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Copper alloying practices of Urartian metalwork: Results of pXRF analysis from Ayanis, Yukarı Anzaf, and Çavuştepe (Türkiye)

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ABSTRACT

Copper alloy metalwork of the Iron Age Urartian kingdom (9th-7th centuries BCE) is famous for its high degree of sophistication and skill. This study presents the results of energy dispersive portable X-ray fluorescence spectrometry (ED-pXRF) analysis used to characterize 73 Urartian copper alloy objects, primarily from the fortresses of Ayanis, Yukarı Anzaf and Çavuştepe in eastern Türkiye. It includes material dating to the reign of three different Urartian kings between the 9th and 7th centuries BCE in order to assess and compare alloying strategies across object types, sites, and time periods. The results indicate that the majority of the objects are made of bronze alloy (Cu-Sn), but there are also a range of other alloys represented, including low-Zn alloys (Cu-Zn-Sn). Cu-Sn alloys appear to have been chosen for objects worked by hammering, such as shields, likely due to their hardness. Cast objects frequently included Pb or Zn in addition to Sn, likely to facilitate easier casting. Arrowheads are enriched in As and Sb, consistent with the use of a fahlore raw material source different from the other artifact classes. These correlations are present in objects from different sites and time periods, suggesting that alloying practices were shared between craftspeople throughout the kingdom.

1. Introduction

The kingdom of Urartu flourished between the 9th and 7th centuries BCE, controlling a large portion of mountainous territory extending across the modern borders of Türkiye, Iran, and Armenia (Fig. 1) (Çifçi, 2017). Copper alloy metalwork played an important role in elite life in Urartu, where it was deposited in tombs and stored within fortress complexes (Batmaz, 2015). Objects inscribed with the names of kings dedicated at temples evince a close relationship between political authority, metalwork, and practices of state religion (Çifçi, 2018; Zimansky, 1995).

Previous archaeometric research on copper alloy objects from Urartu has addressed metalworking techniques and provenance, demonstrating that near the end of the kingdom's existence in the mid-7th century BCE, metal was provisioned from a variety of locales within and beyond Anatolia, that objects were formed and decorated through sophisticated production processes and surface treatments, including tin-plating, and that sheet metalwork (e.g., shields, helmets) was almost exclusively formed from Cu-Sn alloys (Angelini et al., 2010; Batmaz et al., 2019; Ingo et al., 2010; Reindell and Riederer, 2003). It remains to be explored, however: 1) to what degree different alloys were used for objects formed by casting as opposed to hammering; 2) to what degree these patterns extend beyond the site of Ayanis—which has formed the core of archaeometric research due to multiple decades of intensive excavation and research; and 3) and to what degree these alloying practices were developed prior to the 7th century BCE in the region.

In order to address these three questions, this study presents the results of energy dispersive portable X-ray fluorescence spectrometry (ED-pXRF) analysis used to characterize Urartian copper alloy objects found at two other fortresses near Lake Van in addition to Ayanis and inscribed objects dating to the reign of three different Urartian kings dating back to the 9th century BCE. The goals of the study are to examine alloying practices across a range of object types both diachronically and spatially within the Urartian kingdom in order to assess whether and how craft practices varied between the late-9th and the mid-7th century BCE and between sites such as Ayanis and Yukarı Anzaf. We might expect that craftspeople working under the reign of different kings would have used different raw materials as the area under their control changed, or that alloying recipes may have been less standardized and more localized during the late 9th century BCE, when the offices of provincial governors were newly established (Çifçi, 2017, pp. 198–210). The relatively large sample size which could be analyzed here using

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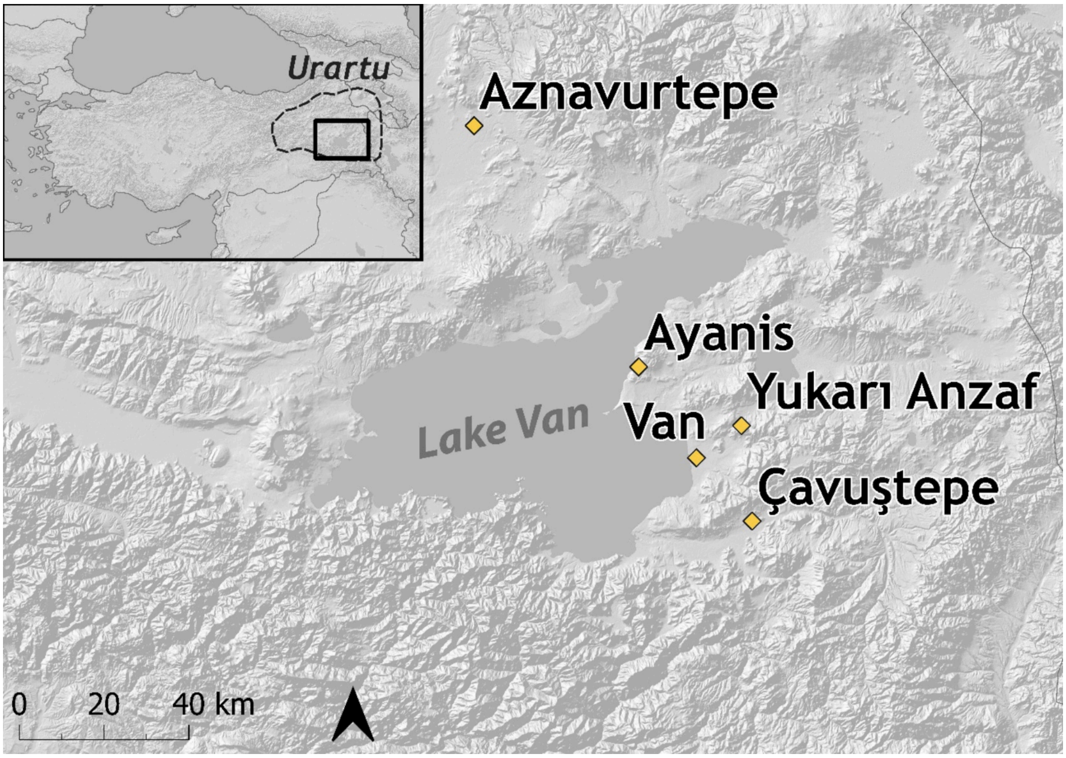

Fig. 1. Map of the study sites mentioned in text and (inset) the approximate extent of the kingdom of Urartu.

Fig. 2. Decorated belt (A).

pXRF and the inclusion of inscribed, and thus datable, objects, offers the opportunity to significantly expand our understanding of the development and degree of standardization of Urartian craft practices. These results are considered within a framework of communities of practice (Orfanou et al., 2024; Roddick and Stahl, 2016; Wenger, 1998), which explores how craft knowledge is developed and shared horizontally and vertically, as a means of explaining how two key aspects of elite-level Urartian life—the centralization and mobility of both people and objects—contributed to the metalworking industry in the kingdom.

2. Background on Urartian metalwork

Bronzework plays an important role in Urartian art and is characterized by a high degree of skill and a sophisticated range of techniques for forming and decoration, including both incised and embossed decoration (Muscarella, 2021). Common classes of artifacts include weaponry and armor, such as shields, quivers, and helmets, as well as more decorative objects such as belts and ornamental nails. An overview of these key object types provides context for the pXRF results.

Produced in different types and sizes, Urartian shields were generally made of single bronze sheets, shaped by annealing and forging into round and conical-convex forms (Erginsoy, 1978, p. 19). The shields are equipped with handles attached with rivets for portability.

Urartian helmets are broadly divided into two main types: conical and crested helmets (van Loon, 1966, p. 119). Conical helmets can be subdivided into flattened and pointed helmets. Although some researchers suggest that the animal-headed helmets belong to the Urartian culture, the debate on this issue continues. Helmets are also classified as votive/ceremonial and defense helmets according to their intended use (Seidl, 2004, p. 68).

Quivers are another important element of military equipment found in Urartian temples and fortresses. Made of bronze and iron, these objects were used for the storage of arrows. There are two main types of quivers: those hung on chariots and those carried on the backs of soldiers (Seidl, 2004, p. 89). It is thought that the large-sized quivers, especially on chariots, also served as spear carriers. To make quivers, long

Fig. 3. Miscellaneous objects (B).

rectangular plates were forged and shaped, and the lower parts were designed in the form of ellipses or drops. The bronze parts of some quivers were riveted, while others were finished with leather.

Belts decorated with engraved and embossed figural scenes are a characteristic element of Urartian ornamental metalwork and are divided into three groups according to their width (Çavuşoğlu, 2002; Kellner, 1991; Seidl, 2004, pp. 133–134). Since most of the belts, which constitute a rich dataset, were recovered as a result of illicit excavations, dating and grouping is based on the inscriptions or depictions.

Ornamental plaques made of hammered metal sheets have been found in excavations at Ayanis (Çilingiroğlu, 2001, p. 53, Fig. 9; Reindell, 2001, p. 386, Fig. 1; Sağlamtimur et al., 2001, p. 233, Fig. 3) and Toprakkale (Merhav, 1991, p. 308, Fig. 5). These plaques were engraved and embossed using techniques similar to those used in making belts, although there is no standard form or decoration for the plaques found in Urartian settlements. Evidence for nail holes suggests that plaques were used for door and wall decorations.

Large ornamental nails with mushroom-shaped heads, some with dedicatory inscriptions, are a special class of artifact within Urartian material culture, referred to as 'sikkat karri/' in Assyrian inscriptions (CAD 15, 1984: 247) and commonly called 'sikkatu' by researchers (Salvini, 2001, p. 271). The five sikkatu unearthed in the Ayanis Fortress/City were recovered from the Temple Complex. Four of these inscribed nails, measuring up to 45 cm in length, were found in front of the core temple, while one was unearthed in the temple storage rooms.

3. Materials and methods

This study includes 73 objects, the majority of which come from the fortresses of Ayanis (n = 46), Yukarı Anzaf (n = 5), and Çavuştepe (n = 4), as well as Aznavurtepe (n = 1). These sites are all monumental Urartian castles founded between the late 9th and early 7th centuries BCE and characterized by large fortification walls, temple and palace complexes, and adjoining storage rooms, often surrounded by lower towns. Detailed information about the sites, their excavation history, and the archaeological contexts of the finds studied here is presented in the Supplement. Bronze objects were typically found in connection to either palace or temple spaces at these sites, reinforcing the link between the production, circulation, and consumption of metalwork and the highest echelons of Urartian society.

