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Archaeometallurgical investigation of a Late Bronze Age hoard from Mahrersdorf in Lower Austria

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ABSTRACT

Chemical and lead isotope analyses show that the 13 objects from the Mahrersdorf hoard (Ha B1; 11th century BCE) were primarily made from two distinct copper alloys that derived from fahlore. A third group, represented by one object, a median-winged axe, was made from recycled Ösenring copper and deposited ca. 150–200 years after its manufacture. At the time, the region was surrounded by several competing copper mines located in southeastern Lower Austria, the Slovak Ore Mountains, and the Kőszeg-Güns-Mountains; other than some deposits in the Slovak Ore Mountains, the ores in these mines lack chemical and lead isotopic characterizations, which precludes their direct use in provenancing. The Mahrersdorf hoard contains several axes belonging to two typological groups: end-winged and socketed axes made in the central and southeastern European traditions, respectively. Analyses show that the two groups coincide with the chemistry of each fahlore copper alloy. Metallographic analyses identified that the bronze objects represent four different stages in the production process: ingots, cast objects without edge hardening, finished objects with edge hardening, and one recycled object. Three socketed axes with T-decoration were deserving of special attention, since they were cast in the same mould.

1. Introduction

Copper production in the Eastern Alps reached its quantitative peak (in terms of copper amount) during the Middle Bronze Age (MBA) in the Mitterberg. The mines in this region produced metal that was dominant for more than half a millennium in many regions throughout Europe (Pernicka et al., 2016) until the Late Bronze Age (LBA). The Mitterberg mines seem to have gradually declined in importance as more deposits were discovered and exploited elsewhere, including minor chalcopyrite and fahlore deposits (Oeggl and Schaffer, 2013; Stöllner and Oeggl, 2015; Turck et al., 2019).

According to recent scholarship, copper ore mining reached its greatest geographical extent in the Eastern Alps during the LBA (Fig. 1). Multiple mines, dispersed from Grisons in Switzerland in the West to Trentino in Northern Italy in the South, including the mines in Tyrol and Salzburg to Upper Styria and southeastern Lower Austria in the East, contributed to copper production and were part of the same distribution networks (Stöllner, 2015). For archaeometallurgists, the extent of copper production during this time obfuscates the relationship between finished objects and specific metal sources, especially compared to previous periods in the Copper and Early and Middle Bronze Ages. Archaeometallurgists have thus seemingly opted to engage in fewer studies for this period with some notable exceptions (see Trampuž Orel, 1996). Another possibility is that some scholars may have assumed that most circulating copper was recycled from older scrap with little fresh metal being produced. Recent investigations of LBA copper ingots from southern Bavaria, for example, contradict this assumption, suggesting that copper production from primary sources was still active (Lutz, 2016; Lutz et al., 2019a; Lutz et al., 2019b). Furthermore, the continued circulation of different copper types during the Early Urnfield Period (Bz D to Ha A1) has been argued based on the analysis of casting cakes from Western Hungary (Czajlik, 1996; Czajlik and Sólymos, 2002; Czajlik, 2013), and those from a hoard dating to the Late Urnfield Period (Ha B2-3) in Schwechat-Rannersdorf (Lower Austria), which contain an average of 13.9 wt% antimony, 6.9 wt% arsenic, and other trace elements. The chemical composition of these cakes suggest the exploitation of the antimony-rich copper deposits of Stadtschlaining in Burgenland (Reiter and Linke, 2016, 163-165).

There are currently several research groups studying centres of LBA copper production dispersed throughout the Eastern Alps (e.g. Gruber et al., 2016; Koch Waldner, 2019; Silvestri et al., 2019; Staudt et al., 2019). Our research focuses on small-scale copper producers in

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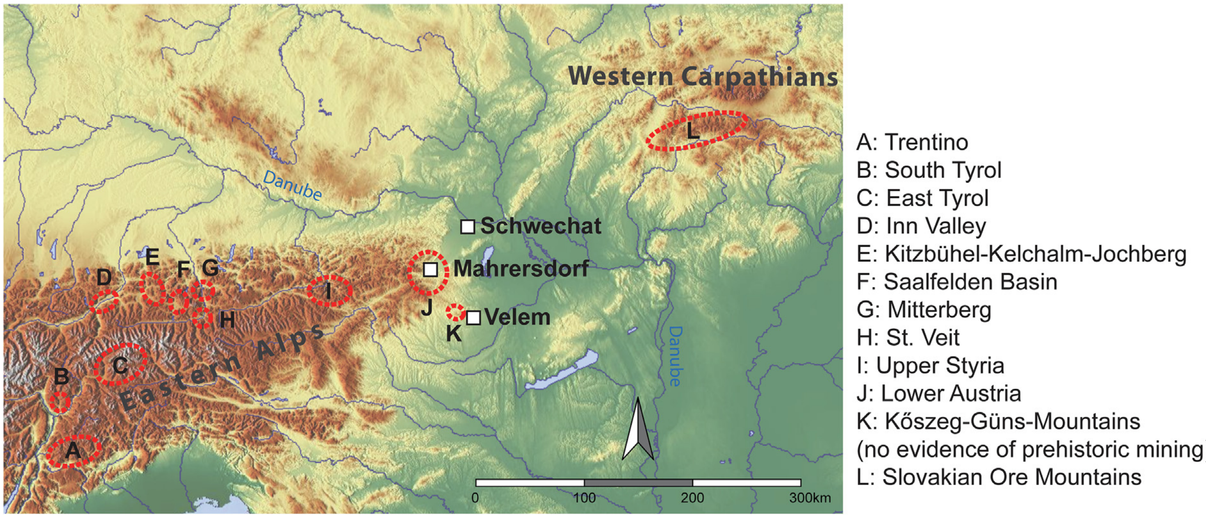

