

SPATIAL INVESTIGATION OF TECHNOLOGICAL CHOICE AND RECYCLING IN COPPER-BASE METALLURGY OF THE SOUTH CAUCASUS*

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Recent research has brought the prolific bronze industry of Bronze Age Colchis (modern western Georgia) into focus, but many aspects are still poorly understood. This study synthesizes and reinterprets legacy Cu alloy compositional data to investigate technological choices and spatial patterning. It reveals a massive injection of fresh copper into the system during the Late Bronze–Early Iron Age, and a high degree of selectivity in the alloys used for different objects, with colour being as important as hardness in determining these choices. Spatial analyses show significant geographical variability in alloying practices, which map onto topographical zones in unexpected ways. We also explore recycling practices and argue that the term encompasses a range of different reuse activities, which may be employed under differing economic conditions. Finally, the data suggest relatively extensive primary alloying of tin and copper in the Late Bronze and Early Iron Ages, which further substantiates the speculation that some local tin sources were exploited.

KEYWORDS: METALLURGY, BRONZE AGE, TECHNOLOGY, SPATIAL ANALYSIS, LEGACY DATA, CAUCASUS, BLACK SEA

INTRODUCTION

The South Caucasus was a major centre of metal production during the Bronze Age. In particular, the eastern Black Sea area, known to the Greco-Roman world as Colchis, developed a complex and highly productive metallurgical industry during the Late Bronze to Early Iron Age (LBA–EIA) (c.1500–600 BCE). Numerous copper smelting sites date to this period, illustrating the scale of production (Khakhutaishvili 2009; Erb-Satullo *et al.* 2014, 2015; Sulava *et al.* 2020). Many copper-base artefacts have also been recovered from hoards and graves (Lordkipanidze 2001; Papuashvili 2011; Sagona 2018, 459–62). These extensive metallurgical industries were predicated upon the rich ore deposits in the Greater and Lesser Caucasus mountains, which include copper and several common alloying elements (Fig. 1) (Kushnareva 1997, 211; Mudzhiri 2011, 165–9).

Although recent research on copper smelting sites has clarified the technology and the organization of smelting activities (Erb-Satullo *et al.* 2014, 2015, 2017), many questions remain about the wider metal economy. Soviet-era research on copper-base artefact chemistry tended to focus more on the identification of alloy types with broad-brush discussions of typological and spatial patterning of the chemical composition (Abesadze *et al.* 1961; Abesadze 1980; Abesadze and

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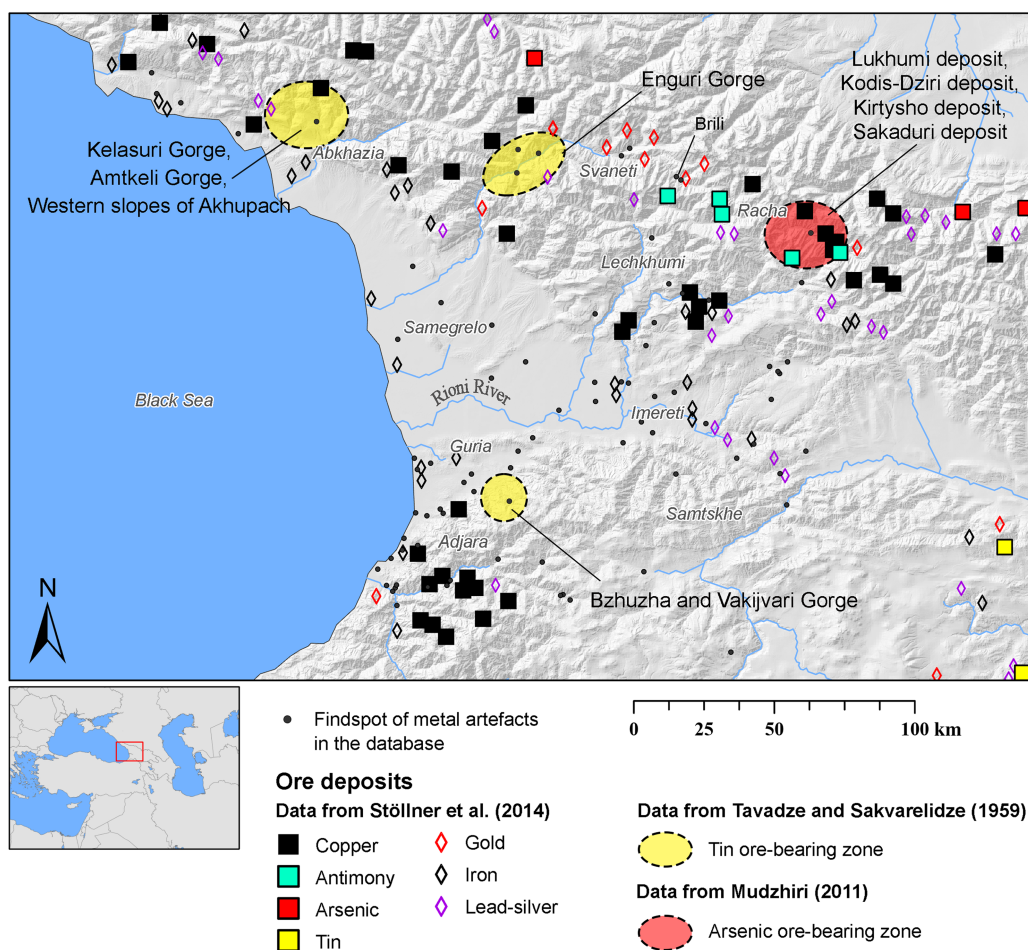


Figure 1 Map of the findspots of metal artefacts in the database and ore deposits in Colchis. The ore sources marked by squares and diamonds are derived from Stöllner et al. (2014, fig.2). The dotted oval areas give the general areas of ore deposits based on the written descriptions in Mudzhiri (2011) and Tavadze and Sakvarelidze (1959). They mentioned other tin- and arsenic-bearing deposits in Abkhazia, Racha and Svaneti, but we were either unable to identify the specific places mentioned or no information was given beyond the general region. The administrative divisions and historical regions are labelled in italics. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

Bakhtadze 2011 [1988]). Recent work on the reanalysis of large-scale metal chemistry data sets has shown the advantages of using spatial analyses and new interpretative frameworks to address questions about the metal economies, touching on questions of recycling, technological choice and the structure of exchange networks (Bray and Pollard 2012; Bray *et al.* 2015; Perucchi *et al.* 2015).

The large compositional data set on Colchian Cu alloys generated by Abesadze and co-authors (Abesadze *et al.* 1961; Abesadze 1969; 2011 [1974]; 2011 [1980]; Abesadze and Bakhtadze 2011 [1988]) provides an opportunity to re-examine the Cu alloy metallurgy. Drawing on these new techniques for the analysis of legacy data, this study reanalyses and reinterprets chemical compositional data of copper-base artefacts dated to the Early to Middle Bronze Age transitional period

(EBA–MBA) (c.2500–2000 BCE), Middle Bronze Age (MBA) (c.2000–1500 BCE), and LBA–EIA (c.1500–600 BCE). The LBA–EIA data set is particularly rich, with a sample size of 369 objects and good geographical coverage. Due to the smaller sample size and more limited geographical coverage, the EBA–MBA ($n = 47$) and MBA ($n = 115$) data sets are mainly analysed for chronological comparisons.

In many respects, these data sets are ideal for this kind of reanalysis. As the metadata (findspots, artefact type) are mostly well recorded and accompanied by illustrations, it is possible to examine the data from multiple perspectives. The patterning reveals the choices made in the production of Cu alloys, and allows us to make inferences about alloying technologies and the causes of geographical and typological variation.

The compositional patterns also contribute to a broader discussion of metal recycling, a topic of considerable recent interest in archaeometallurgy and economic archaeology (Cuénod *et al.* 2015; Duckworth and Wilson 2020; Liu *et al.* 2020). It is increasingly clear that recycling is not a monolithic phenomenon, and there is considerable variability in practices of reuse. For instance, one might differentiate between recycling that involves small-scale re-melting and immediate recasting of artefacts within a single workshop, and a large-scale system of scrap collection and exchange of re-melted stock metal. Analysis of large Cu alloy chemistry data sets can differentiate between different kinds of recycling practices. The patterns also shed light on the extent of primary alloying, which is related to questions about the possibility of local Caucasian tin sources—a problem that has been a matter of significant debate (Courcier 2014; Erb-Satullo *et al.* 2015).