As these are some of the best excavated Urartian sites—with particularly remarkable bronze deposits, in the case of Ayanis—material from them offers the ability to examine craft practices in the kingdom at a contextually-specific level. All of these objects are currently storedat the Van Museum, and represent the majority of those on display from the Urartian period. A number of objects donated to the museum by locals in the 1950 s and 1960 s which are Urartian in typology (n = 17) are included in order to extend the patterns identified in the objects with secure archaeological context. 18 objects in this study have royal dedicatory inscriptions, dated to the reigns of the Urartian kings Minua (810-785/780 BCE), Sarduri II (756-730 BCE), and Rusa II (ca. 673-652 BCE) (Çifçi, 2017, p. 310).

Objects were cleaned mechanically after excavation, but due to the fact that they are on display, further removal of corrosion down to metal surfaces prior to analysis was not possible. The objects donated in the mid-20th century were likely cleaned similarly. If they were treated using electrolysis, as was common practice globally at the time (Drayman-Weisser, 1994), this could have led to the deposition of exogenous Zn granules on the surface, but we have no specific reason to believe that this was the case. Moreover, elevated Zn values are present

Fig. 4. Horse frontlets (C).

Fig. 5. Cauldrons and cauldron attachments (D).

in only some of the donated objects but not others, and are also found in many of the objects with secure archaeological contexts which were cleaned mechanically, indicating that the phenomenon is related to the composition of the alloy and not prior conservation treatment.

The analyzed surfaces have been cleaned down to a stable low corrosion layer in the majority of cases, except where indicated. Only a few objects on display which were too badly corroded were not analyzed. This selection of objects represents a random sample of metalwork from the Urartian period, but one which includes a wide range of types and is thus representative of the range of objects produced by metalworkers during the 9th to 7th centuries BCE: belts, horse harnesses, cauldrons, vessels, plaques, helmets, nails, shields, quivers, arrowheads, and miscellaneous types, such as fibulae (Figs. 2-12).

As all of the objects are inventoried museum pieces, non-destructive pXRF analysis was necessary. The relatively homogeneous and sufficiently atomically heavy matrices of copper alloy metal objects make pXRF an appropriate and widely used technique for characterizing the composition of archaeological copper alloy objects, particularly for questions of alloying technology (Charalambous et al., 2014, 2021; Charalambous and Webb, 2020; Dardeniz, 2020; Frahm, 2024; Kladouri et al., 2021; Martinón-Torres et al., 2014; Orfanou and Rehren, 2015). The instrument used here was a handheld Olympus InnovX Delta model with silicon-drift detector and Ta anode X-ray tube. Analysis was carried out with the pXRF in a fixed position, although the size of the artifacts precluded the use of a chamber. Measurements were conducted on cleaned surfaces in the majority of cases. Analysis surface and number of analyses are indicated in Supplementary Table 1. Data were collected in the ‘alloy plus’ mode for 35 s, with settings of 40 kV and 38 μA. The elements detected and quantified using the fundamental parameters approach across all of the samples were Fe, Cu, Zn, As, Sn, Sb, and Pb. The certified reference material CD 314/UNS C31400 was analyzed in order to assess instrument accuracy for Fe, Ni, Cu, Zn, and Pb (Table 1). Results for all elements except zinc were acceptably accurate when compared to nominal values. The measured zinc value, however, was lower than nominal by between 2 % and 4 % by weight.

Furthermore, five of the shields in the current study have previously

Fig. 6. Vessels (E).

Fig. 7. Plaques (F).

been analyzed by atomic absorption spectroscopy (AAS) (Reindell and Riederer, 2003). A comparison of results indicates that the present pXRF data are largely consistent with the AAS data (Table 2). The one substantial disparity, the tin concentration of I-11, is discussed below.

In general, iron, tin, and lead are known to be overestimated in pXRF data, particularly with measurement of corroded areas, making it safest to interpret results in terms of comparison between objects and the identification of overall trends rather than emphasizing absolute concentrations (Martinón-Torres et al., 2014; Orfanou and Rehren, 2015). To that end, alloys were identified qualitatively on the basis of > 2 % concentration for lead due to the possibility of the uptake of natural impurities from ores and > 1 % concentration for all other elements (all reported values are wt%). The use of naturally polymetallic ores can lead to zinc concentrations of several percent, and higher thresholds for defining an alloy have been used elsewhere (e.g., Thornton, 2007), but given the underestimation of zinc indicated by the analysis of the standard, a threshold of 1 % is used here. It was not possible to clean to a metal surface for analysis in this case; however, comparison of results obtained using the same pXRF instrument and settings on other Urartian copper alloy objects which were cleaned below corrosion with ICP-MS and SEM-EDS results and a comparison between pXRF results on the cleaned/corroded surfaces for some of these objects (Supplementary Material) together indicate that the method is sufficiently reliable for qualitative identification of alloys on a presence/absence basis using these cutoff percentages.

4. Results

The assemblage is characterized by the prevalence of Cu-Sn alloys (**Supplementary Table 1**). Tin concentrations appear to exhibit a bimodal distribution, with a group normally distributed around 8–10 %, a typical composition for ancient bronze, and another group around 14 % (Fig. 13). There is also a small number of high-tin objects, including a group around 18 %. As pXRF is a surface analysis, it is difficult to determine how representative these high tin compositions are, particularly in the case of the belt at the very high end. Tin may be enriched at the surface of copper alloys, either as the result of deliberate surface treatment, or due to the preferential enrichment of tin at the surface of copper corrosion products.

Zinc values are generally low, with the vast majority of the assemblage displaying values below 1 %; however, a subset of objects ($n = 9$) have zinc values distributed evenly between 1 % and 5 % (Fig. 14). Zinc invariably occurs with tin in these objects, and there are no Cu-Zn alloys. Low-Zn alloys are known from elsewhere in Urartu and from other sites in western Asia during the early 1st millennium BCE, and binary Cu-Zn alloys appear to have been deliberately produced in Urartu (Güder et al., 2023; Thornton, 2007). It is an open question whether the Cu-Zn-Sn and Cu-Zn-Sn-Pb alloys like those in this study were deliberately produced or were inadvertently created due to the use of a naturally polymetallic ore or through the recycling of Cu-Zn alloys made elsewhere in Urartu with Cu-Sn alloys. Regardless, the inconsistent distribution of zinc values suggests a relative lack of control in working with these alloys.

Lead values are also low, with the majority below 5 % (Fig. 15). Objects with lead concentrations between 5 % and 10 % may represent deliberate alloying for beneficial casting properties.

4.1. *Alloy and object types*

Eight different alloy types are qualitatively identified here. Not surprisingly, Cu-Sn is predominant (Fig. 16, Fig. 17). This alloy was used for 10 out of the 12 object types and for the majority of the objects ($n = 45$). Alloys of Cu-Zn-Sn ($n = 8$), Cu-Sn-Pb ($n = 7$), and Cu-As-Sn-Sb ($n = 6$) are next in frequency. The other four alloy types are infrequent, each found in between one and three objects.

Fig. 8. Helmets (G).

Although only a single belt was analyzed, its composition is noteworthy due to the presence of zinc and tin together (Cu-Zn-Sn), which is paralleled in other Urartian belts, for example at Murat Tepe and in the Elazığ Museum (Güder et al., 2023, p. 11).

The horse frontlets (C) are made of both Cu-Sn and Cu-Zn-Sn alloys. Cauldrons (D), Plaques (F), Helmets (G), and Shields (I) are made exclusively with Cu-Sn, while cauldron attachments are primarily Cu-Sn-Pb, likely to afford better casting properties. For vessels (E), Cu-Sn is the main alloy, with most objects containing around 10 % tin.The bowl with embossed fluting (E-5) is a ternary Cu-Zn-Sn alloy. The large ornamental nailheads (H) are made of a range of alloys, including Cu-Sn, Cu-Sn-Pb, and Cu-Zn-Sn.

Shields (I) are invariably made of Cu-Sn, while the lion head shield attachment (I-13) is a Cu-Zn-Sn alloy. Shields I-3, I-10, and I-11 contain less than 5 % tin. Since these lower tin alloys would not have the strength of alloys around 10 % tin, these objects may have been made solely to be dedicated rather than as functional armor. Only one of them (I-3) has an inscription, however. Shield I-11 contains the lowest amount of tin of any of the objects at 1.0 %. Previous AAS analysis of the same object indicated a concentration of 6.9 % tin, as shown in Table 1 (Reindell and Riederer, 2003). This discrepancy could be due to the analysis of the patinas, but it is also possible that this shield was originally tin-plated, as demonstrated through metallography for other shields from Ayanis (Ingo et al., 2010). The pXRF analysis could be of an area where this plating has corroded away, while the AAS data could represent a tinned surface or a combination of the surface and substrate. Other shields appear to not have been tin-plated, however, as a comparison of corroded and cleaned surfaces for shield I-4 showed similar percentages of tin (13.4 %, 14.4 %, respectively).

Quivers (J) are primarily Cu-Sn, with one example of a leaded bronze, Cu-Sn-Pb (J-3). Arrowheads (K) are made of a range of alloy types, including arsenic and antimony alloys, which are not found in use for other object classes. The diversity of alloys used for arrowheads suggests either the use of different raw materials and/or mixing as a result of recycling. Regardless, it appears that tin was deliberately added in high quantities, as arrowheads generally display higher concentrations than other object types (Fig. 18). Producing high tin objects increases hardness but results in objects that are more brittle and have less workability. The intentional selection of higher tin compositions in arrowheads has been explained in other contexts as the result of craftspeople prioritizing penetrating power (Martinón-Torres et al., 2014, p. 546), and similar dynamics may have been at play here.

Most of the arrowheads are also enriched in antimony and arsenic relative to the other objects studied here. In addition to a more widespread use in the Early Bronze Age in Anatolia, antimonial copper alloys have been detected in Late Bronze to Early Iron Age objects from the

Fig. 9. Decorative nails (H).

Kars and Erzurum museums as well as nearby in the south Caucasus (Dardeniz, 2020; Işıklı and Altunkaynak, 2014). The concentrations of the arrowheads here should be interpreted with caution, as arsenic values are known to read erroneously higher for ED-pXRF due to spectral overlap with lead, and antimony is known to be enriched at the surface of corroded objects (Orfanou and Rehren, 2015, pp. 394–395).