Fig. 1. Location of Velem, Mahrersdorf, Schwechat, and important LBA mining regions mentioned in this paper. Cartography: © OpenStreetMap contributors.

southeastern Lower Austria located at the easternmost geographical extent of prehistoric copper production in the Alps (Fig. 1, J). In this study, we examine the evidence for copper production in this region from excavation records, geophysical prospections, and core drilling samples from the LBA mine of Prigglitz-Gasteil (Trebsche, 2013; Trebsche and Pucher, 2013; Trebsche, 2015a,b; Haubner et al., 2019) as part of the Austrian Science Fund project "Life and Work at the Bronze Age mine of Prigglitz". We conducted archaeometallurgical analyses and studied contemporaneous find assemblages for the region to understand metal circulation and estimate the scale of copper production from the Prigglitz mine.

In this paper, we present new archaeometallurgical data from the Mahrersdorf hoard dating to the 11th century BCE, which is located only 7.5 km from the Prigglitz copper mine in the district of Neunkirchen in the state of Lower Austria (Fig. 1). Its ingots and other artifacts were selected for analysis because of their typological and progressional variety, which comprises two types of ingots, semi-finished bronze products, used bronze tools, and a unique socketed pickaxe that was probably used for mining. The artefacts in the hoard were metallographically and chemically analysed using Scanning electron microscopy with Energy-dispersive X-ray spectroscopy (SEM-EDXS) as well as X-ray fluorescence (XRF), and high-resolution multi-collector inductively coupled plasma-mass spectrometry (HR-MC-ICP-MS) for their lead (Pb) isotope ratios, in order to discern their relationship to the circulation and availability of copper from different sources in the surrounding regions.

We chose the Mahrersdorf hoard for our study because it contains three socketed axes that were cast in the same mould. Several LBA deposits also contain duplicate socketed axes (e.g. Wolfsthal in Lower Austria: Lauermann and Rammer, 2013, 139 Taf. 49/1–3, Taf. 50/2; Carpathian Basin: Born and Hansen, 2001, 146-147 Fig. 121; 219 Fig. 164–165). The repetition of these objects can likely reveal information about production methods and intended alloy compositions. Nine socketed axes from the Karmin hoards in Poland have also been attributed to four different casting moulds using 3D-documentation (Baron et al., 2019, 73-85; 88-90 Table 3; 5). Table 4

Most analyses of objects identified as being cast from the same mould have been aimed at reconstructing distribution networks of specific products; for instance, Christoph Jahn's systematic investigation of Bronze Age sickles (Jahn, 2013, 56-59 Fig. 2.17) and Katharina Schäppi's study of LBA knives (Schäppi, 2014, 106–107 Fig. 11). We, however, have focused on determining the technical skills of individual metalworkers through their ability to reproduce objects and the variety of alloys used for objects cast in the same mould.

2. Materials and methods

2.1. Background

The Mahrersdorf metal hoard was discovered in a small village in 1870 in what is today the city of Ternitz in the district of Neunkirchen, Lower Austria. It is one of the earliest undisturbed prehistoric hoards from Eastern Austria (Lauermann and Rammer, 2013, 27). The finds from the hoard were first published in detail by Moritz Hoernes in 1900, who interpreted the assemblage as relics from a casting workshop (Hoernes, 1900, 69-70 pl. II/Figs. 1–12; pl. III/Fig. 1). For illustrations of the finds, see Mayer (1977, pl. 125) and Lauermann and Rammer (2013, pl. 44–47). The finds are now kept in the Prehistoric Department of the Museum of Natural History in Vienna (inventory numbers 34.776–34.785). The deposition of the hoard is generally dated to HaB1 (Mayer 1977, 197; 205; Pare, 1998), or, more precisely, to SB IIC (HaB1a), between 1080 and 1020 BCE (Sperber 2017, 173).

