zonation resulted in different suites of associated paragenetic minerals, and that metalworkers at different sites were using slightly different ore sources. This conclusion has several possible implications. The sites may date to different periods, and the pattern may reflect the cessation of activity at one mine and its initiation at another point on the same ore body. Alternatively, this variation could be the result of independent small scale mining and smelting operations occurring at roughly the same time. This perspective is consistent with the dispersed spatial arrangement of the smelting sites, which suggests a lack of coordination in mining activities. The latter case would differ significantly from models of copper production in other areas of the Southwest Asia. In this wider region, archaeological evidence such as fortified smelting camps (Levy et al., 2004; Rothenberg, 1990:8–12) and the association of institutional structures with copper production (see Kassianidou, 2012), has reinforced traditional arguments proposing a significant degree of elite involvement in production and trade of copper (Knapp, 1986:71–72, Knapp, 2012:18, Mirau, 1997:110–111).

5.2. *Chaîne Opératoire of the smelting process*

The data clearly show that metalworkers were adding copper sulfides as part of the primary furnace charge. Furthermore there is a consistent patterning between the presence of copper metal and the presence of more copper-enriched sulfides such as Cu_9S_5 and Cu_2S and the absence of more iron-enriched sulfides. These data have several possible interpretations for the copper smelting sequence. First, one might argue that the ancient metalworkers used only ore from the partially oxidized zone, and that the sulfides remained as inert impurities while the oxides and carbonates alone were reduced (see Craddock, 1995:153). However, this view is problematic for a number of reasons. The geological literature, which discusses the mineral composition of copper deposits in southwestern Georgia in some detail, rarely mentions the presence of oxidized minerals (Ghambashidze, 1919:80–81, Nazarov, 1966:118–132). By contrast, chalcopyrite, sphalerite, pyrite, and galena are all frequently mentioned. Although small oxidized zones may not be mentioned by modern mining geologists interested in large economically-profitable deposits (D. Killick, personal communication), the quantity of copper produced by ancient exploitation suggests that they would have quickly exhausted these oxide zones.

In addition, the presence of rectangular low platforms or areas with traces of reddish burning found at a number of previously excavated smelting sites, (Khakhutaishvili, 2009 [1987]:21, 41, 53, 71), suggests that roasting of ores was a key aspect of the production process. Roasting, an important step in the processing of sulfide ores, would have increased the copper yield by converting the sulfides to oxides, allowing for direct reduction of oxides. In combination, these lines of argument strongly suggest that copper was extracted from the sulfide component of the ore source.

At least three different possibilities exist for the extraction of metal from sulfide ores. In one process, a first smelting episode would have eliminated iron from the chalcopyrite ore, and separated the copper-bearing phases from the silicate gangue, producing a matte. Subsequently, the matte would have been crushed and roasted to drive off the sulfur and oxidize the copper. A final second smelting stage would yield copper by direct reduction. Eibner (1986) argues that this process was used in Bronze Age central Europe to smelt chalcopyrite ores from the Mitterberg using a pair of furnaces working in tandem, though other interpretations are possible (Tylecote, 1987:130). Like the Mitterberg smelting sites, a number of Colchian smelting sites, including Site 8 (Askana II), and site 54 (Leghva I) are outfitted with double furnaces (Khakhutaishvili, 2009 [1987]:50, 58).

An alternative hypothesis would envision the roasting of the ore prior to smelting. This process would produce copper metal, derived from the direct reduction of oxides or oxide-sulfide interactions, as well as some matte from the remaining unroasted sulfides. In this case, the absence of copper metal in some slags would be due to the near-complete separation between metal and slag.

Finally, theoretical and experimental research has shown that copper can be extracted from mixed ore containing both sulfides and oxides in a process that does not require roasting or reducing conditions (Rostoker and Dvorak, 1991; Rostoker et al., 1989). Despite the rare occurrence of primary oxide or carbonate copper minerals in the slags or in test excavations, and the lack of references to oxide ores in geological reports, it is possible that near-surface mining would have supplied a mixed ore suitable for co-smelting. However, the presence of open burned platforms strongly suggests that ore roasting was practiced. The process of roasting could only have increased the yield of smelt relative to a co-smelt alone, especially for furnace charges with only a small amount of oxide. Incomplete roasting of ores, would virtually guarantee that some copper would be reduced by co-smelting, and the presence of copper sulfides in slags with metallic copper demonstrates that roasting was not carried out to completion. Thus, while co-smelting reactions probably occurred in these furnaces, roasting was very likely a key element of the process.