Nevertheless, the correlation of higher antimony and arsenic values in the arrowheads compared to the other objects is notable (Fig. 19). One explanation could be the use of fahlore deposits (tetrahedrite-tennantite), which are known to be enriched in As and Sb, for the copper used to make these arrowheads (Hauptmann, 2020, p. 316). Fahlore deposits are found in the Pontide and Tauride ore bodies in Turkey (Akaryali, 2016; Revan et al., 2014; Yıldırım et al., 2019), and lead isotope analysis of other objects from Ayanis has demonstrated that both sources were exploited during the 7th century BCE, so metal from these types of deposits was available to Urartian metalworkers (Batmaz et al., 2019). It seems reasonable to infer that the arrowheads were made from copper derived from the exploitation of fahlores, either from these deposits or elsewhere. The cluster of arrowheads studied here is predominantly composed of objects from Ayanis, but it is interesting that the example from Yukarı Anzaf also lies within the group of high antimony and arsenic. The two arrowheads from Çavuştepe display low arsenic and antimony values, on the other hand, suggesting they were made from a different, non-fahlore-derived raw material source.

4.2. Manufacturing techniques

Comparison of alloy type and likely method of manufacturing provides the clearest indication of the selection of particular alloys. Objects such as the arrowheads, fibula, ornamental nails, and shield and cauldron attachments were made by casting. As discussed, the range of alloys used for arrowheads makes their production unique, and they are excluded from the discussion here. The majority of Cu-Sn-Pb alloys are used for cast objects, which is consistent with the addition of lead for increased casting properties. However, Cu-Sn-Pb alloys represent only 20 % of cast objects overall, with the majority of cast objects made of either Cu-Sn (40 %), Cu-Zn-Sn (33 %) or Cu-Zn-Sn-Pb (7 %) alloys (Fig. 20). In other words, cast objects were made with a range of alloys that included leaded, unleaded, and low-Zn alloys. It is also noteworthy that low-Zn alloys are more commonly used for cast objects than for hammered ones. Despite the known limitations of pXRF for accurately quantifying Zn and Pb based on the analysis of corroded surfaces (Orfanou and Rehren, 2015), it remains remarkable that the objects in this study identified with elevated concentrations of these two elements are disproportionately made by casting, as opposed to hammering. In other words, in general terms, it seems reasonable to infer that Pb and Zn were more frequent components of cast as opposed to worked objects, a suggestion that is consistent with the increased casting properties afforded by both elements.

Microstructural analysis of Urartian metalwork has indicated that shields and quivers were worked by cycles of hammering and annealing (Ingo et al., 2010; Muşkara et al., 2023), and belts, cauldrons, vessels, plaques, horse tack, and helmets were presumably also shaped through hammered. The objects of these types analyzed here have broadly similar compositions–Cu-Sn alloys with around 10 % tin–and Cu-Sn is the predominant alloy for hammered objects. Exceptions include the use of Cu-Zn-Sn alloy for the belt and one of the horse frontlets, and the use of a leaded Cu-Sn-Pb alloy for one of the quivers.

4.3. Alloying practices by site

As with working techniques, the discussion of alloying practices by site excludes arrowheads, given their unique composition. The remaining 54 objects, from Ayanis, Yukarı Anzaf, and donations, show a

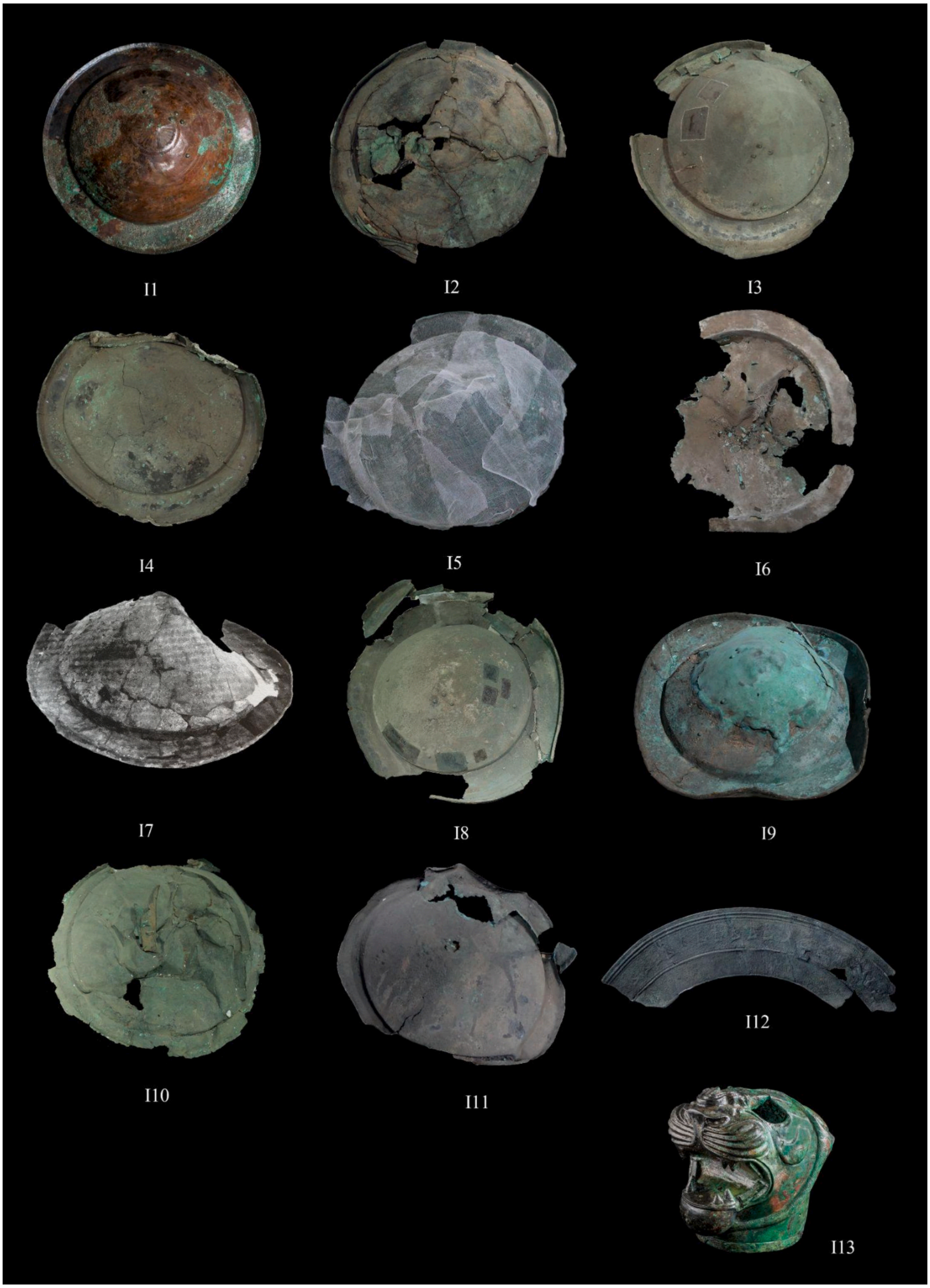

Fig. 10. Shields and shield attachments (I).

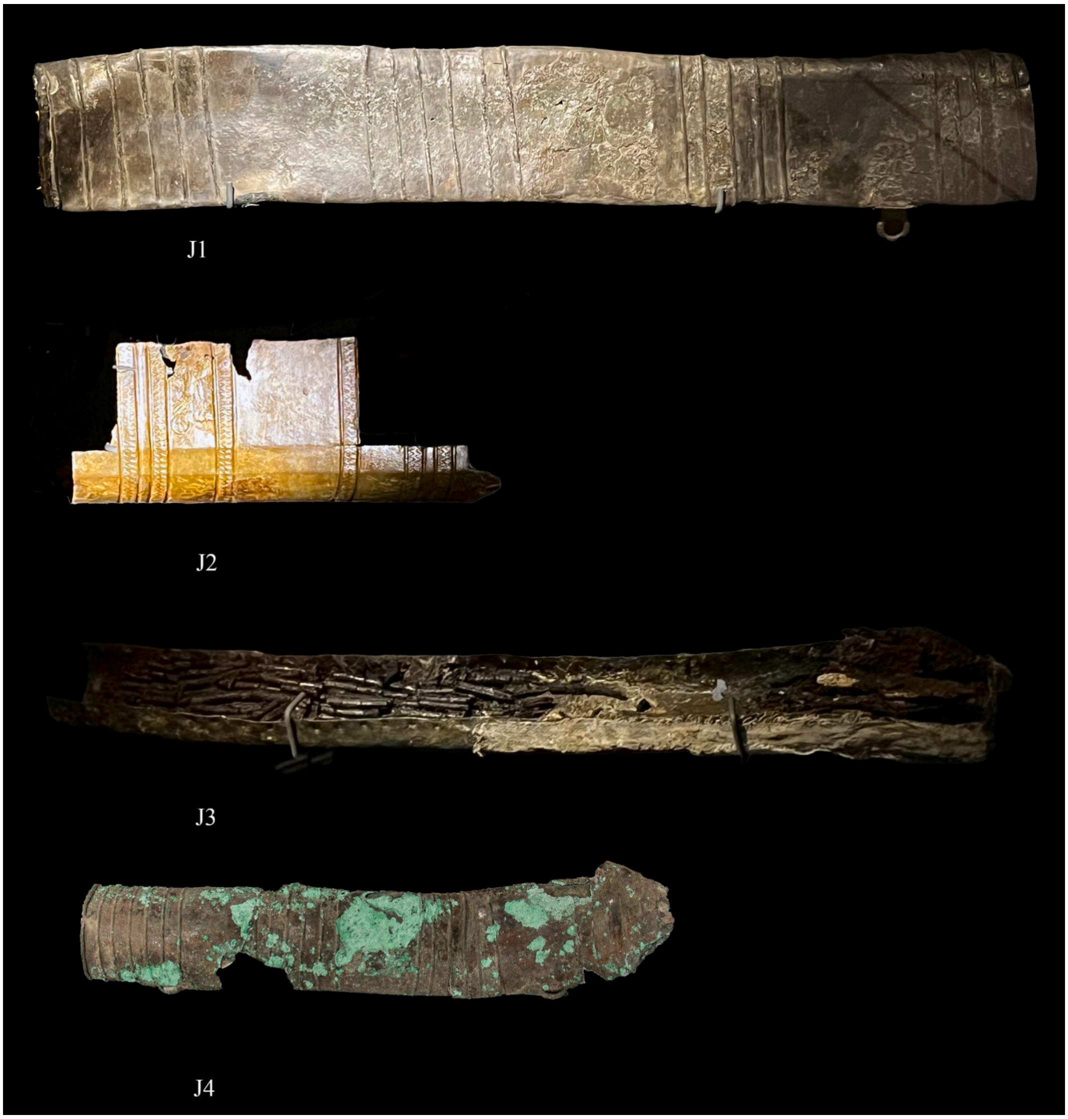

Fig. 11. Quivers (J).

generally similar distribution of alloying practices, particularly when grouped by working technique (Fig. 21, Fig. 22): a predominance of Cu-Sn alloys for hammered objects, and a combination of Cu-Sn, leaded, and low-Zn alloys for cast ones. In other words, the pattern established by archaeologically secure finds can be extended through the inclusion of donated objects to indicate that a consistent principle underlay Urartian metalwork, regardless of where objects were made or deposited.