DATA SETS AND METHODOLOGY

This study analyses the chemical compositional data of 531 copper-base artefacts from five legacy data sets, including 47 artefacts from the EBA–MBA transitional period (Abesadze 1969), 115 artefacts from the MBA (Abesadze 1974; 2011 [1980]) and 369 artefacts from the LBA–EIA (Abesadze *et al.* 1961; Abesadze and Bakhtadze 2011 [1988]). Relevant compositional data are selected and collated in light of the chronology and location of sites. Chemical compositions are recorded along with the artefact types, museum numbers and findspots. For their findspots, most assemblages are geolocated to the nearest modern settlement, though a few are located only to a region. Only for 13 artefacts was it impossible to determine an approximate findspot, either because the findspot was unspecified or because we could not locate the listed place name. These analyses were naturally excluded from the spatial analysis.

Integrating legacy chemical data sets produced by different laboratories, which may employ different analytical instruments, procedures, reference standards and sampling strategies, can pose challenges for synthetic analysis. In this case, the compatibility of different data sets is less of a concern. All the data sets discussed here were published by the same group, so sampling and analytical approaches were likely similar, if not the same. Published data sets report that chemical compositions were determined by ‘chemical spectral analyses’ (Abesadze *et al.* 1961, 140; Abesadze 1969, 126; 2011 [1980], 252; Abesadze and Bakhtadze 2011 [1988], 294, 346). While details about the analytical methods used to generate these chemical analyses are limited, it seems likely that this refers to optical emission spectroscopy. Collating data with consistent data collection techniques limits the problems of precision, accuracy and detection limit variations between different approaches.

We pay particular attention to the concentration of Sn, As and Sb, as these are the most common Cu alloying elements in prehistoric Colchis. Copper deposits in Racha and Abkhazia that

show evidence of ancient mining seemingly lacked Sn, As and Sb, though deposits containing alloying elements are found in separate deposits in the Greater Caucasus range (Fig. 1) (Mudzhiri 2011, 56–7, 166–70). Since these elements are commonly found in copper-base artefacts at a considerable concentration (Abesadze *et al.* 1961; Abesadze 1969; 2011 [1974]; 2011 [1980]; Abesadze and Bakhtadze 2011 [1988]), they were likely to be intentionally added to Cu to create alloys. These additions could theoretically have happened at different stages in the metallurgical *chaîne opératoire*, through the mixing of ores or the mixing of already-smelted metal, and compositional comparison between raw metal and finished artefacts helps to clarify this process.

We categorized compositions using two classification systems: compositional histograms with bin widths of 1% for key alloying elements, and a more coarse, binary categorization based on a cut-off value. Patterning in the data set was explored chronologically, typologically and regionally to examine the concentration of alloying elements. The shape of the concentration histogram was used to shed light on the degree of primary alloying (i.e. the creation of new alloys from constituent materials) as opposed to re-melting and recycling existing alloys (Bray *et al.* 2015; Cuénod *et al.* 2015; Pollard *et al.* 2018, 118–26).

The binary classification system divides metal artefacts into alloy types based on a cut-off value set at 1%. The cut-off mark is arbitrary and is typically 1% or 2% in most studies (Cuénod 2013, 157). In any event, testing with the current data sets showed that minor variations in the threshold do not blur the overall compositional patterns. Cu–Sn alloys with > 1% Sn, for example, are probably intentionally produced, either by mixing of separately smelted copper and tin metal, intentionally co-smelting ores, or by alloying by cementation. They could also be the products of metal recycling. Sn contents in alloys with < 1% Sn are more likely to be unintentionally produced through the smelting of accessory minerals (e.g., stannite) ore sources, or very heavily diluted by recycling. Similar arguments can be made with respect to Cu–As and Cu–Sb alloys.

The two classification systems not only accommodate poor reproducibility of data generated by optical emission spectroscopy (Pollard and Heron 2008, 24–8) and potential errors of the data sets, they also tolerate the data entries that are non-numeric (e.g., ‘trace’) or contains signs of ‘~’, ‘<’ and ‘>’ by fitting the data into groups. Data entries marking ‘–’ and ‘no’ or ‘trace’ were categorized in the 0–1% and < 1% groups in two classifications respectively. For the estimated values of the approximated data, ‘~10%’, for example, was naturally classified in the > 1% group for one classification system and in the 10–11% bin for the histogram analyses, since their precision hardly disturbed the general pattern of the distribution. Fortunately, as all data with only their upper limit stated (e.g., ‘< 0.1%’) are < 1%, they were all categorized in the 0–1% and < 1% groups. However, for compositions reported as a lower limit (e.g., ‘> 10%’), it was sometimes possible to fit them into one of the two categorization systems, but occasional entries such as ‘> 0.01%’ and ‘> trace’ were excluded from both, as they may be typographical errors, but this is unclear.

To examine the spatial patterns in technological choices, each artefact was mapped using ArcGIS Pro. The coordinates of the findspots (often the nearest settlement) were obtained from online sources, past literature and Soviet-era topographical maps, particularly useful in cases of post-Soviet name changes. The disperse markers tool was used to display overlapping points (e.g., multiple analyses from the same hoard) in an intelligible manner, at the expense of spatial precision. The artefacts with the approximate regional findspots recorded in the legacy data sets ($n = 24$) were positioned roughly at the centre of the region. Because of these choices, and because findspots are generally not recorded with greater specificity than the nearest modern

settlement in the legacy data sets, the maps reflect the approximate location of the artefact findspots. Nevertheless, we found this to be an effective method of data visualization that illustrated spatial variability effectively with different symbologies representing various alloy types and artefact typology.

RESULTS

The broad classification of alloy types revealed some significant chronological variations. Cu-As alloys with $> 1\%$ As predominated in the EBA–MBA transition and MBA, while unalloyed Cu was rare (Fig. 2). Alloys with Sn emerged in the MBA and became more significant in the LBA–EIA. Sb-containing alloys were commonly found in the EBA–MBA transitional period and the MBA (mostly as Cu-As-Sb alloys), but became considerably rarer in the LBA–EIA. In contrast, the proportion of finished objects that were effectively unalloyed Cu increased by more than four times in the LBA–EIA. Large numbers of unformed lumps, ingots and ingot fragments, most of which have $< 1\%$ Sn, As and Sb (Fig. 3), also date to this period (Abesadze and Bakhtadze 2011 [1988], 362–5). The chronological attribution of these unformed metal ingots and chunks is determined in many cases by their association with other typologically LBA–EIA artefacts, for instance, in hoards (Abesadze and Bakhtadze 2011 [1988], 346–65; Sulava *et al.* 2020). There was a lack of quaternary Cu-Sn-As-Sb alloys in all periods (Fig. 2).

All transitional EBA–MBA artefacts have Sn concentration $< 1\%$. Some tin bronze with an Sn content ranging from 1% to 13% emerged in the MBA (Fig. 3). By the LBA–EIA, even if the unformed metal lumps are excluded, a sharp peak at 0–1% can be seen in the

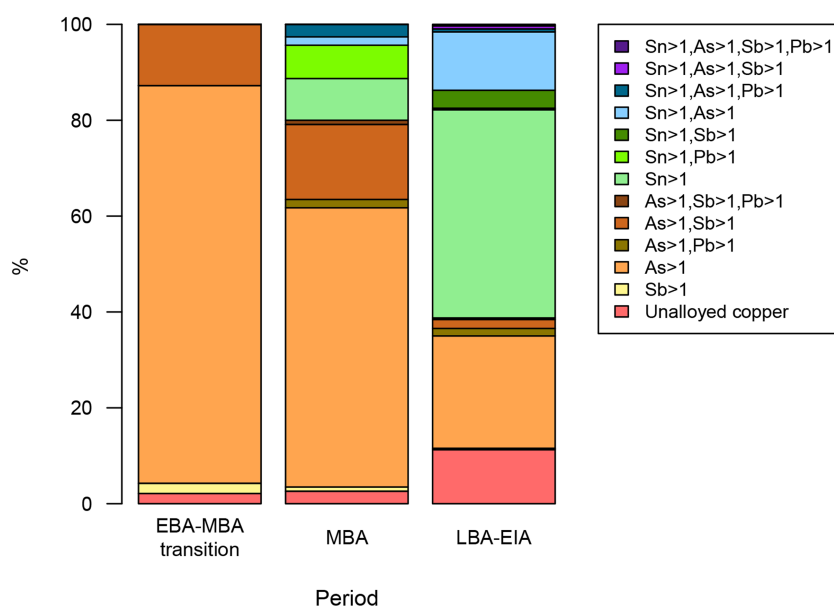


Figure 2 Proportions of different chemical compositional types in the Early to Middle Bronze Age (EBA–MBA) transitional ($n = 47$), MBA ($n = 115$), and Late Bronze to Early Iron Age (LBA–EIA) assemblages without unformed metal lumps ($n = 320$). [Colour figure can be viewed at wileyonlinelibrary.com]