Distinguishing between the two alternative sequences of roasting and smelting is challenging, and previous studies have offered different interpretations. Slags containing copper sulfides and matte prills but no metallic copper have been identified in both 9th–8th century BC Italy (Chiarantini et al., 2009) and in Late Bronze Age Cyprus (Knapp and Kassianidou, 2008). Chiarantini et al. interpret matte-rich slags and the copper-rich slags as being the result of tapping the slag at different points in a single smelting stage (2009:1634). By contrast, at the 16th century BC Cypriot smelting site of Politiko Phorades, Knapp and Kassianidou report slags without copper metal, and argue only matte would have been produced. The argument hinges on whether one sees the chalcopyrite-rich, metal-poor slags and the matte and metal-rich slags as products of distinct stages of the smelting process, or simply the result of density segregation.

Given the current evidence, it is not possible to argue conclusively for one or the other of these two copper sulfide processing pathways. The single small fragment of matte found on the surface of site 15 could be interpreted either as an unutilized waste product discarded after copper was extracted, or as a rare fragment that was accidentally discarded prior to roasting. However, the inter-site variance in the proportion of copper-metal rich slags may offer some clues. If one argues that copper-rich slags represent a completely separate stage of smelting, one would need to explain why copper metal appears more regularly in slags from certain sites. Given the dearth of other spatial and archaeological evidence for functional differentiation and coordination between these sites, it seems highly unlikely that matte production and the final smelting were carried out at different sites. Thus, at least some of this variation is probably due to the varying abilities of different groups of metalworkers to achieve a good separation between the slag and the metal, rather than the result of two distinct processes. Moreover, contrary to the predictions of Rostoker et al. (1989:83) for a two-step true matte smelting, there are no clear bulk chemical differences between slags with copper metal in them, and those without copper metal (Fig. 8). On the other hand, it is difficult to envision how density segregation would explain the complete lack of copper metal in some samples. Furthermore, if the matte produced by the smelting of sulfide ores was not processed in a second stage, one might also ask why such fragments are not more common at smelting sites. Some samples and sites remain puzzling, and there may be some variations in technical practices which will become apparent after more detailed examination of certain sites. What is eminently clear from this analysis, however, is that ancient metalworkers were able to smelt sulfide ores at high temperatures and long reaction times, achieving good separation between slag and metal.

The products of these furnaces would have been very rich in iron metal, as indicated from the presence of iron, sometimes as a distinct phase, in the copper prills. In order to make useable copper or bronze, secondary refining and alloying must have been carried out. Chemical analyses of copper-base artifacts show that tin bronzes were common in this region (Chernykh, 1992:283, Japaridze, 2001:118). However, so far there is little to suggest casting and forging of bronze artifacts occurred at the sites where primary smelting occurred. The location and method of alloying is still currently unclear. Despite the fact that many casting molds for axes, mattocks, and other artifacts have been found at numerous settlement sites in western Georgia (Mikeladze, 1990:26), none have been published from primary smelting sites. As a result, bronze artifact manufacture must have been spatially segmented.

5.3. *Implications for the rise of iron production*

Scholars have long sought the beginnings of the use of iron in the technologies of complex copper smelting, with some suggesting that iron would have been accidentally produced in intended copper smelts (Charles, 1980:165–166, Gale et al., 1990). However, there is little direct evidence, such as the presence of copper in early iron artifacts, to support the idea that usable metallic iron was regularly produced in ancient attempts at copper smelting. Merkel and Barrett (2000) demonstrated that several iron artifacts with elevated copper, originally thought to have been accidentally produced during copper smelting (Gale et al., 1990), are actually contaminated with post-depositional copper. Nevertheless, slag analysis has shown that the thermodynamic parameters necessary for the reduction of iron were achieved in copper smelting furnaces. Wüstite has been reported in copper smelting slags (Knapp and Kassianidou, 2008:143, Koucky and Steinberg, 1982:121, Pleiner, 2000:254). While not as common as in typical bloomery iron smelting slags, the occasional appearance of metallic iron and wüstite in slags from western Georgia suggests fairly high reducing conditions in the furnace. The size and homogeneity of the slag cakes also indicates an ability to reach very high temperatures for a sustained period, achieving a fluid molten slag. Previous research showed that the slags melt at about 1150–1250 °C (Inanishvili, 2007:12–13). This evidence demonstrates that, regardless of whether iron was accidentally produced during copper smelting, an inability to produce sustained high temperature reducing conditions in a sizable reaction chamber was not a limiting factor preventing the invention and adoption of iron technology. Moreover, the presence of partially reacted ore fragments demonstrates that iron oxides were a major component of the ore sources, placing ancient copper producers in a key position to observe and experiment with the behavior of iron oxides at high temperatures.