4.4. Inscribed objects

The majority of inscribed objects, 16 out of 18, are made of Cu-Sn (Fig. 23). Shields are the only class of object with inscriptions from all three kings. All of the shields, both inscribed and uninscribed, are Cu-Sn. All of the objects inscribed with the names of Minua and Sarduri II (late 9th to mid-8th centuries BCE) are made of Cu-Sn. Two of the 10 objects inscribed with the name of Rusa II (early-mid 7th century BCE) are made of Cu-Zn-Sn: an ornamental nail and the lion head shield attachment from Ayanis. It is difficult to know whether there is any chronological significance to the use of Cu-Zn-Sn during the reign of Rusa II, as the objects inscribed with the names of Minua and Sarduri II do not include object types comparable to the nail and the shield attachment. It does appear that low-Zn alloys were used for special ornamental objects in addition to the inscribed nail and inscribed shield attachment, namely the belt, the Patnos lion statuette, the bulls head cauldron attachment, and the fluted bowl. Unfortunately, comparison of object typology for these uninscribed low-Zn objects at present does not allow a closer understanding of chronology. Their dating remains based on the archaeological context: i.e., a mid-7th century BCE date for the objects from Ayanis.

5. Discussion

These results offer several insights into alloying practices in Urartu between the 9th and 7th centuries BCE. Craftspeople working across the region had regular access to tin, which was consistently used in high quantities, around or above 10 %. There are no tin sources in eastern Anatolia, implying the maintenance of long-distance exchange, while the creation of low-Zn alloys likely relied upon locally available polymetallic mineralizations (Belli, 1991).

There is a relatively close relationship between alloy type and object type, evident, for example, in the exclusive use of Cu-Sn for shields and cauldrons, and the use of specific polymetallic alloys only for

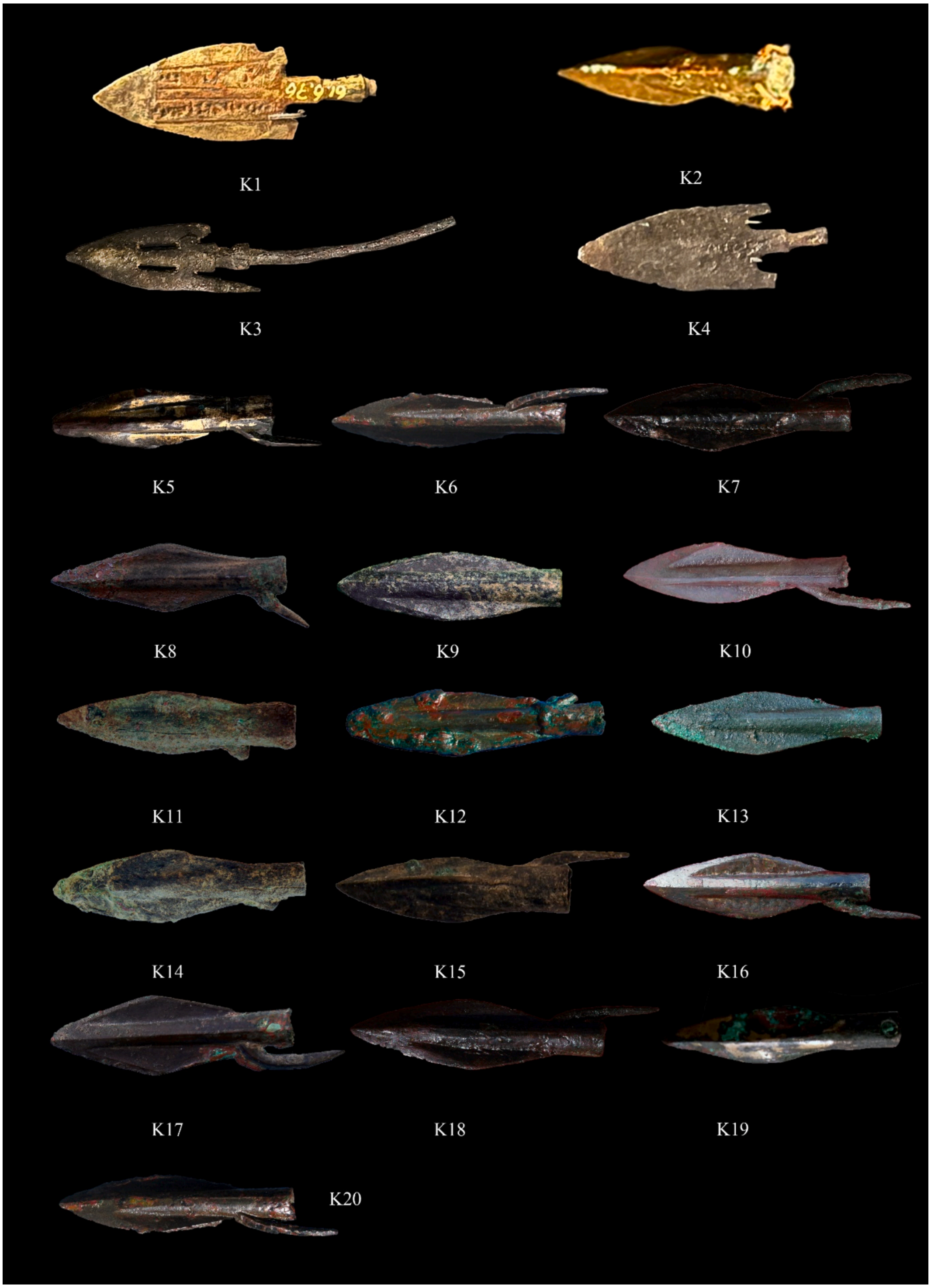

Fig. 12. Arrowheads (K).

Table 1
Analysis of reference standard UNS C31400.

Date	Standard	Fe	Ni	Cu	Zn	Pb
11/23/2020	C31400	0.1	0.8	88.6	4.0	2.3
	reference	0.1	0.7	87.5–90.5	Remainder (6.2–10.4)	1.3–2.5

arrowheads. These object class patterns appear to reflect the consistent selection of particular alloys based on working technique. In particular, objects formed from hammered sheets were almost always made of Cu-Sn, while cast objects were made of a greater range of alloys, including leaded and low-Zn alloys. The extensive and exclusive use of Cu-Sn for shields, quivers, and helmets (i.e., sheet metalwork) has been documented in other objects from Ayanis (Batmaz et al., 2019; Muşkara et al., 2023; Reindell and Riederer, 2003).The use of low-Zn alloys for ornamental objects is known elsewhere in Urartu (Güder et al., 2023), and the objects studied here from Ayanis,Yukarı Anzaf, and Aznavurtepe add to our growing understanding of the distribution of these alloys across western Asia in the 1st millennium BCE (Thornton, 2007). Urartu appears to have been a major center of consumption, if not production, of low-Zn alloys in the Iron Age, and metalworkers appear to have used the alloy for particular ornamental objects. The selection of particular leaded and low-Zn alloys for cast objects is consistent with the beneficial material properties these elements add to alloys. Our results are the first presentation of a widespread investigation of cast Urartian objects, and the finding of specific alloys frequently and disproportionately used for casting indicates an added degree of sophistication to the production process.

Alloys appear to have been selected for specific object types in the same manner across the three principal sites and three periods studied here. In other words, there are no site-specific or period-specific alloys, but hammered and cast objects from different periods and sites have similar signatures. The fact that the objects were dedicated as votives at elite-controlled palace and temple complexes, and that some bear royal inscriptions, makes them part of what has been called the 'state assemblage' of Urartian material culture, along with material such as highly burnished pottery and practices such as the cult of Ḫaldi (Zimansky, 1995). That is, production and circulation of these classes of

Table 2
Comparison of pXRF and AAS results for samples analyzed in the present study and by Reindell and Riederer (2003). Values for I-2 through I-11 are error of single pXRF measurement, value for I-13 is standard deviation of two measurements.

Sample	Cu (pXRF)	*Cu (AAS)*	Sn (pXRF)	*Sn (AAS)*	Pb (pXRF)	*Pb (AAS)*	Fe (pXRF)	*Fe (AAS)*
I-2	86.9 ± 0.17	*89.54*	11.9 ± 0.17	*9.90*	0.1 ± 0.02	*bdl*	0.2 ± 0.03	*0.05*
I-5	91.3 ± 0.16	*92.68*	7.6 ± 0.15	*6.69*	0.1 ± 0.02	*0.07*	0.4 ± 0.03	*0.20*
I-10	94.0 ± 0.14	*89.76*	4.2 ± 0.13	*9.34*	bdl	*bdl*	1.2 ± 0.05	*0.26*
I-11	96.6 ± 0.10	*92.78*	1.0 ± 0.07	*6.70*	bdl	*bdl*	1.2 ± 0.05	*0.15*
I-13	89.1 ± 0.50	*86.73*	8.1 ± 0.01	*9.83*	1.1 ± 0.53	*0.4*	0.1 ± 0.04	*0.19*