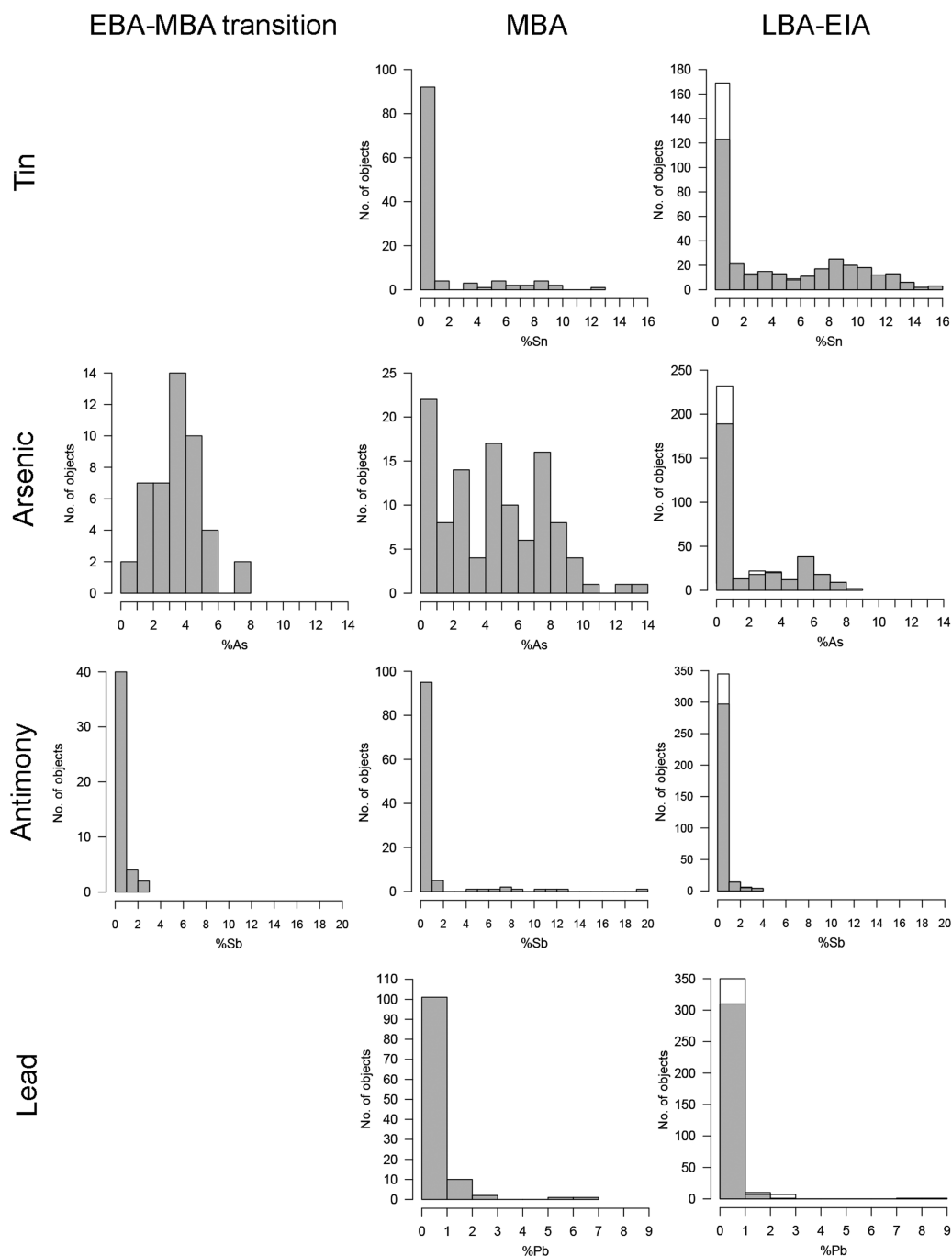


Figure 3 Distributions of Sn, As, Sb and Pb concentration in the Early to Middle Bronze Age (EBA–MBA) transitional, MBA, and Late Bronze to Early Iron Age (LBA–EIA) assemblages. All artefacts from the EBA–MBA transitional period have < 1% Sn and Pb, so they are not plotted. An outlier with 19–20% As (measured on metal inlaid on a tin bronze buckle) is excluded from the LBA–EIA plot. The white portion represents the composition of unformed metal (lumps, ingots and ingot fragments), while the grey portion represents the composition of finished items. Note that the axes vary between plots.

profile of Sn content. Most of the finished artefacts represented by this peak are Cu-As alloys with little Sn ($n = 87$), but a significant number are effectively unalloyed Cu ($n = 36$). There is also a small approximately symmetrical peak at 8–9%. While the distribution of As content in the EBA–MBA assemblage has a symmetrical peak at 3–4%, the MBA one is multimodal and slightly skewed right, with most As < 8%. The profile of As content in the LBA–EIA assemblage is similar to that of Sn. Excluding the unformed metal lumps, it also shows a sharp peak at 0–1% with a small peak at 5–6%. Finally, most artefacts have < 1% Sb. No EBA–MBA and LBA–EIA artefacts have Sb > 4%. In the MBA, nine artefacts from Eshera (Abkhazia) and 11 from Brili (Racha) have 1–20% Sb. The latter site, a cemetery, is near known antimony mines (Fig. 1) (Maisuradze and Gobedzhishvili 2001). Regardless of the alloying element and the chronological period of the assemblage, all histograms in Figure 3 have a significant spike at 0–1%.

The alloy composition of the MBA and LBA–EIA artefacts shows strong patterning with respect to object typology and, for some object types, geography. Among the MBA assemblage, while ornaments (e.g., bracelets, buckles, pendants, pins) were the artefact class with the highest fraction of Sn-containing alloys, weapons such as axes, daggers and spears were also made from Cu-Sn alloys (Fig. 4, a). The trends toward selecting tin bronze primarily for specific object types was intensified during the subsequent LBA–EIA when most ornaments and weapons (axes, spears, daggers) were made of tin bronzes (Fig. 4, b). The distribution of Sn concentration in the LBA–EIA ornaments skews left with a peak at 11–12% (Fig. 5). Similar to the compositional patterns of ornaments, spears and daggers have very high proportions of tin bronzes (Fig. 4, b). Their distribution of Sn content also skews left but peaks at 10–11% (Fig. 5). A majority of axes contain > 1% Sn, but arsenical copper axes are also commonly found (Fig. 4, b). Arsenical copper axes are relatively more frequent south of the Rioni River (Fig. 6, a). The distribution of Sn concentration in axes skews towards 0%, but it also shows an approximately symmetrical peak in the distribution at 8–9%, several per cent lower than the modal Sn concentration for ornaments of the same period (Fig. 5).

In addition, mattocks and so-called ‘segment-shaped tools’, which may have been tools for cultivation (Apakidze 2000, 188), though their function is unclear, share a similar compositional pattern of alloying elements. Both types were made using Cu-As alloys and unalloyed Cu in an almost equal proportion for the region as a whole (Fig. 4, b). Intriguing, despite the broad similarities in material culture throughout Colchis (Sagona 2018, 450–63), the alloy choices for these object types show clear spatial variation. Cu-As alloys dominate the south of the Rioni River, while unalloyed Cu is the preferred alloy for agricultural tools in the north (Fig. 6, b). The As concentration of Cu-As agricultural tools mostly falls between 3% and 7%, with the optimal proportion at 5–6% (Fig. 5).

To further explore spatial variation in alloy chemistry, concentration histograms were produced for five different topographical zones: the northern highlands (Greater Caucasus mountains), the southern highlands (Lesser Caucasus mountains), the northern and southern lowlands, and inner Colchis, a region inland from the coast corresponding roughly to modern Imereti. Even excluding the unformed copper lumps, all regional distributions of Sn and As content have a significant peak in the 0–1% range (Fig. 7). The distributions of Sn content of the northern lowland, southern lowland and southern highland assemblage also consist of small approximately symmetrical peaks in the distribution at various concentrations > 8% Sn (Fig. 7, a). Small peaks are also observed from the distributions of As level of the southern lowland and southern highland assemblages at 5–6% (Fig. 7, b).