However, we have yet to find evidence of copper and iron smelting at the same site, and there are significant problems with the iron-from-copper-smelting hypothesis, aside from concerns raised by Merkel and Barrett (2000). Even though small pieces of metallic iron are found in copper smelting slags, chemical properties make it nearly impossible to remove the copper while leaving the iron in its metallic state. No macroscopic lumps of iron, or “bears,” have been discovered in ancient copper smelting slag heaps, as one might expect if this was a regular occurrence. Lastly, the presence of sulfur from the ores has the potential to make any iron produced unworkable.

In light of these considerations, we must reassess the possible connections between technical practices in copper production and the emergence of iron production. Despite a lack of solid evidence for the discovery of iron in the process of smelting other metals, no viable alternative model exists for the mechanism of invention. One possibility is that the variation within the ore deposit played an important role. The evidence suggests that metalworkers were exploiting ore bodies with varying paragenetic mineral assemblages and very likely, varying copper content. Ancient metalworkers were probably experimenting with different ore deposits, testing which deposits were more effective in yielding copper. Given the intimate association between copper and iron ores in these deposits, it is conceivable that iron was produced during this process of experimentation. Nevertheless, conclusive proof of this mode of discovery is lacking, and the absence of direct evidence has frustrated attempts to understand the technological process by which iron was invented.

A more achievable goal is the comparative examination of copper and iron smelting in the same region, to identify elements of continuity and change in metallurgical practices associated with copper and iron smelting. Rather than focusing on the moment of invention, this approach focuses on the process of adoption. Specifically, it examines whether iron production existed as a distinct social and economic system, or whether copper and iron production were integrated systems of knowledge, with metalworkers of both types operating within the same social networks. While we may not be able to determine whether iron technology emerged through the experimentation of local metalworkers, or was introduced by a migrating smith from an adjacent region, we can distinguish between an iron smelting technology that developed from earlier, local metallurgical traditions, and one which arrived as a distinct tradition with little connection to earlier practices. This avenue of research promises far more interesting results than attempts to identify the exact mode of discovery, since it would tell us more about the social and economic processes of technological adoption. The patterns and practices of copper smelting presented in this paper lay the groundwork for these comparisons.

While iron slags dating to the Early Iron Age have not yet been identified by our project, it is highly likely that iron was smelted in the region. Archaeological excavations have yielded huge quantities of copper-alloy and iron artifacts dating to the first half of the 1st millennium BC (Mikeladze, 1985; Papuashvili, 2011). Iron artifacts often closely match those made from copper-alloys, so a local production industry probably did exist. Textual sources, though dating to a later period and problematic in some of the specifics (see Braund, 1994:90, Tsetskhladze, 1995:321), describe the Black Sea coastal region as a center of iron production (Khakhutaishvili, 2009 [1987]:125). Taken together, the evidence strongly suggests that western Georgia is a premier region to explore metallurgical changes in the Late Bronze and Early Iron Ages.

6. Conclusions

Investigations of ancient smelting sites on the southeastern coast of the Black Sea demonstrate that metalworkers carried out complex copper smelting in a highly dispersed landscape of production. Slag analysis, combined with geological and archaeological evidence, demonstrates convincingly that copper was extracted from copper sulfides in a process that involved roasting of ores. Key variations in the chemistry and mineralogy of slags suggest that metalworkers at sites in proximity to one another exploited different ore sources. Yet despite their dispersed distribution, the smelting sites investigated thus far display a surprising consistency in their layout and form (Khakhutaishvili, 2009 [1987]). This configuration of production constitutes an unusual example of copper exploitation which has not been documented elsewhere in Southwest Asia, contrasting with traditional models of centralized copper production geared towards elite consumption (e.g. Mirau, 1997:110–111). The data presented in this paper demonstrate that we can use slag analysis in order to examine homogeneity and heterogeneity of metallurgical practice at Colchian smelting sites. Future work will examine the spatial patterning of these variations—particularly the presence of zinc, and the higher frequencies of metallic copper, in order to determine more closely how metal production was organized.

In addition to opening up possibilities for exploring variations in technological practice over space and time, investigations of copper production are also relevant to the discussion of the origins of iron production. During prospection and experimentation in the smelting of different ore deposits, it is possible that ancient metalworkers worked out the process of smelting iron. More importantly, however, the study of copper smelting technologies forms the basis for a new approach that moves beyond difficult-to-prove theories about how iron was invented, and looks closely at how an emerging iron production industry related to established copper smelting practices. By looking at how certain practices were adapted and changed as iron was adopted, we gain a much clearer understanding of the interplay of conservatism and innovation in technological change.

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