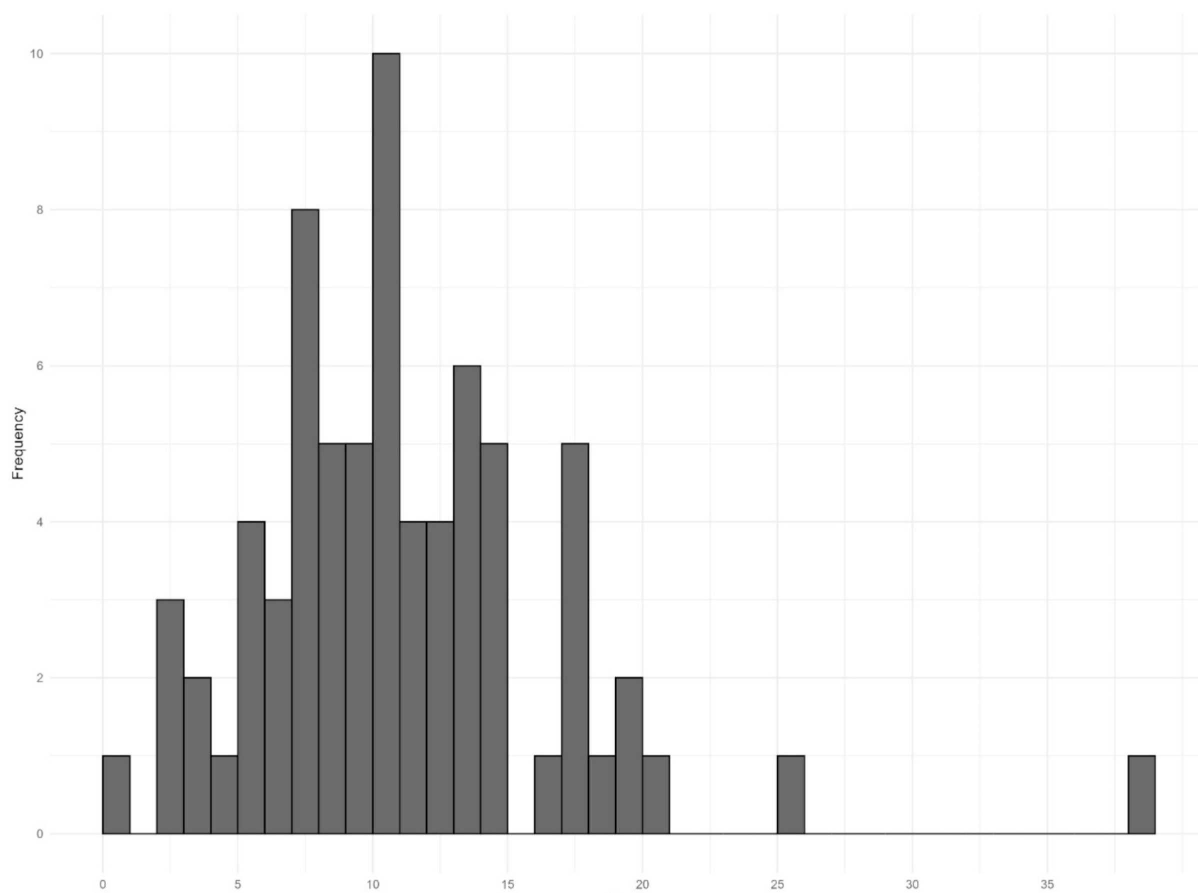

Fig. 13. Histogram of Sn wt%s showing a bimodal distribution around 8–10 % and 14%, with a group of high tin objects.

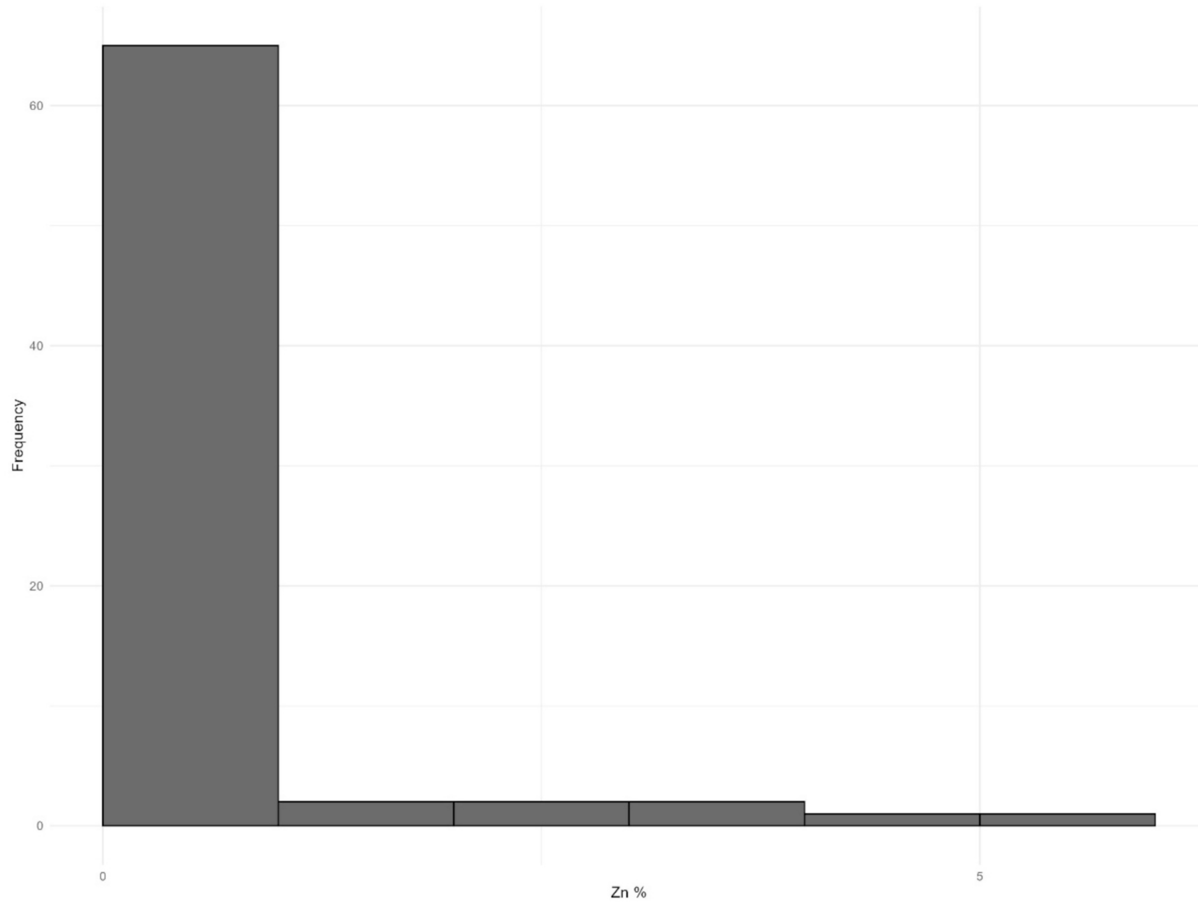

Fig. 14. Histogram of Zn wt% showing the inconsistent use of the element for alloying.

luxury copper alloy objects was closely controlled, which may have contributed to the development of a relatively standardized repertoire of techniques and alloys and their circulation between sites.

It is remarkable that alloying and deposition practices for these elite-tier items appear to have been shared across the kingdom. This confluence of visually similar object forms, common working techniques, and comparable alloying practices across object types dedicated in temples and stored in palaces suggests that metalworkers creating objects for elites across Urartu constituted a community of practice (Orfanou et al., 2024; Roddick and Stahl, 2016; Wenger, 1998). That is, craftspeople appear to have made similar choices in the production process in terms of materials and technical gestures (Kuijpers, 2018; Lemonnier, 1993; Sillar and Tite, 2000), leading to the use of Cu-Sn alloys for hammered armor and sheet metalwork and a more diverse range of leaded and low-Zn alloys for cast, ornamental objects. This community of practice appears to have shared the knowledge about alloying and working practices in the area around Lake Van; whether these shared practices reflect multiple groups of craftspeople active in the kingdom or the circulation of products of a single community to multiple sites, the homogeneity remains noteworthy.

The concentration of objects at fortresses, and the presence of a secondary production workshop at Çavuştepe (Müller-Karpe, 1994, pp. 101–102) indicates that at least some activities of metallurgical production were directly tied to political and religious institutions and likely centrally coordinated (Costin, 1991; Erb-Satullo, 2022). This nucleation may have facilitated the transfer of specialized knowledge, as one of the hallmarks of a community of practice is “sustained mutual engagement” (Wenger, 1998, p. 114). Even if objects were made beyond the fortresses where they were dedicated, it is remarkable that similar principles apply to objects from Ayanis, Yukarı Anzaf, and Çavuştepe, suggesting comparable, controlled production and circulation patterns. The degree to which this community of practice may have extended beyond this core Van region to include metalworkers in other areas of Urartu, or whether multiple communities of practice existed within the kingdom, deserves further exploration through systematic comparison of working and alloying data from other sites, as does the chronology of the development of these practices. At present, our best indication of chronology comes from the inscribed objects, which demonstrate that the preferential selection of Cu-Sn alloys for hammered objects developed by the time of Minua, at the end of the 9th century BCE, and was maintained until the reign of Rusa II, in the mid-7th century BCE.

The results of the analysis of the arrowheads give further insight into the organization of metal production in Urartu, as the higher concentration of arsenic and antimony likely reflects a different source of metal, conceivably derived from fahlore deposits. Such sources may have been used to create arrowheads that circulated across the kingdom, judging by the presence of high arsenic/antimony objects at both Ayanis and Yukarı Anzaf. Indeed, a cuneiform tablet found at Yukarı Anzaf provides evidence of the regulated distribution of arrows to soldiers (Çifçi, 2017, pp. 244–245: CT An-1), and this may have included the products of different workshops, some of which used fahlore-derived metal.

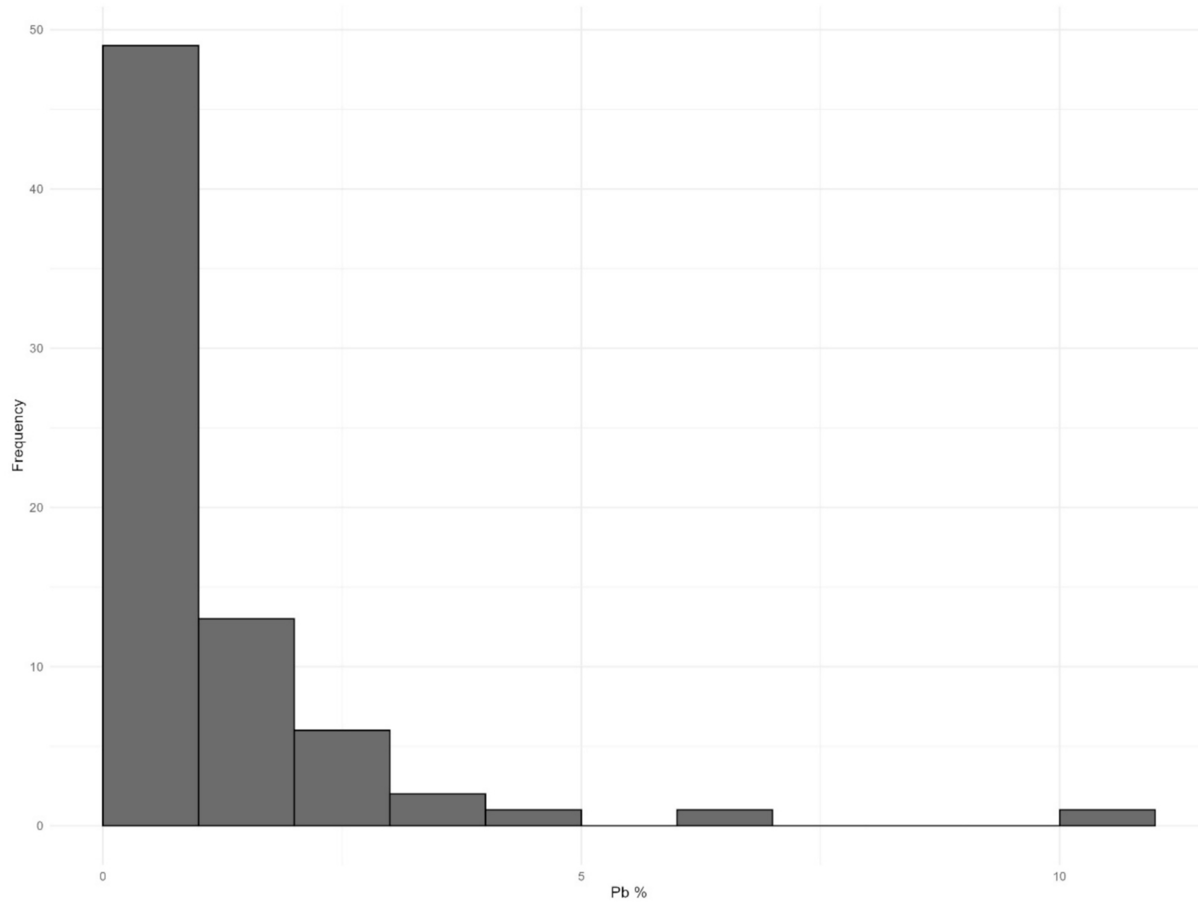

Fig. 15. Pb histogram showing low values associated with natural impurities and/or recycling, and the likely presence of intentional alloying between 5 % and 10 % Pb.