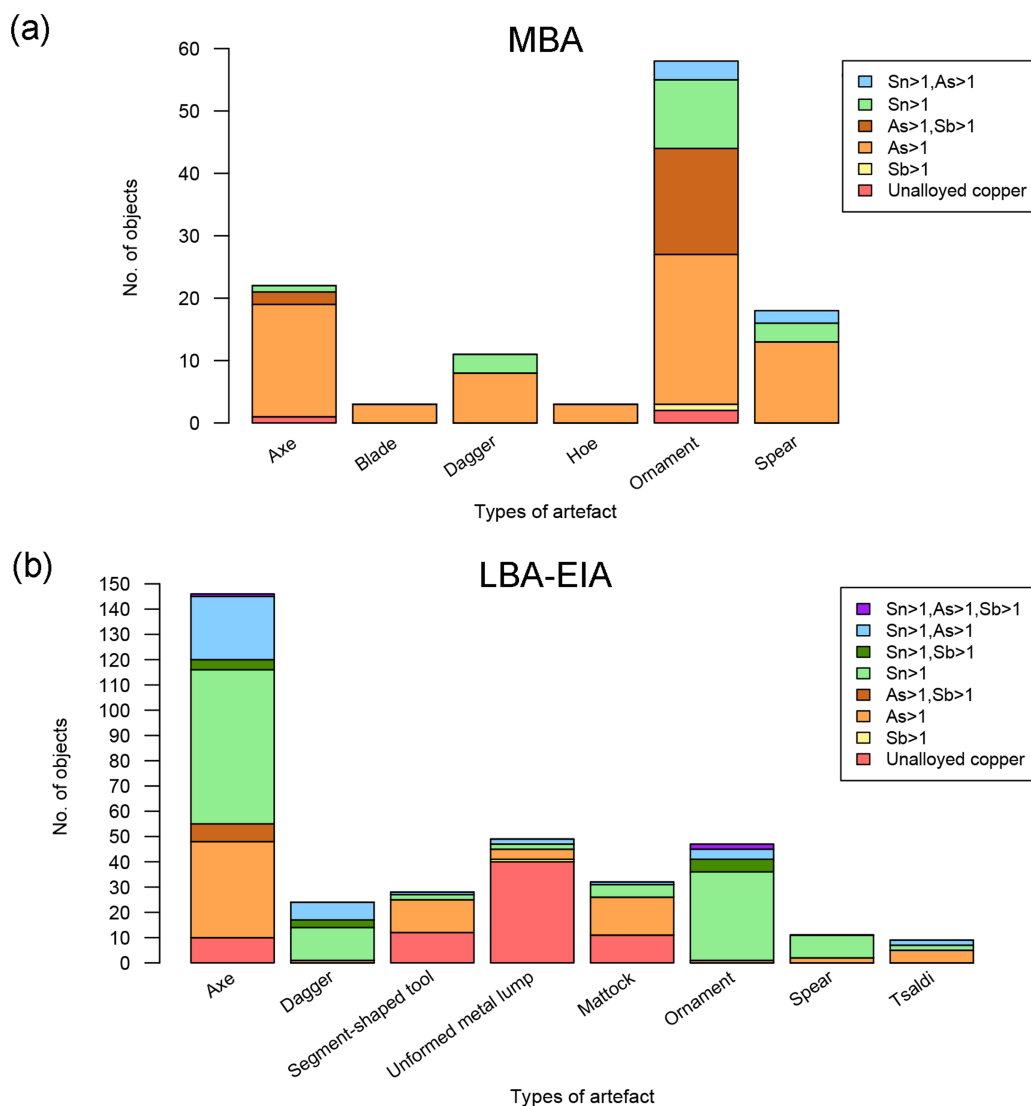


Figure 4 Alloys types of (a) Middle Bronze Age (MBA) and (b) Late Bronze to Early Iron Age (LBA–EIA) assemblage. Unlike Figure 2, Pb is excluded because it was likely not a significant intentional alloy in Bronze Age Colchis. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1111/jarcm.12668)]

It is worth mentioning several compositional features beyond the main alloying elements of Sn, As and Sb. Although Pb, Fe and Zn are occasionally $> 1\%$, we did not include them in the analyses of alloy choice and selection here. Pb-rich alloys were found in the Bronze Age South Caucasus (Meliksetian *et al.* 2011), but in this study Pb only occasionally appeared in quantities $> 1\%$ ($n = 33$ or 6.2% of all analysed objects) (Fig. 3), usually in association with Sn or As ($n = 26$ or 78.8% of objects with $> 1\%$ Pb). Even fewer objects ($n = 13$, 2.5% of all analysed objects) had Pb $> 2\%$. Among LBA–EIA artefacts with $> 1\%$ Pb ($n = 19$), 47.4% ($n = 9$) of them are unformed chunks or ingots. None of these unformed lumps has $> 3\%$ Pb, but

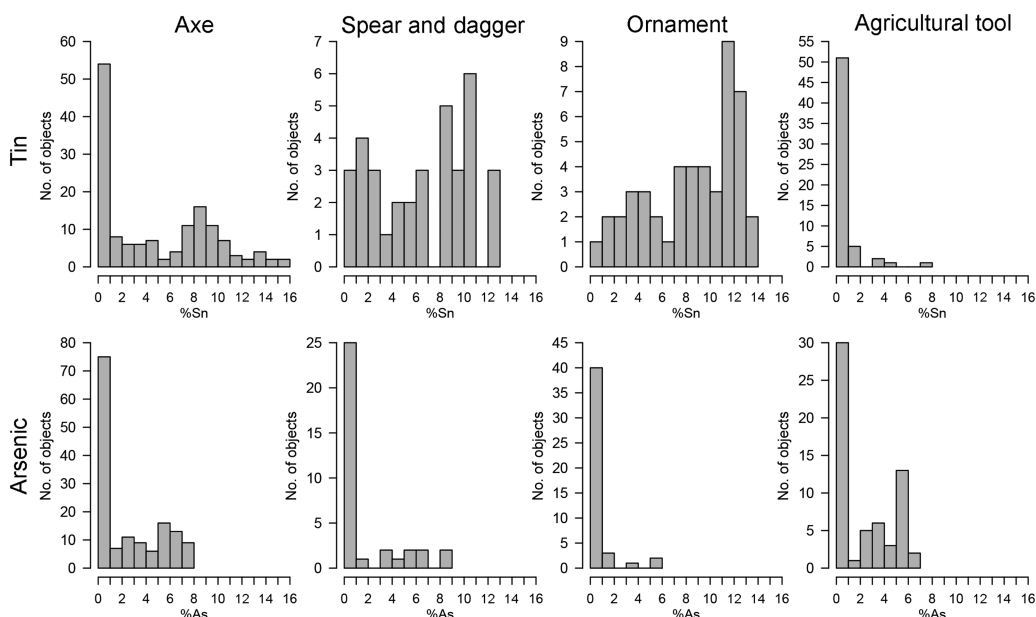


Figure 5 Distributions of Sn and As concentrations in Late Bronze to Early Iron Age (LBA–EIA) axes ($n = 146$), spears and daggers ($n = 35$), ornaments ($n = 47$), and agricultural tools (mattocks and segment-shaped tools; $n = 60$). An outlier with 19–20% As (measured on metal inlaid on a tin bronze buckle) is excluded from the ornament plot.

most contain $< 1\%$ Sn, As and Sb. The ingots that mostly lack the alloying elements of Sn, As and Sb (Fig. 4, b) and that seem to be mostly freshly smelted copper instead of remelted scrap metals, suggest an origin for the Pb in the copper ore deposits. On the contrary, the correlation with Sn and As in finished objects suggests a connection with alloying elements, but in either case, the relative rarity and low content when it appears suggests it was an accessory, and not the primary desired addition. One interesting feature, as yet difficult to explain, is the increase in Cu–Pb–Sn and Cu–Pb–Sn–As alloys in the MBA, which largely disappears in the subsequent period (Fig. 2). Similarly, Fe rarely appeared $> 1\%$ ($n = 21$, 4% of all analysed objects), and none of the objects contained $> 3\%$ Fe. Among objects with $> 1\%$ Fe, 48% ($n = 10$) were unformed chunks or ingots with $< 1\%$ Sn, As and Sb. Again, this is consistent with the interpretation of unformed chunks and ingots as being freshly smelted metal: unrefined copper smelted in highly reducing conditions often contain several per cent of Fe, which is reduced through oxidative loss during subsequent metallurgical processes. The Fe content in artefacts is therefore likely to be derived from the raw materials and irrelevant to the technological choices of alloying.