2.2. The Late bronze Age hoard from Mahrersdorf

The Mahrersdorf hoard contains 13 copper or copper alloy objects with a total weight of ca. 12 kg (Fig. 2), including a planoconvex bun, a double-axe shaped ingot, a socketed pickaxe, a median-winged axe, three end-winged axes, four socketed axes, a socketed adze and a lancet-shaped chisel (Table 1). The planoconvex bun is among the heaviest ingot specimens of this type (Fig. 2/2) with wide distribution in the north-Alpine area and a chronological range from Bz D to Ha B, according to recent analyses of bun ingots from Tyrol, Salzburg and Southern Bavaria (Lutz et al., 2019b; Lutz et al., 2019a; Modl, 2019). The double-axe shaped ingot (Fig. 2/1) has mainly been found in the southeastern Alpine region (Slovenia), in Northern and Central Italy, and Sardinia, with most dating to the LBA (Ha B1). These ingots are often characterized by high Pb content (Sperber, 2000; Turk, 2003) compared to bun ingots. Both bun and double-axe shaped ingots have been found together in hoards from Northern Italy and Slovenia, with the Mahrersdorf hoard being the most north-eastern example (Mayer, 1977, 18-19; Borgna and Turk, 1998; Sperber, 2000; Turk, 2003). The socketed pickaxe (Fig. 2/3) was miscast with the two halves slightly out of alignment with one another, as can be seen in the cross-section of the edge. Mayer was the first to interpret it as a miner's tool because of its extraordinary length (33 cm) in comparison to similarly shaped and shorter socketed chisels (Mayer, 1977, 226). Regarding parallels in the Ural region, Peter Thomas proposed to label it a socketed pickaxe of the Mahrersdorf type (Thomas, 2018, 231 fig. 218). The winged axe

Fig. 2. The Mahrersdorf hoard (photo by Anton Kern, NHM Wien). The numbers correspond to the ones in Table 1.

(Fig. 2/7) was classified as a unique form without parallel (Mayer, 1977, 181), despite it being attributable to the median-winged axes (types "*Lappenbeil mit zur Schneide herabgezogenen Lappen*" or "*Lappenbeil mit abgesetztem, hohen Oberteil*", Mayer, 1977, 145-147; 148-149) from the late MBA or early Urnfield period. The neck of the median-winged axe was cut off, which is evidenced by a straight groove hammered into the upper end (cf. Hoernes, 1900, 70). After modification, this considerably older axe could then be mounted on a wooden knee-hafting similar to those produced for end-winged axes from the Late Urnfield period. Three of the end-winged axes belong to the Bad Goisern type (Fig. 2/5–6), with one being a smaller Bad Aussee variant (Fig. 2/8). They date to the younger Urnfield period (Ha B1; Mayer, 1977, 159-164). The socketed axe with V-shaped decoration (Fig. 2/10) also shows signs that it was miscast at the socket (Ha B1; Mayer, 1977, 192-198). The three socketed axes with strict T-shaped decoration in Fig. 2/11–13 date to the same period and deserve special consideration. They were cast in the same mould as evidenced by their similar weights and identically shaped loop and decoration composed of three horizontal and vertical ribs. These similarities, and the fact that they were not finished and partially retained the original casting seams, has also been observed by several scholars (Mayer, 1977, 193; Lauermann and Rammer, 2013, 130). A stone casting mould for the same type of axe, but with slightly different ornamentation compared to the Mahrersdorf axes, and several specimens of this type, were found at the site of Velem-Szentvid in Western Hungary (Miske, 1908, Pl. XIV/40; XV/5; XIX/12; Wanzek, 1989, 113 Pl. 50/1b), indicating that it was a production centre for socketed axes with several variants of T-decoration. The interpretation of Velem-Szentvid as a metallurgical production site is further supported by the presence of a considerable number of casting moulds for different types of socketed axes and other bronze objects. Socketed axes with T-decoration have also been found as far as Hallstatt in Upper Austria to the West and Slovakia and Romania in the East, suggesting the extent of Velem bronze product distribution (Wanzek, 1989, 113 Pl. 33 with supplements: Kleedorf – Mayer, 1977, Nr. 1066 Pl. 77/1066; Michelstetten – Lauermann and Rammer, 2013, 106 Pl. 28/3). The socketed adze (Fig. 2/9) was classified as a separate type by Mayer; however, it could also have been the end result of a re-worked socketed axe ("*Verziertes Tüllenbeil mit verbreiterter Schneide*"; Mayer, 1977, 200-205). Finally, the Mahrersdorf hoard contains a lancet-shaped chisel (Fig. 2/4) with a large handle.

2.3. Methods

All of the objects were sampled for chemical analysis. A select few were also analysed for their Pb isotopic ratios and metallographic structures (Table 1).