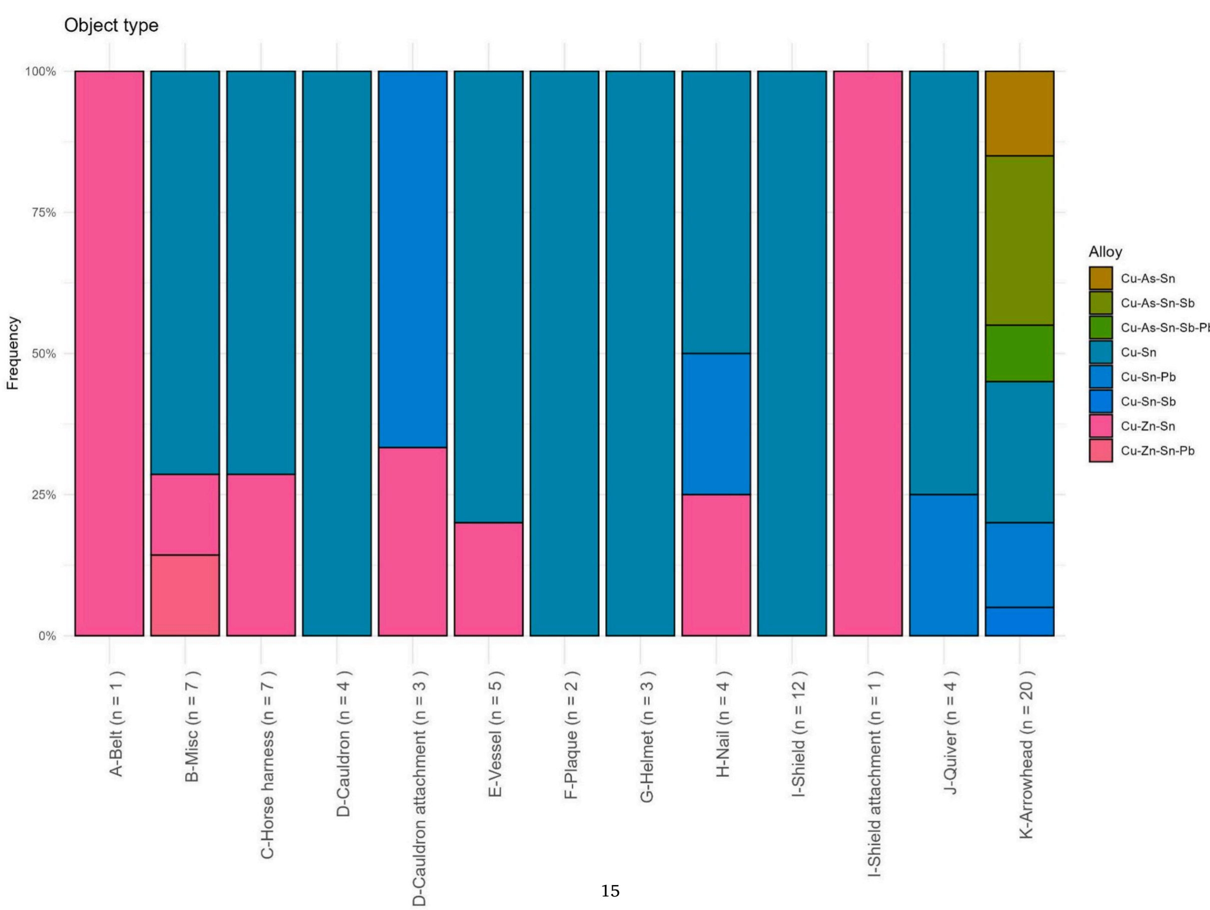

Fig. 16. Alloys by object type, indicating the ubiquity of Cu-Sn, and the variety of alloys used for arrowheads.

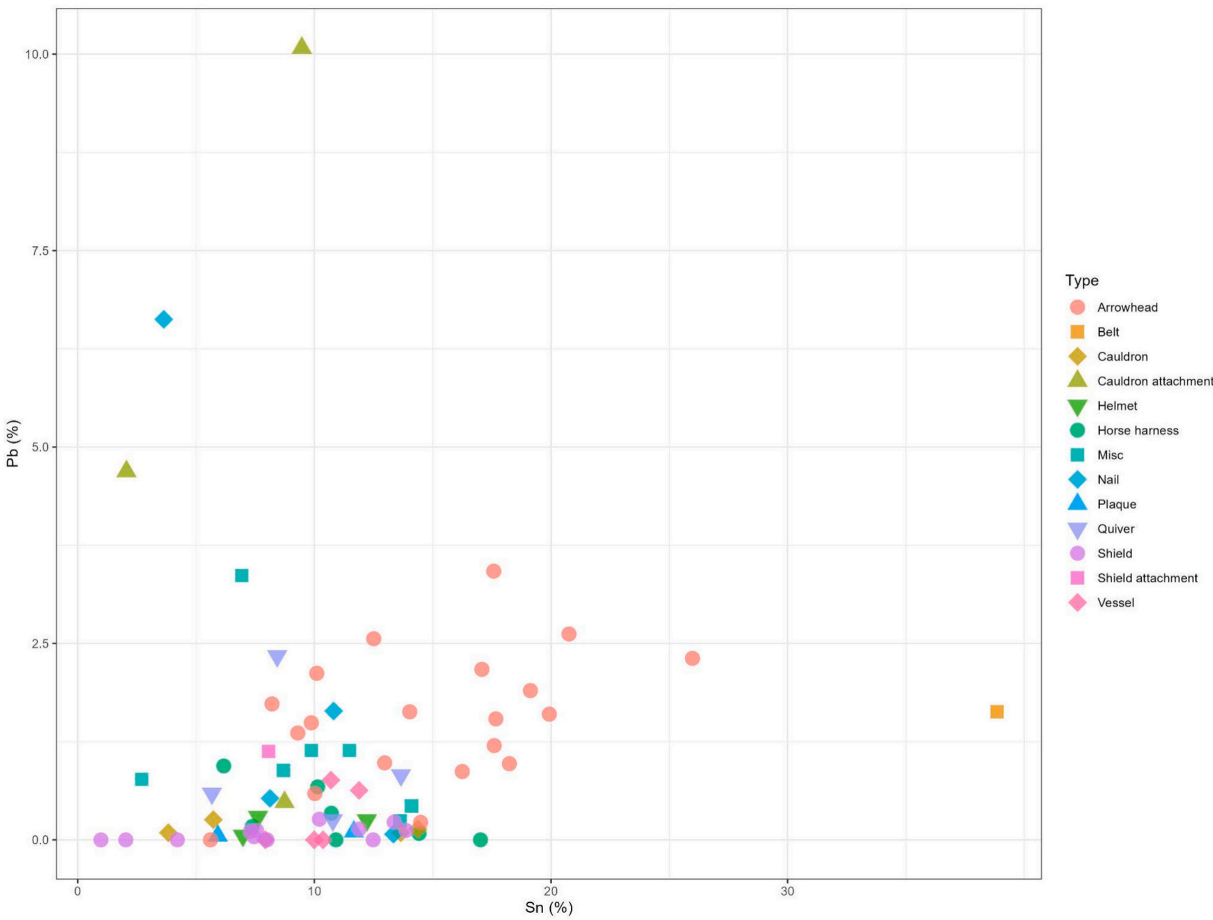

Fig. 17. Sn vs Pb for all object types. Note the high Sn nature of the belt, the presence of leaded cauldron attachments and nails, and the overall clustering of objects other than arrowheads around 10% Sn. The higher Sn concentrations of arrowheads is discussed in relation to Fig. 17.