Reports of $> 1\%$ Zn in some of these objects ($n = 44$ or 8.3% of all analysed objects) are difficult to interpret. On one hand, brasses, while rare, are reported in the Bronze Age Near East, so this possibility should not be discarded out of hand (Thornton and Ehler 2003). In addition, many copper smelting slags from Colchis do have appreciable Zn content (Erb-Satullo *et al.* 2014). On the other hand, Zn in the ores may partition preferentially into the slag (Tylecote *et al.* 1977), and as yet, no metal prill containing $> 1\%$ Zn has been identified in Colchian copper smelting slags (Erb-Satullo *et al.* 2015). Even more suspect, some early conservation techniques result in the deposition of Zn on the surface of metal objects. Examination of objects in museum collections,

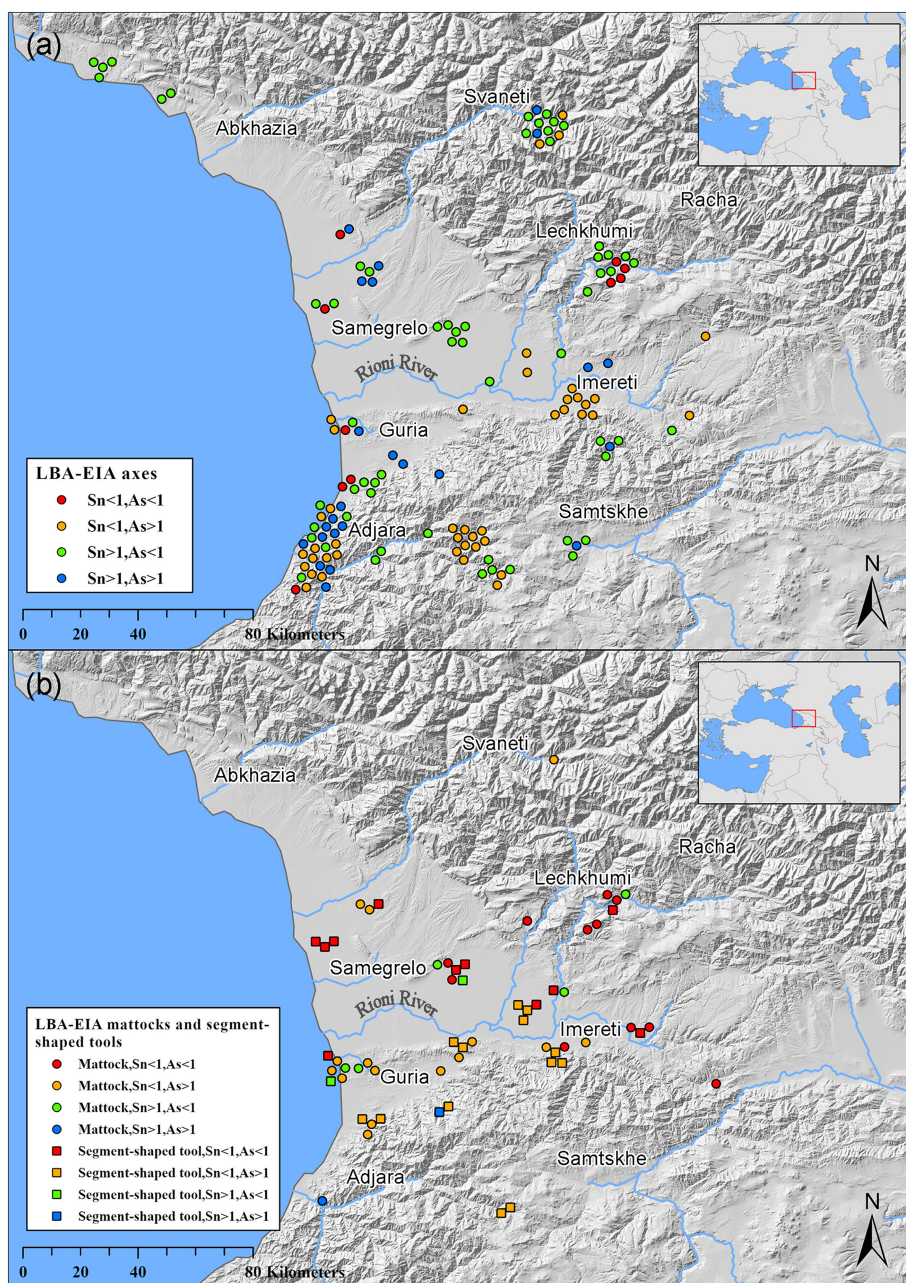


Figure 6 Map of Sn and As concentrations of Late Bronze to Early Iron Age (LBA–EIA) (a) axes and (b) mattocks and segment-shaped tools. Each point represents the chemical composition of a single artefact. Locations are approximate. [Colour figure can be viewed at wileyonlinelibrary.com]

including some in this study, by one of the authors (N.E.S.) reveals that this conservation practice was previously common in Georgia. If post-conservation sample drillings from the surface of the artefacts were not carefully separated and discarded, it is possible erroneous Zn would have been