The chemical analyses were performed using a JEOL JSM-6460LV SEM with an Oxford Instruments SDD XMax 20 under high vacuum (IRAMAT-CRP2A, France) and an ARL Quant'X (Thermo Fisher Scientific) XRF at 28 kV (with Pd filter) and 50 kV (with Cu filter) at the CEZA laboratory in Mannheim, Germany. The SEM was calibrated using the internally provided software database standards library, as well as certified pure standards of Si and Co for quantification. The results shown are the mathematical average of 5–8 spectra of approximately 200 × 600 µm taken for 60 s each. In addition to the SEM-EDXS analyses, XRF measurements were carried out on drilling samples and the freshly polished surfaces of the metallographic samples (measured with Fischerscope). The drilling samples were measured with an ARL

Fig. 3. Copper and bronze finds from the Mahrersdorf hoard. The numbers refer to Table 1. Drilling samples were taken in discretely visible locations on the objects (for instance, inside of the socket of the socketed axes). Sampling locations for metallographic analyses are marked red. Drawings after Mayer, 1977, pl. 125.

Quant'X (Thermo Fisher Scientific) XRF at 28 kV (with Pd filter), and 50 kV (with Cu filter), and for the metallographic samples, a Fischerscope X-ray XAN 150 was used (parameters: W-Röhre, 50 kV, Al-filter, 1 mm Kollimator, SD-Detektor, 50 s measuring time/spot, 1–2 measurements/sample, depending on the sample size). Quantification and measurements closely followed the procedure described in Lutz and Pernicka (1996). The element concentrations were delineated as follows: alloying (wt% > 1), trace (< 0.1 wt%), and not detected (n.d.). Moreover, since sulfur (S) was only measured with EDXS, the indicated results should be considered qualitative. Element percentages are given