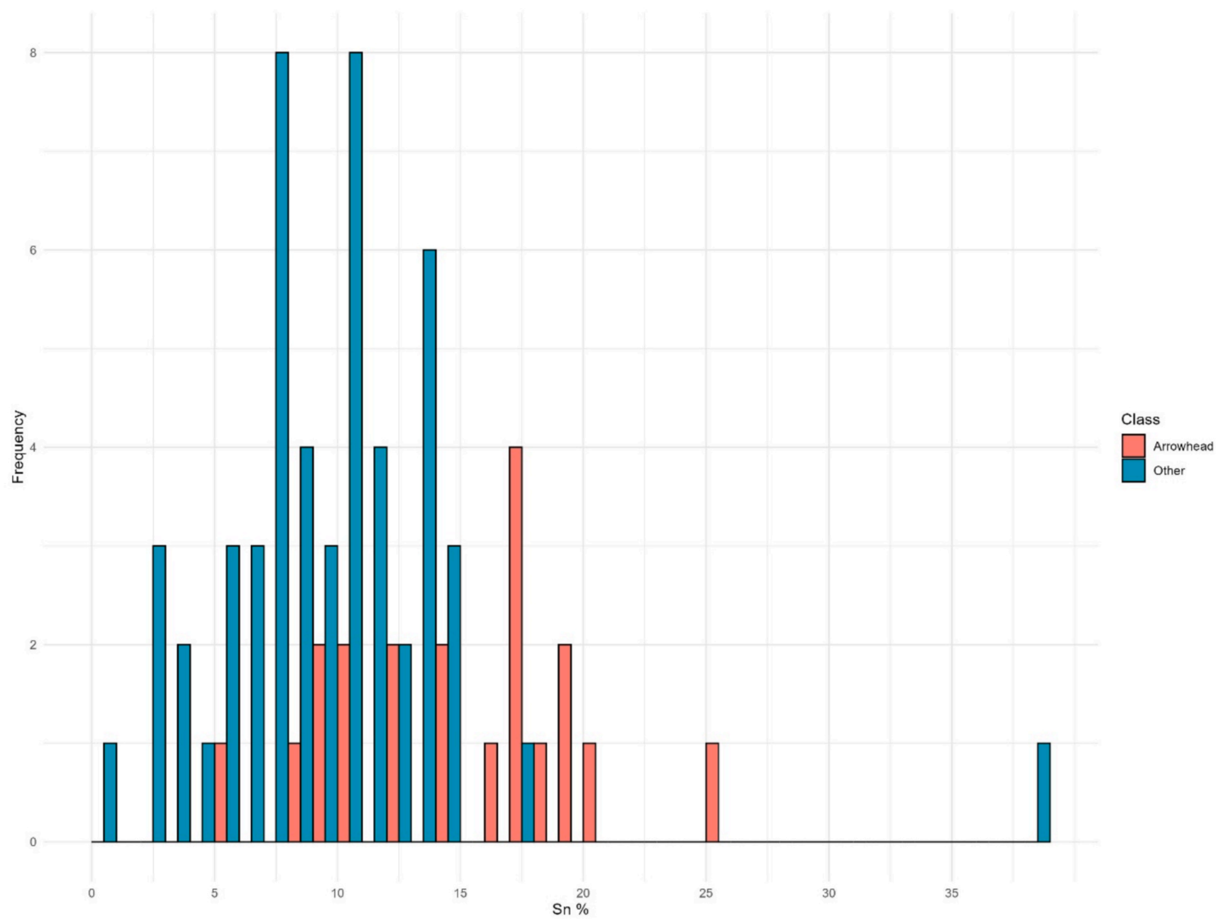

Fig. 18. Histogram of Sn values showing that arrowheads are on the whole made of a higher Sn alloy than other object types.

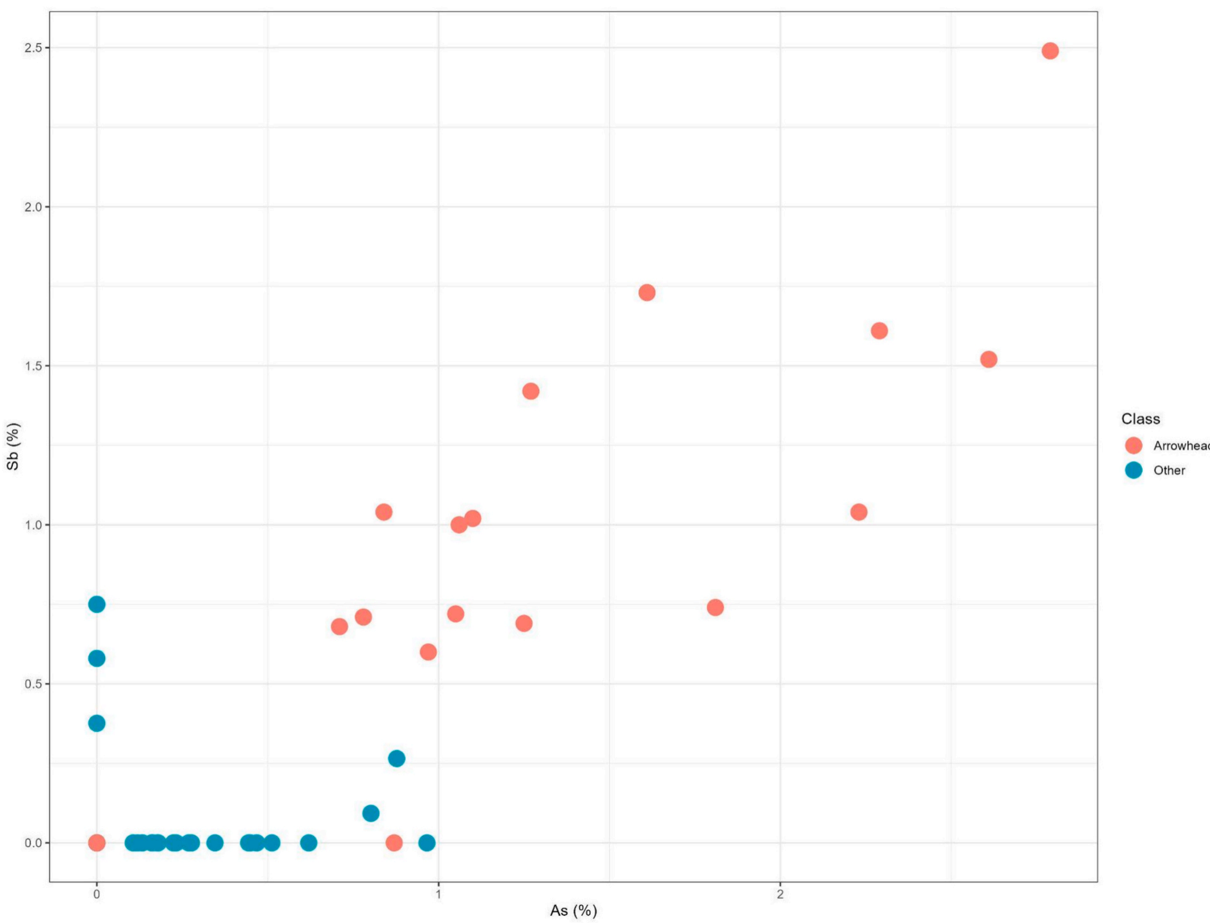

Fig. 19. As vs Sb showing a correlation in arrowheads for the majority of Ayanis arrowheads, consistent with the use of fahlore-derived copper.

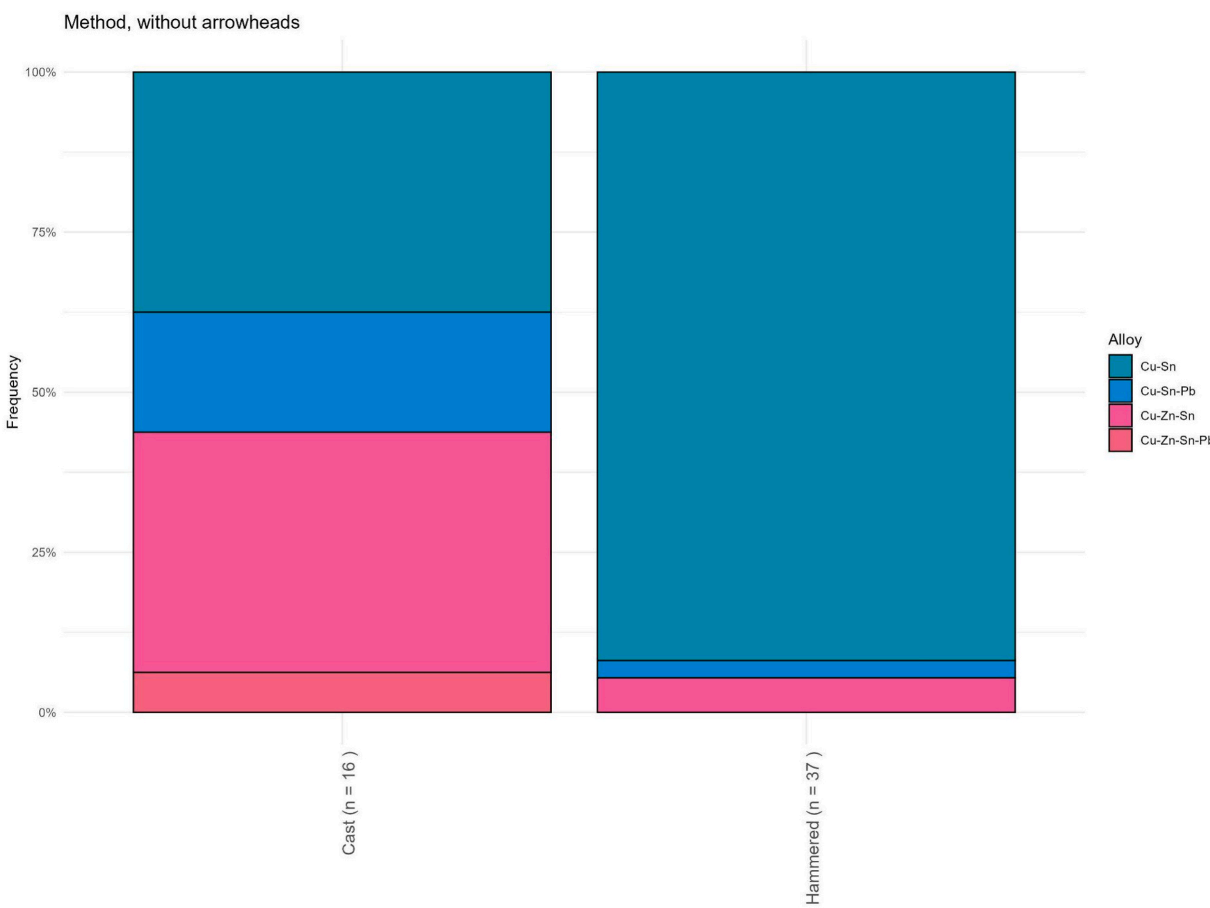

Fig. 20. Frequency of alloys according to production method, excluding arrowheads, showing the use of low-Zn and leaded alloys for cast objects and the predominance of bronze for hammered objects.