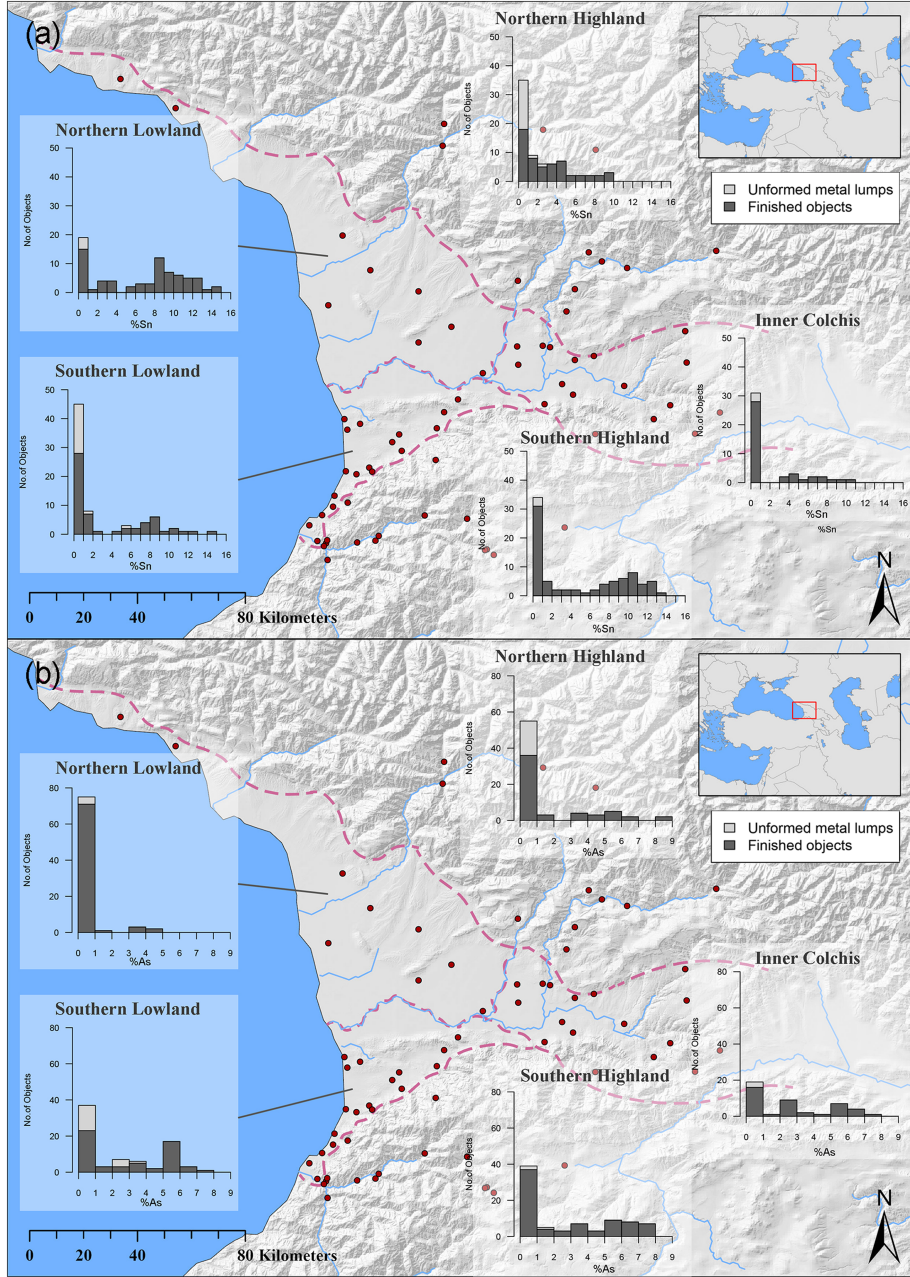


Figure 7 Regional distributions of (a) Sn and (b) As concentration in the Late Bronze to Early Iron Age (LBA–EIA) assemblage. Each point represents an artefact findspot. The light grey portion represents the chemical composition of unformed metal (lumps, ingots and ingot fragments). The red dash lines represent the arbitrary boundaries of topographical zones that categorized the artefacts into regional groups. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

introduced to the analysis. While we cannot exclude the possibility that the Zn reflects the original composition of the metal, the current balance of evidence does not favour this interpretation, and we have chosen not to include Zn in our discussions of alloy selection.

DISCUSSION

Implications of chronological changes in alloy types

Tin bronzes emerged in Colchis during the MBA but became prevalent only in the LBA–EIA. It shows a time lag between Colchis and elsewhere in the South Caucasus, including Armenia and southern Dagestan, where tin bronzes appeared during the EBA and were extensively used during the MBA (Peterson 2003; Meliksetian *et al.* 2011). Antimonial copper was common in MBA Colchis, but became rare in the LBA–EIA, whereas antimonial copper was relatively rare in MBA and LBA Armenia (Meliksetian *et al.* 2011). These distinctive patterns contrasting with the broader South Caucasus is probably attributable to general separation of Colchis from these areas, as seen in many spheres of material culture. Many cultural horizons common throughout much of the South Caucasus, including the EBA Kura-Araxes culture and the MBA Trialeti culture, are largely absent in Colchis (Kushnareva 1997, 78–9, 84–9). The fact that the region is hemmed by mountains and situated in a distinctive ecological setting could have fostered this isolation (Kushnareva 1997, 85).

Another observation is the significance of unalloyed Cu as both finished items and unformed chunks in the LBA–EIA. While unalloyed Cu was common among metals during the Chalcolithic, it had become rare since the EBA Kura-Araxes period, when arsenical copper dominated in the South Caucasus (Courcier 2014; Inanishvili 2014, 233). While the use of unalloyed Cu for finished objects in Colchis is relatively insignificant before the LBA–EIA, the late second millennium BCE saw a rise in the use of unalloyed Cu for objects, and of the appearance of unformed copper chunks. This trend suggests an injection of fresh copper into the system during LBA–EIA, probably due to the extensive smelting of the rich chalcopyrite-dominated Cu sulphide deposits in the Greater and Lesser Caucasus mountains at this time (Gugushvili *et al.* 2010; Mudzhiri 2011, 165–70; Erb-Satullo *et al.* 2014). With the exception of an unusual Sn-containing crucible fragment found at a smelting site in Guria, the vast majority of analysed copper smelting debris contains very few of the alloying elements commons found in the finished artefacts. Though zinc sulphide was a very common accessory mineral in the ore deposits exploited for copper, at present it seems that the zinc mostly partitioned into the slag rather than into the metal (Erb-Satullo *et al.* 2014, 2015).

The massive introduction of relatively pure copper into the metal economy stimulated the circulation of raw chunks and ingots between production sites, with some of these materials ending up deposited in hoards. The raw copper was then either cast into objects directly or used to produce tin bronze and arsenical copper. The analysis of production debris has suggested the addition of cassiterite to molten copper in the production of tin bronzes in Guria (Erb-Satullo *et al.* 2015). Importantly, the abundance of effectively unalloyed Cu ingots and ingot fragments strongly suggests that alloying with As (as with Sn) occurred in a separate stage, rather than through co-smelting of Cu- and As-rich ores. Arsenical copper could have been manufactured through mixing copper with iron arsenide (speiss), as this method has been suggested in Cu-As alloying elsewhere in the South Caucasus (Erb-Satullo *et al.* 2020) and Iran (Thornton *et al.* 2009; Rehren *et al.* 2012).

Factors determining the technological choices of alloys

During the LBA–EIA, while most agricultural tools (mattocks and segment-shaped tools) were made of unalloyed Cu in the north and Cu–As alloys in the south, ornaments and weapons (axes, daggers, spears) were predominately made of tin bronzes. The As concentration of Cu–As agricultural tools mostly falls between 3% and 7%, with the optimal proportion at 5–6%. The distribution of Sn content among tin bronze artefacts suggests the optimal proportion of Sn to be at around 8–9% and the upper limit to be at 16%. Since unalloyed Cu is significantly softer than cast Cu–Sn and the coldworked Cu–As and Cu–Sn alloys (Lechtman 1996), its selection as a material for agricultural tools reflects the fact that obtaining hardness was of secondary interest for this artefact type. Though the hardness differences between tin bronze and arsenical copper are less significant, it is still likely that the hardness of metals did not determine the use of Cu–As alloy in southern Colchis. If harder agricultural tools were the driving factor in the selection of As alloys for agricultural tools in the south, it is likely that tin bronzes would not be almost entirely excluded from this assemblage. Instead, colour may have been a more significant determinant of technological choice, as has been suggested elsewhere (e.g., Lechtman 1984; Hosler 1988). The data indicate that the selective use of tin bronze for weapons and ornaments appeared during the MBA, when tin bronzes firstly emerged in Colchis, and intensified in the LBA–EIA. The modal proportion of Sn in alloys with > 1% Sn is 8–9% for axes and 11–12% for ornaments respectively. Most tin bronze ornaments and weapons have 4–16% Sn, giving them a golden colour and distinguishing them from the silvery arsenical copper and the reddish unalloyed Cu (Mödlinger *et al.* 2017).

It is worth noting that Colchis is somewhat distinctive for its large numbers of copper and Cu alloy agricultural tools, particularly in the LBA–EIA. In other areas of the Near East, stone continued to be used for many agricultural tools right up until the Iron Age, when iron became the preferred material (Mirau 1997, 110). Cu alloys, in contrast, were generally considered as a material for weaponry, ornaments and prestige items during the Bronze Age (Stech 1999; Weeks 2003, 188–95; Keswani 2005). In the Colchian case, it may be that the colour of metals played the role of differentiating the socioeconomic value between agricultural tools and prestige goods, namely ornaments and weapons. This is not to say that the use of tin for weaponry was not influenced by the fact that Cu–Sn alloys are harder than pure copper, a feature which ancient metalworkers undoubtedly recognized. Rather, it is to be noted that the metal economy of LBA–EIA Colchis was defined by a high demand for metal, and the supply of copper seems to have exceeded the corresponding supply of tin and possibly other alloying elements. Within that system, metalworkers made a conscious choice to direct a considerable proportion of tin toward the manufacture of decorative items where hardness was irrelevant, and not to agricultural tools, where hardness could conceivably have impacted tool effectiveness.

The preference of gold colour is intriguing given the lack of gold in Bronze Age Colchis, a phenomenon that stands in dramatic contrast to the later Classical and Hellenistic periods (Kacharava and Kvirkvelia 2008). Though gold sources are known in Svaneti and Racha (Kekelia *et al.* 2016) and gold was mined in eastern Georgia since at least the EBA (Stöllner *et al.* 2014), gold objects of any kind are fairly rare in Colchis before the first millennium BCE (for rare examples, see Gambashidze *et al.* 2010, 231). Accordingly, it is not entirely clear whether the preference for tin bronze is a case of skeuomorphism in the strict sense of producing cheaper imitations of more costly items executed in gold, but it is clear that the golden colour of tin bronzes was valued. Considering the fact that gold colour was a rare feature of metal objects before the emergence of tin bronzes, when silvery arsenical or antimonial copper and reddish

copper predominated, the gold colour of tin bronzes may have added value to objects, regardless of whether metalworkers were intentionally imitating gold itself.