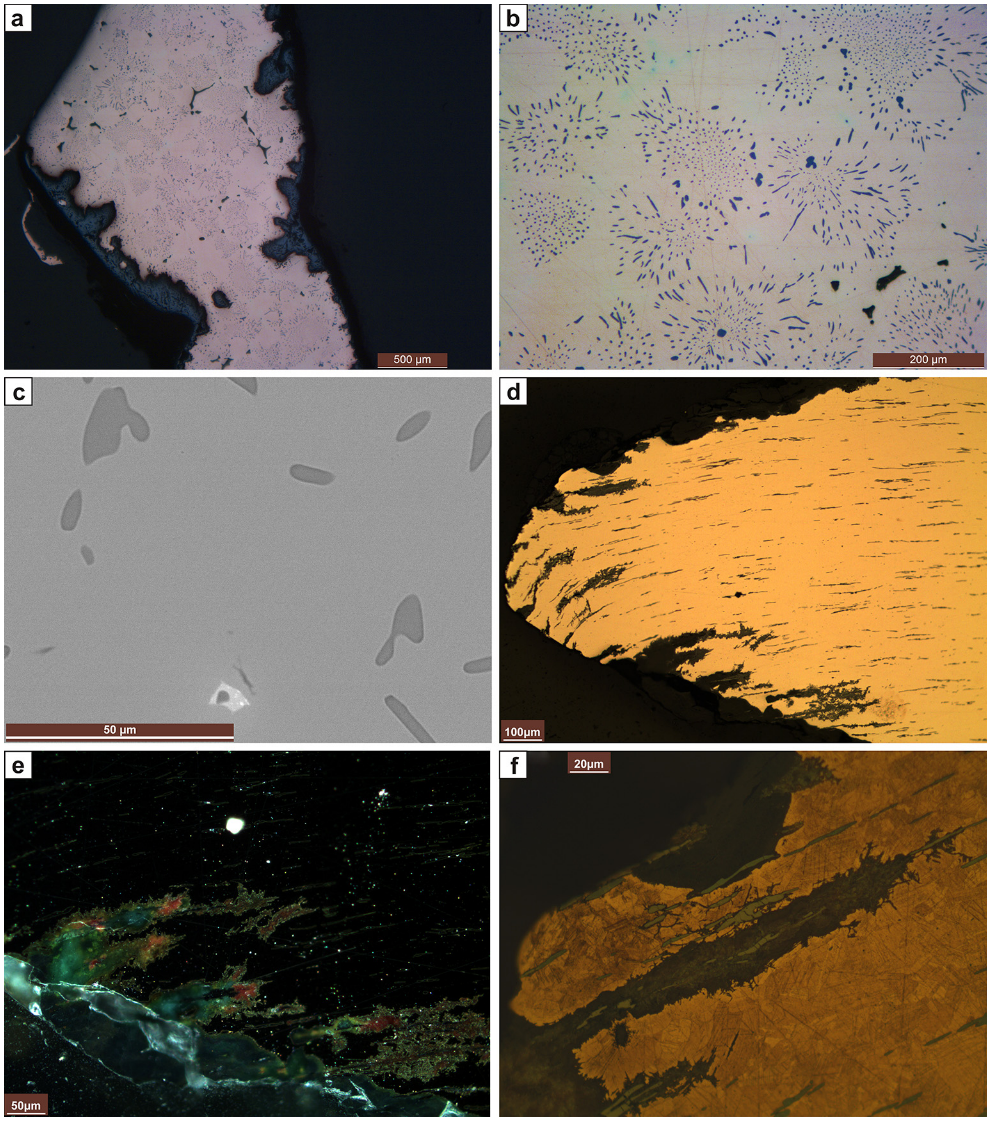

Fig. 4. Microstructures. Mahrersdorf, casting cake (inv. no. 34.785). Coring is visible, especially around the Cu-Sb-Bi inclusions in both unetched samples (a, b). c) SEM-image of the casting cake. Dark grey $Cu_{2-x}Fe_2S$-inclusions, light grey Cu-Sb-Bi inclusions (~35 wt% Sb, and 3 wt% Bi), and white inclusions (~28 wt% Sb and 30 wt% Bi) inside the Cu-Sb-Bi inclusions are visible. Lancet-shaped chisel images (34.783) in d) unetched, e) unetched and under polarized light, and f) etched with ferric chloride. The edge shows deformed grains of alpha solid solution and both twined and strain lines.

in wt%.

Lead isotope analyses were carried out on a Thermo Scientific Neptune Plus high-resolution multi-collector inductively coupled plasma-mass spectrometry (HR-MC-ICP-MS) at the CEZA laboratory, Mannheim, following the procedure described in Niederschlag et al. (2003). The samples were dissolved in nitric acid to separate the Pb from the matrix by ion chromatography. Then, for the measurements, an aliquot of the solution was separated and analysed via a Thermo Scientific iCAP 7200 Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES).

Microstructural characterisation of the samples, and chemical analyses with EDXS, were performed on cross-sections at the edge of the blades (axes, chisels) or the rim of the casting cake. Additional XRF and Pb isotope analyses were later carried out on the same, freshly polished samples and drillings taken with a 1 mm bit. Each sample for microstructural analysis was mounted in cold epoxy resin and polished using 400–1200 SiC papers followed by a diamond suspension paste of up to 0.25 µm granulometry. The samples were characterised using optical microscopy in both bright and dark fields, chemically analysed using EDXS, and then etched for metallographic examination using ferric chloride and Klemm II. The total amount of deformation applied in each sample was calculated by measuring the shape factor (SF) of the CuS- or $Cu_{2-x}Fe_2S$ inclusions (see Mödlinger and Piccardo, 2013). Vickers hardness measurements were also taken using a Leitz Durimet 72-1b instrument at 100 g load over 10 s. A FT-9929195 test block from Future-Tech-Corporation was used as a standard.

3. Results

3.1. Chemical and isotope measurements

The analysed composition of the objects is reported in Table 2. Tellurium (Te), Selenium (Se), and Manganese (Mn) were always detected at trace amounts (< 0.005 wt%) in each sample. Cadmium (Cd) was detected at concentrations of < 0.01 wt% in objects with Tin (Sn) in excess of 10 wt% (inv.no.s 34.776 and 34.783), and all other drilling samples showed < 0.01 wt% Cd. Cobalt (Co) was detected at ≤ 0.01 wt%, except in inv.no. 34.776 where it was 0.06 wt%. The Bismuth (Bi) content is related to the amount of Antimony (Sb) with Sb < 0.5 wt% and Bi < 0.005 wt% with rising Sb, and Bi up to