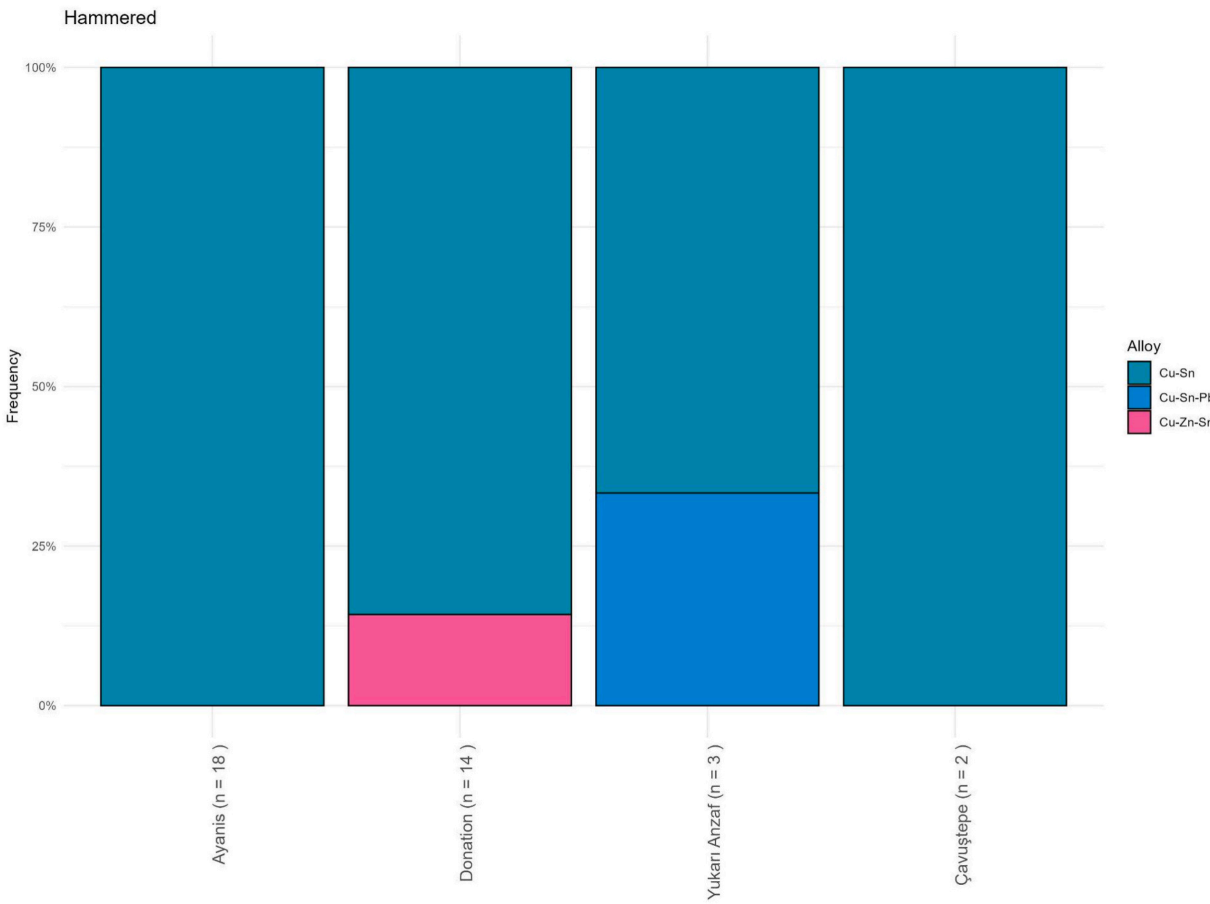

Fig. 21. Frequency of alloys for hammered objects by site.

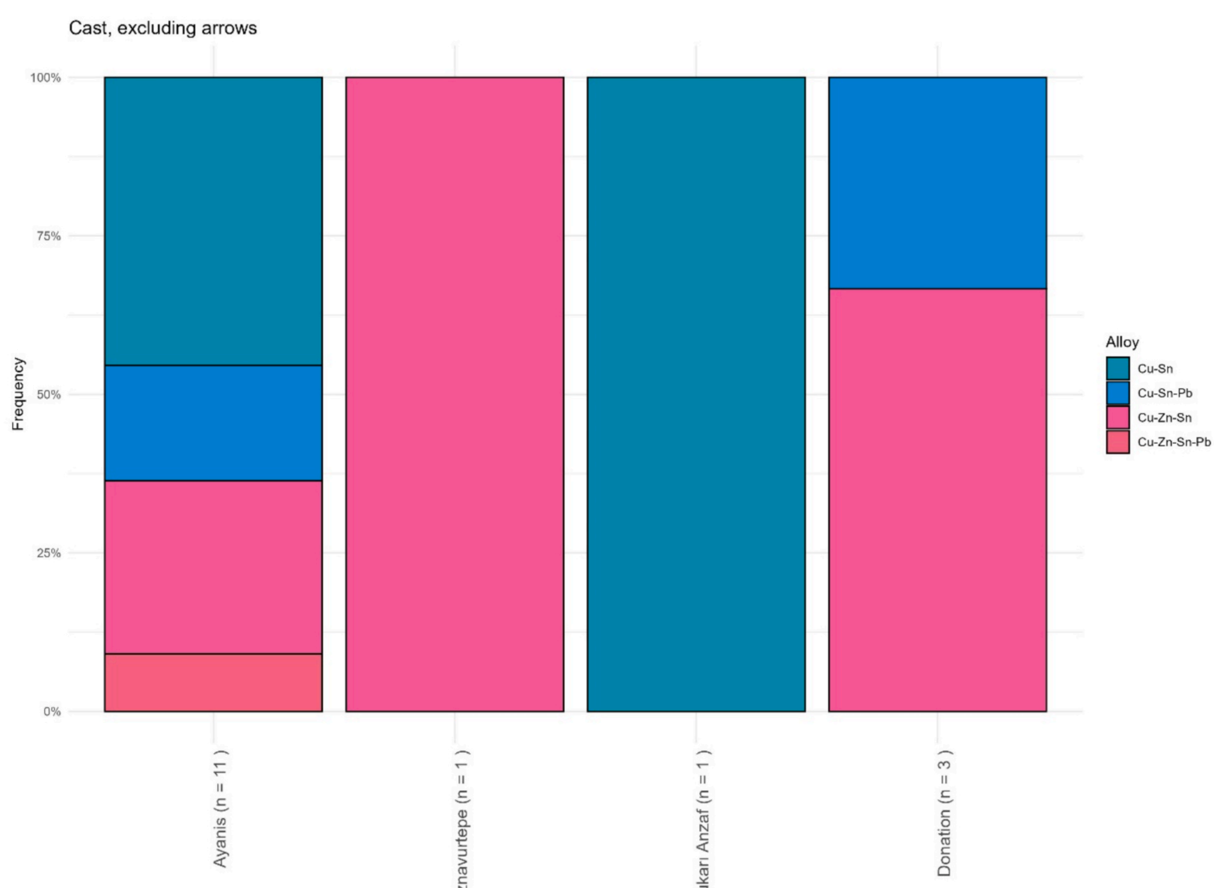

Fig. 22. Frequency of alloys for cast objects by site, excluding arrowheads.

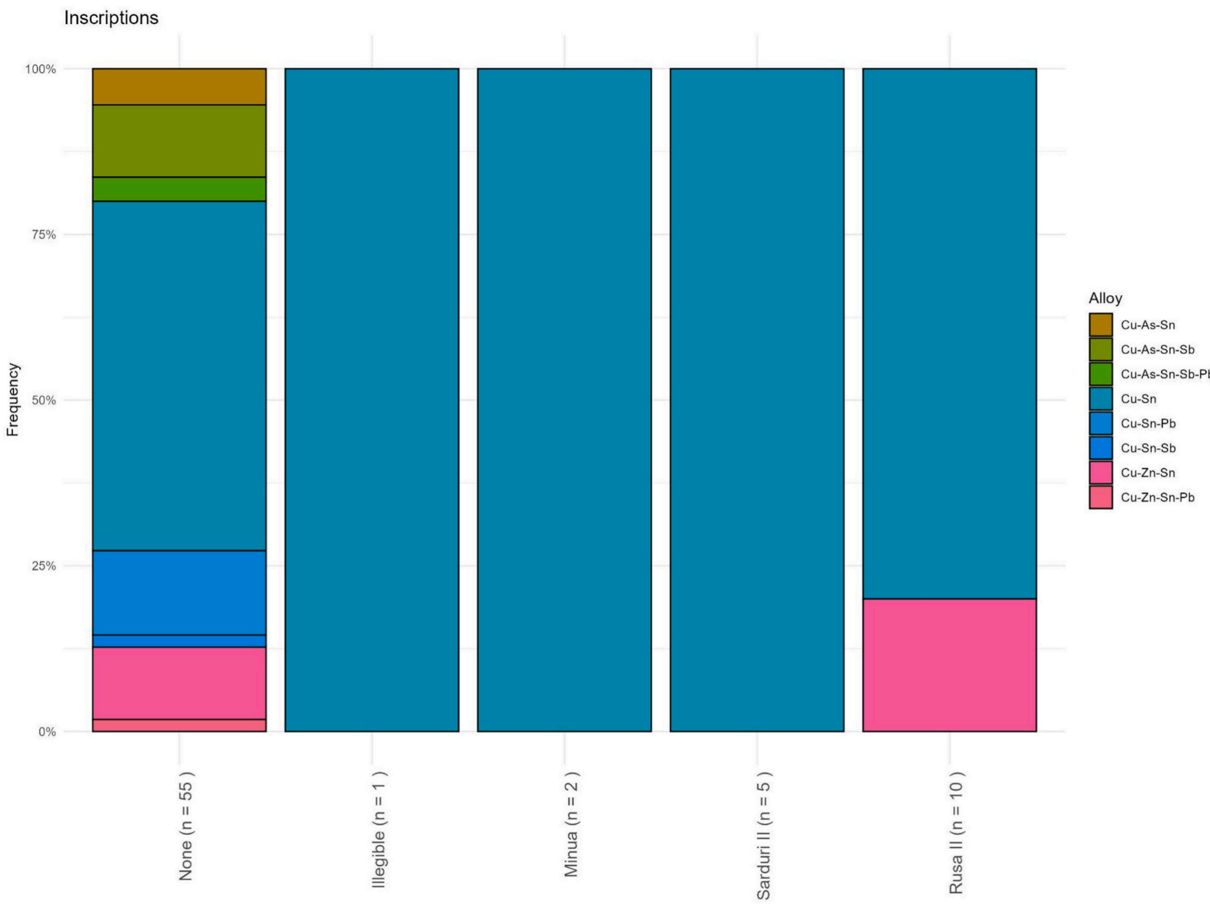

Fig. 23. Frequency of alloys for inscribed objects.

6. Conclusion

This study analyzes 73 Urartian copper alloy objects from the Van Museum using handheld pXRF in order to examine their chemical composition. It finds that alloying practices appear consistent across the different periods and sites studied, with certain alloys preferred for specific object types, generally based on working technique, which we suggest is reflective of a community of practice. As with other Urartian metalwork, the craftspeople responsible for the objects in the Van Museum displayed a high degree of control over a range of techniques and materials, including the use of low-Zn alloys.

CRediT authorship contribution statement

Braden W. Cordivari: Writing – original draft, Visualization, Formal analysis. **Oğuz Aras:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105417.

Data availability

Data will be made available on request.

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