Geographical variability in the choices of alloys

LBA–EIA axes, mattocks and segment-shaped tools show spatial variation in alloy composition across the region. Axes and agricultural tools were more frequently made of arsenical copper at the south of the Rioni River, which runs east to west and divides Colchis roughly in half (Fig. 6). Agricultural tools discovered north of the river, however, were mostly unalloyed Cu. Since As in most arsenical copper surpasses 2%, their white-silver colour is perceptible to the naked eye and differentiable from reddish unalloyed Cu (cf. Mödler *et al.* 2017). Interestingly, the north–south division of alloy choices does not map onto expected topographical barriers. While the Rioni is a significant river, and its lower reaches run through what is now extensive marshlands, there is no reason to expect that these would have been major physical barriers to north–south movement or exchange in the lowlands. Indeed, the broad similarities in material culture across the lowlands suggest overall cultural continuity.

The spatial patterning seems to imply that, in terms of metallurgical industries, lowland areas were more closely tied to adjacent foothill and mountain zones rather than to other neighbouring lowlands. Indeed, previous research on metallurgical landscapes of the region has identified functionally complementary production sites in different topographical zones, with smelting sites located in the foothills and secondary processing sites in coastal lowland settlements (Erb-Satullo *et al.* 2017). Interestingly, despite clear differences in alloying practices, other aspects of copper smelting practices appear quite similar in both the northern Greater Caucasus system and the southern Lesser Caucasus system. Copper smelting technologies are better documented for the latter region (Erb-Satullo *et al.* 2014, 2015), but preliminary examination of production sites and debris from Svaneti, Lechkhumi and Samegrelo suggests a broadly similar smelting process involving pit furnaces and producing types of slag, consisting of dense cakes and spongy porous masses (Khakhutaishvili 2009; Sulava *et al.* 2020). More detailed analytical research is necessary to assess whether the spatial variations in technological style seen in alloying practices extends the nuances of the primary production technologies.

The highland–lowland orientation of metal economy was possibly fostered by the supply of ores and raw smelted metal procured from the highlands and foothills to the lowlands. Rich copper, arsenic and antimony ores were exploited in Svaneti and Racha in the Greater Caucasus mountains (Fig. 1) (Kushnareva 1997, 211; Mudzhiri 2011, 166–9). Copper ores are also abundant in the Lesser Caucasus mountains (Fig. 1) (Gugushvili *et al.* 2010; Mudzhiri 2011, 165). Metal smelting sites have been discovered in the mountainous regions and foothills zones (Erb-Satullo *et al.* 2014). Since no copper deposits have been reported in the Colchian plain (Gugushvili *et al.* 2010) (Fig. 1), it is likely that the secondary casting workshops discovered in lowland settlements were dependent on metals mined and smelted in the adjacent mountain and foothill zones (Erb-Satullo *et al.* 2017). In this scenario, communities in highland, foothills and lowland were bound together by systems of production and exchange. Such an orientation could have resulted in a sharing of alloying preferences and metallurgical traditions between adjacent highland and lowland communities, fostering the development of distinct local practices even within the broader shared technological horizon. Thus, while some movement of metal between different parts of the lowlands probably did occur, the dominant axis of economic connectivity was the lowland–foothill–mountain system. At the same time, many questions remain about the nature of connectivity between the lowlands and the high mountain regions, which

are far less known archaeologically. Peaceful trade is only one mechanism of connectivity; episodic raiding also links communities together and results in flows of material goods and technological knowledge (the latter through captured craftspeople, for example).

Another possible cause of the regional variability in alloy types would be the socio-cultural divergence between the north and the south, though societies in Colchis shares a largely consistent material culture and metallurgical technology (Erb-Satullo *et al.* 2017, 2018). Adjacent highland and lowland communities possibly shared a similar value system of metals, including aesthetic and cultural perceptions towards metal colours. Besides, the fact that most analysed artefacts are from hoards or mortuary contexts could imply that certain tools carried symbolic meaning beyond the purely utilitarian (Lordkipanidze 2001; Sagona 2018, 460). For symbolically laden objects, the preference of reddish unalloyed Cu in the north and silvery arsenical copper in the south might have reflected or even reproduced social identities (Lemonnier 1992, 85), and are not simply a passive indication of the relative availability of raw materials.

Recycling practices

Observed patterns in artefact chemistry have significant implications for the kinds of recycling behaviours practiced in Colchis. The distributions of As and Sn concentration in the LBA–EIA generally have peaks in the 0–1% range, regardless of the region and artefact type specified. Most profiles of Sn concentration also reveal a smaller peak with an approximately symmetrical distribution somewhere in the high single digits, except the ones of inner Colchis and northern highlands (Fig. 7).

The shapes of these distributions are attributed to several possible causes. The right-skewed features are due to two factors: (1) a surge of unalloyed Cu supply and (2) the relatively small proportion of quaternary and ternary alloys, meaning that tin bronzes are generally low in As and arsenical copper objects are generally low in Sn. A massive amount of copper was introduced to the system during the LBA–EIA, leading to a relative, though perhaps not absolute, scarcity of arsenic and tin sources, which is attested by the large amount of unalloyed Cu among the raw unformed metal chunks analysed. Despite the rich arsenic deposits attested in the Greater Caucasus range (Mudzhiri 2011, 165–70; Rubinstein 2002, 85), we do not as yet have any clear evidence for ancient exploitation, and no arsenic deposit is currently known in the Lesser Caucasus (Fig. 1) (Gugushvili *et al.* 2010; Kekelia *et al.* 2016)—a somewhat surprising pattern given the greater preference for Cu–As alloys in the south. Moreover, the availability and quantity of tin sources in the Caucasus is ambiguous (Courcier 2014; Erb-Satullo *et al.* 2015). While there is good evidence that there was at least some local exploitation of cassiterite deposits (see the following discussion), the scale of tin ore mining was unlikely to have matched the aggregate output of copper smelting.

It is also important to consider the lack of ternary and quaternary alloys as another factor contributing to the skewness of distributions—Cu–Sn alloys are low in As, while Cu–As alloys are low in Sn. Agricultural tools, generally low-tin, intensify the spike at 0–1% in the Sn profile, while Sn-containing low-As ornaments and weapons contributes to the spike at 0–1% in the As profile. As discussed in the above section, producers possibly neglected the hardness and colours in the production of agricultural tools. If tin and arsenic sources were relatively less available than copper, their metalworkers may have prioritized their use in objects, like ornaments and weapons, where symbolic significance or mechanical performance was more crucial.

Some interpret right-skewed distributions of alloying content with an asymptotic peak in the 0–1% range as the results of extensive metal recycling (Bray *et al.* 2015; Cuénod *et al.* 2015).

In these models, the 'tail' toward higher concentration of alloying elements is due either to oxidative loss on re-melting or to the introduction of fresh stocks of low-As copper. Other evidence for recycling is the proliferation of ternary and quaternary alloys produced as alloys of different types remelted together (Bray *et al.* 2015). Early Saxon Britain (AD 430–650) is a prime example of this phenomenon, as quaternary Cu–Sn–Pb–Zn alloys increase dramatically relative to previous periods (Pollard *et al.* 2015). It is important to underline, however, that these different indicators of recycling actually reflect different *kinds* of recycling behaviour (Bray 2020). A rise in ternary and quaternary alloys, for instance, might be correlated with widespread collection, pooling and circulation of recycled stock in a market economy. Right-skewed distributions of alloy concentrations, on the other hand, might reflect a form of workshop-base recycling where the supply of alloying metals was 'stretched': a single object melted down, mixed with fresh unalloyed Cu stock and then immediately recast into two new objects. This kind of recycling obviously depends on an abundant supply of fresh copper, but does not involve a market for the collection and trade of recycled stock, and therefore might occur under different economic conditions.