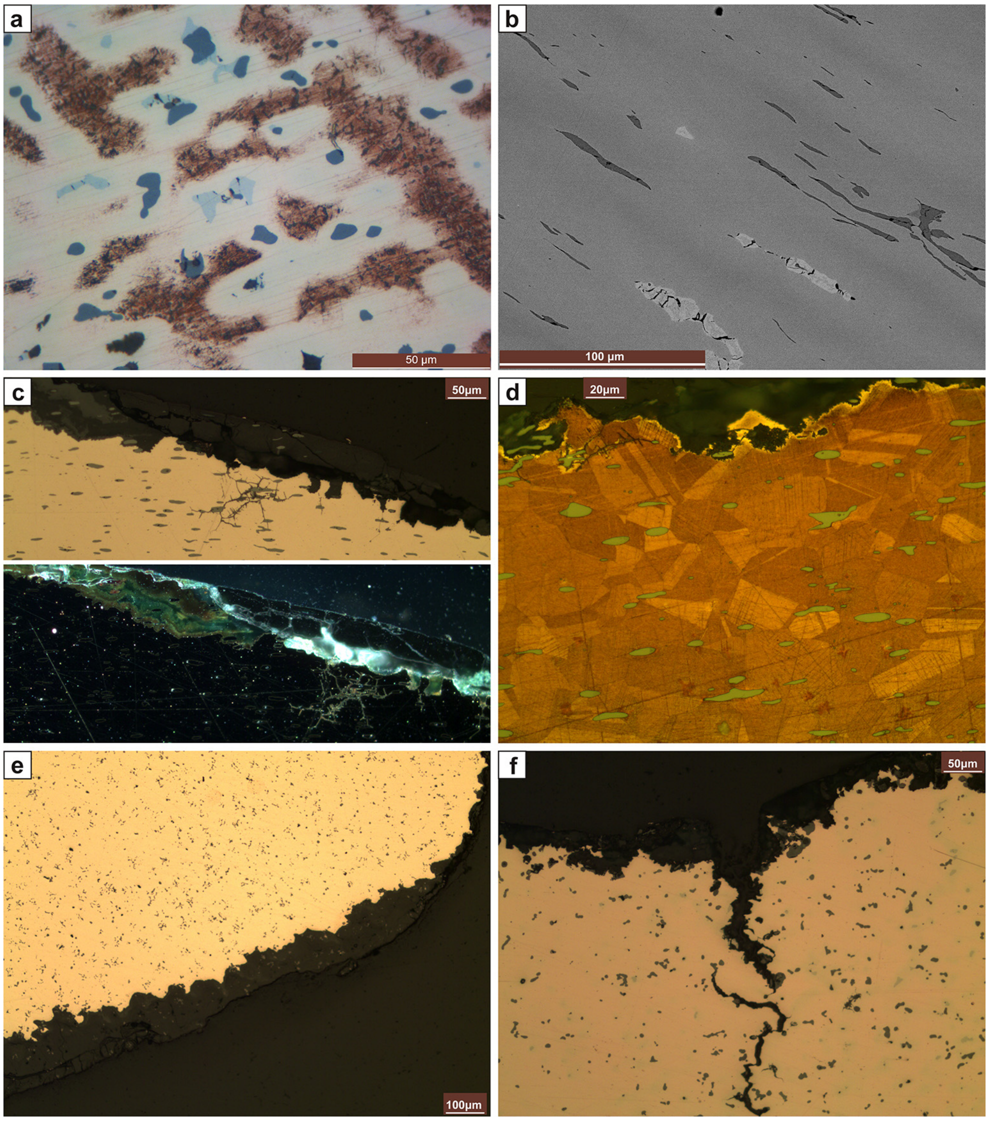

Fig. 5. Microstructures. Mahrersdorf, socketed pickaxe (inv. no. 34.782). a) Etched with ferric chloride. b) SEM-image. The dark grey inclusions consist of $Cu_{2-x}Fe_2S$, while the light grey inclusion contains about Cu-Sb-Sn inclusions with about 28 wt% Sb and 6 wt% Sn. The white inclusions inside the latter, light grey inclusions contain about 75 wt% Bi, 7 wt% Sb, 1.5 wt% Sn and 16 wt% Cu. Mahrersdorf, median-winged axe (inv. no. 34.776): c) Unetched, in polarized light. d) Etched with ferric chloride. The light-grey CuS-inclusions are only slightly deformed, the polyhedric grains with twins show almost no sign of final cold deformation. End-winged axe (inv. no. 34.777 A): e) Unetched. Mahrersdorf, socketed axe (inv. no. 34.779 A): f) Unetched. Note the crack along the grain boundaries due to material stress and the low deformation of the $Cu_{2-x}Fe_2S$-inclusions.

0.09 wt%. Zinc (Zn) was also detected at < 0.01 wt% in all objects, and all but three had ≤ 0.005 wt% Pb (34.776; 34.777 A, and 34.779 B). The slightly higher amounts of Pb do not seem to be correlated to any of the detected elements.

The casting cake contains the highest amount of Fe of all the objects at 1.2 wt%, followed by the socketed axe (34.779 A) at 0.5 wt%. The lancet-shaped chisel (34.783) has 0.7 wt%, and the median-winged axe (34.776) 0.05 wt%. The latter is also the only sample with CuS-inclusions and no $Cu_{2-x}Fe_2S$.

Antimony is present in all samples as a minor element except the median-winged axe (34.776). Of note are its high concentration in four objects in greater percentages than Sn (socketed axes 34.779A-C and 34.780). As for Sn, the casting cake (34.785) does not contain any significant amount; however, several of the socketed axes, pickaxe and the double-axe shaped ingot (34.779 A-C, 34.780, 34.782, and 34.784) contain low percentages at usually < 2.7 wt% with significant amounts of Sb. In particular, two socketed axes (34.779 B and C) contain about 0.5 wt% Sn, 1–1.2 wt% As, and 2.9 wt% and 3.4 wt% Sb, respectively. Socketed axe 34.779 A, which was cast in the same mould as the other two, instead contains about 1.1 wt% Sn and only 0.4 wt% As. The other objects contain about 7–11 wt% Sn, which is a percentage range where the alloy is worked.