In the Colchian case, the quaternary and ternary alloys of various combinations of Cu, Sn, As and Sb may also provide an indicator of recycling. Cu–As–Sb ternary alloys are an exception, as they are far more likely to be the result of alloying with fahlores in the tennantite–tetrahedrite series than recycling and mixing of separate Cu–As and Cu–Sb alloys. Not counting Cu–As–Sb alloys, ternary and quaternary alloys of Cu, Sn, As and Sb reaches 15.7% ($n = 58$) of the LBA–EIA assemblage, a significant increase over the MBA, when such alloys comprised 4.3% ($n = 5$) of the assemblage, but overall still a modest proportion of the whole. An even smaller proportion of the LBA–EIA ingots and unformed metal (4.1%, $n = 2$) fell into this category, which suggests a lack of circulation of remelted scrap as a bulk commodity, and supports the hypothesis that ingots are mostly freshly smelted copper. As a comparison, in Roman and Early Saxon Britain, the ubiquity of leaded gunmetal (Cu–Sn–Zn–Pb) increases from around 15% to more than 70% from the first century CE to the Early Saxon period (Pollard *et al.* 2015). The proportion of complex alloys in the Colchian case is considerably less, an indication of very different economic conditions in the Colchian Bronze Age, when large amounts of freshly smelted metal were being pumped into the system.

Systematic segregation of alloys collected for recycling, probably according to their colours, could have also contributed to the relatively low proportion of complex ternary and quaternary alloys, but the sorting would have had to be tightly controlled. Ethnographic research also suggests a discrepancy between how producers perceived an alloy's composition and its actual chemical composition (Lahiri 1995). Given the modest proportion of quaternary and ternary alloys and a lack of archaeological evidence for institutional control of metal production, recycling of scrap metals with conscious selections of alloys was unlikely to be organized at a large scale. Hence, collection, pooling and trade of scrap metals, as has been suggested for the Gelidonya shipwreck in the LBA Mediterranean (Bass *et al.* 1967), is unlikely to have occurred in the Colchian metal economy beyond a limited scale, perhaps in part because of the almost inexhaustible supply of fresh copper.

The evidence of a surge of fresh copper metals into the system suggests that recasting metal with an addition of fresh copper into the melt was the more common form of recycling practiced in Colchis. This type of recycling possibly resulted in objects of intermediate composition between the 0–1% spike and the small peaks of the approximately symmetrical shape in the histograms (usually 8–12% for various object types), as the latter feature in the distribution is interpreted as the preferred proportion of Sn alloying. We note, however a certain degree of equifinality, as direct alloying with a less-than-preferred ratio of Sn to Cu may also contribute

to this distribution, without any secondary recycling. Both activities may have occurred, and in any event, they are reflective of the same kinds of economic conditions.

Primary alloying of Sn and its implications

Despite the possible occurrence of specific types of recycling, the approximately symmetrical peaks in many Sn and As profiles presented, regardless of the artefact typology and region, could be ascribed to primary alloying in relatively fixed proportions (Bray *et al.* 2015; Cuénod *et al.* 2015; Pollard *et al.* 2018, 121–2). The left-skewed distribution with a peak at about 11–13% in the Sn profile of ornaments implies a preferred Sn composition in the low double digits, but the mixing in of relatively pure copper to extend the metal supply led to the ‘fat tail’ in the 2–10% range.

The existence of tin deposits in the Caucasus sufficient to supply Bronze Age economies is debated. While some scholars question the presence of any significant tin ores in the Caucasus (Dayton 1971; Selimkhanov 1978), others have speculated, on limited evidence, about the supply of tin from the Caucasus to Mesopotamia (Crawford 1974; de Jesus 1978). The basic and ultrabasic geology in some areas of the Caucasus is generally unfavourable to tin mineralization (Courcier 2014; Erb-Satullo *et al.* 2015). Nonetheless, there are tantalizing reports of tin deposits in western Georgia, including Svaneti, upper Racha, Abkhazia, Guria and Adjara (Tavadze and Sakvarelidze 1959, 53). More recent research has provided stronger support for local tin exploitation in the form of evidence for Cu–Sn alloying using cassiterite placer ores that were probably local to Colchis (Erb-Satullo *et al.* 2015).

Artefact chemical data also suggest that at least some tin sources were exploited locally. In research on Cu alloy compositions, normal distributions of Sn content are interpreted as evidence of primary mixing of metals in relatively fixed proportions, with the implication that these areas have access fresh supplies of alloying metals and are potentially closer to ore deposits. On the other hand, areas distant from fresh sources of alloying metals would have distributions with asymptotic peak in the 0–2% range and a long tail extending to higher values—the result of volatilization (e.g., of As) on remelting, or by ‘stretching’ the supply of alloying metal by introducing more of the base metal (Cu) (Cuénod *et al.* 2015). In the case of LBA–EIA Colchis, the regional histograms of Sn content in the northern lowlands, southern lowlands and southern highlands all show a small approximately symmetrical peak in the high single or low double digits (Fig. 7). We argue these distributions reflect the overlay of two distinct processes: (1) the creating of new Cu–Sn alloys in roughly consistent proportions through mixing metals, through cementation, or less likely, through co-smelting; and (2) the influx of raw copper from the highly productive Colchian copper smelting industry, contributing to the significant number of finished artefacts that are essentially unalloyed Cu.

Given the speculation of tin ore exploitations from the Bzhuzhi and Vakijvari gorges in the metal productions in Guria (Fig. 1) (Erb-Satullo *et al.* 2015; Tavadze and Sakvarelidze 1959, 53), this area might have been a source of tin for Colchian bronzes. Another possible tin ore source would be mountainous Abkhazia, where Tavadze and Sakvarelidze (1959, 53) also mentioned the presence of several tin deposits (Fig. 1). Unfortunately, the number of artefacts from Abkhazia is too limited to see whether the Sn histogram for this region differs significantly from other regions. Considering the geology in Colchis, the small peaks at the high single or low double digits, and the frequently large spike in the 0–1% range, the exploitation of local tin sources was likely to be modest relative to the production of copper. This *relative* scarcity may have

increased the socioeconomic value of tin bronzes relative to copper and arsenical copper, giving rise to the preference of tin bronzes in the production of prestige goods.

CONCLUSIONS

A careful re-examination of legacy metal artefact chemistry reveals in the impact that the expanded mining and smelting of copper sulphide ores in the LBA–EIA had on the metal economies of ancient Colchis. The new supply of copper seemingly outstripped that of the main alloying elements, forcing metalworkers to make careful choices about alloy types and debase (to a certain extent) the content of tin bronzes either by mixing recycled alloys with fresh Cu in order to meet an expanding demand for metal objects, or by reducing the Sn content of primary alloys. Patterns in Cu alloy chemistry also strongly support a separation between the smelting and the alloying stages of production for Cu–As alloys, a process that has been speculated on previously. Moreover, the preference of tin bronze in weaponry and ornaments suggests that colour was one of the key determinants of alloy choice. The north–south division of alloy choices in agricultural tools and, to some extent, in axes, which separated the Colchian lowlands into two metallurgical spheres, points to a higher degree of connectivity in highland–lowland relationships, especially in terms of exchanging metallurgical materials and ideas.

Although right-skewed profiles of Sn and As contents are sometimes interpreted as the result of dilution of the alloying elements due to extensive recycling (Bray *et al.* 2015; Cuénod *et al.* 2015), the relatively modest proportion of quaternary and ternary alloys suggests that large-scale pooling and market exchange of re-melted scrap was unlikely to have occurred in Bronze Age Colchis. Instead, multiple technological processes can explain the shape of the profiles. First, a surge of fresh copper available in the LBA–EIA led to a rise of unalloyed Cu as unformed lumps and finished objects in the assemblage, contributing to the sharp 0–1% peak in most histograms. Second, producers manufactured tin bronzes and arsenical copper by primary alloying that followed a fairly consistent optimum proportion of Sn and As, with the procedures of copper smelting and alloying being separated. A predominance of primary alloying in the production of tin bronzes and arsenical copper gave rise to the peaks in the distributions at high single or low double digits. Third, when the availability of alloying elements was insufficient, metalworkers probably mixed fresh Cu with remelted Cu–As and Cu–Sn artefacts to create metal products with lower Sn and As contents, or perhaps resorted to creating primary alloys with less Sn than they would have otherwise desired. Some limited mixing and recasting alloys of different types may have also contributed to the modest increase in ternary and quaternary alloys of Cu, As, Sn and Sb in the LBA–EIA. Distinguishing different recycling patterns is fundamentally important for delineating the constraints and pressures at work in ancient economies.

Based on the evidence of cementation (Erb-Satullo *et al.* 2015) and the inference that primary alloying predominated in the production of tin bronzes, we argue that tin ores were probably available on a limited scale though mining of local deposits. Though more field and laboratory research is required to substantiate local tin exploitation in Bronze Age Caucasus and assess its scale, it should be considered a distinct possibility.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1 Supporting information.



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