The results of the lead isotope analyses are given in Table 3.

3.2. Metallography

The casting cake (34.785) consists of nearly pure copper with only 1.5 wt% S, 1.2 wt% Fe and small amounts of Sb (0.2 wt%). Other elements, such as As, Bi, Ag, and Ni, are present at trace amounts. The copper matrix is homogenous without any coring or dendrites, but does have inclusions. Sulfur and Fe are mainly present in $Cu_{2-x}Fe_2S$-inclusions, which are distributed in a firework-like pattern in the matrix. Other inclusions consist of ca. 28–35 wt% Sb and 3–27 wt% Bi with some Ag. Overall, the sample does not show much porosity and has an average hardness of 90 HV (86–97 HV). Corrosion on the surface of the ingot mainly consists of cuprite oxides and an outer layer of carbonates (mainly azurite and malachite).

The lancet-shaped chisel (34.783) was sampled along the edge and shown to contain 10.7 wt% Sn, 0.5 wt% Sb, 0.7 wt% S, and ~ 0.7 wt% Fe. Sulfur and Fe are mainly present in $Cu_{2-x}Fe_2S$-inclusions, and Ni, As, Ag, and Pb are in trace amounts. The unetched sample, with its long deformed $Cu_{2-x}Fe_2S$-inclusions, indicates a total amount of deformation of close to 90%. Etching the sample with ferric chloride revealed severely deformed equiaxed grains of twinned α-solid solution as well as strain lines, indicating several cycles of annealing and heavy deformation. The chisel was cold deformed as a final working step. Examination of the corrosion shows that it follows both the original dendritic structure, indicating that the sample is not entirely

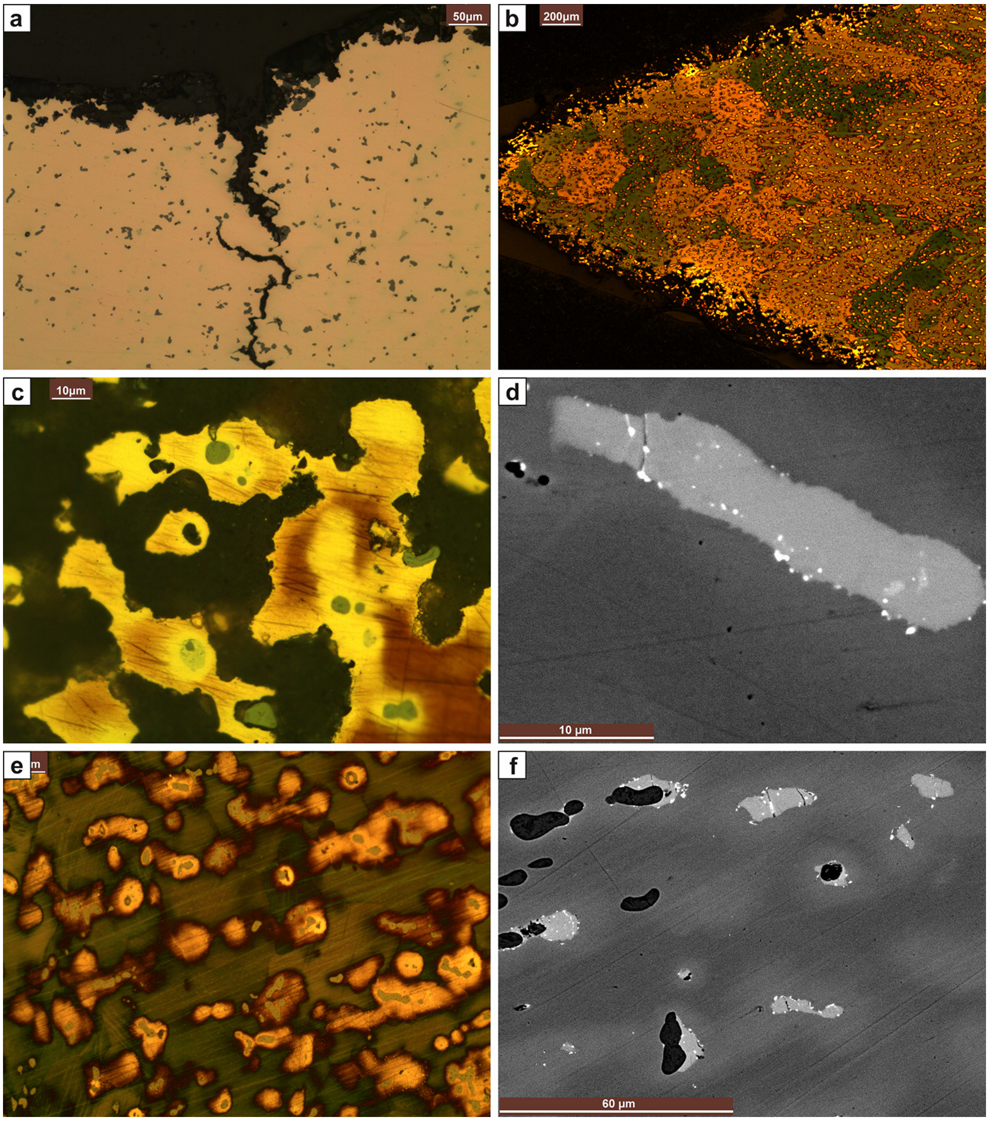

Fig. 6. Microstructures. Mahrersdorf, socketed axe (inv. no. 34.779B): a) Etched with Klemm II. The original casting structure and size of the dendrites are visible. b) Etched with Klemm II. Note the δ-phase of the Cu-Sb system; they also contain significant amounts of Bi. c) SEM-image of δ-phase of the Cu-Sb system. The white dots visible in the inclusion contain apart copper also about 9 wt% Sb and 12 wt% Bi. Mahrersdorf, socketed axe (inv. no. 34.780): d) Etched with Klemm II. The $Cu_{2-x}Fe_2S$-inclusions are dark grey, while the δ-phase of the Cu-Sb system is visible in light grey. Mahrersdorf, socketed adze (inv. no. 34.781): e) Etched with Klemm II. Note the dendritic structure and the recrystallised alpha solid solution visible in the blue etched area. f) Etched with Klemm II. The $Cu_{2-x}Fe_2S$-inclusions show almost no deformation at all, while the surrounding recrystallised grains show both twins and strain lines, indicating a final cold deformation.

homogenised, and the grain boundaries of the α-solid solution equiaxed grains. Under polarized light, the colours in show both copper oxides (cuprite) and carbonates (mainly azurite and malachite). The high hardness values of 176–206 HV throughout the sample correspond with both the extreme final deformation of the sample and relatively high concentration of Sn at ca. 12 wt%.

The socketed pickaxe (34.782) edge was cast with an Sb-Sn-Cu alloy containing ~ 2 wt% Sn, 2.8 Sb, 1 S, and 0.2 Fe and As. Nickel, Ag, and Pb are also present in trace amounts. The unetched sample shows non-deformed $Cu_{2-x}Fe_2S$-inclusions and light grey Cu-Sn-Sb inclusions, which contain about 1 wt% Ag. In these inclusions, smaller white Bi inclusions are common containing ~ 0.03 wt% Bi according to XRF analysis. The latter consist of about 75 wt% Bi, 7 Sb, 1.5 Sn and 16 Cu (Fig. 5, a-b). In most cases, the Cu-Sb-Sn inclusions show cracks, even though no deformation is noted even after the sample was etched. Etching the sample with ferric chloride revealed an as-cast dendritic structure with macrosegregation ranging from 6 wt% Sn and 7 Sb to ~ 1 wt% Sn and Sb each. The corrosion follows the dendritic structure and consists mainly of copper carbonates (azurite and malachite) indicated by a green-turquoise colour under polarised light, as well as copper oxides (mainly cuprite) in orange-red colour. Other elements present in the corrosion, such as Si, Ca, and Ir, most likely derive from the soil. Hardness measurement values are 160–181 in the copper-rich areas and 193–206 HV in the tin-rich areas.

The median-winged axe (34.776) was sampled on the edge and is a tin-bronze containing 11 wt% Sn, 0.9 S, 0.6 Ni, and 0.2 As. Iron, Ag, Sb, and Pb are present in trace amounts. It is the only axe from the Mahrersdorf hoard and, too typologically, the oldest, that contains significant amounts of Ni. The unetched sample shows ca. 10–20% deformed light-grey CuS-inclusions that contain ~ 0.3–0.4 wt% Ni and 4.5–7.5 Sn. After etching with ferric chloride and Klemm II, slight coring was revealed, indicating incomplete homogenisation and large polyhedric twinned grains. A few grains along the edge showed strain lines, but without much deformation of the grains themselves or more intense deformation of the CuS-inclusions, indicating that it was only light deformed (Fig. 5, c-d). Corrosion was found to be both inter- and intra-crystalline. Copper oxide crystals (cuprite; dark red in polarised light) and alternating copper oxides and carbonate layers cover the surface of the sample. Hardness measurements for the sample are ~ 162–193 HV with a harder edge than in the core.

The end-winged axe of Type Bad Goisern (34.777 A) was sampled on the edge and contains 7.3 wt% Sn, 1 Sb, 0.8 S, 0.3 Fe, and 0.1 As. Sulfur and Fe are mainly present in $Cu_{2-x}Fe_2S$-inclusions, and Ni, Ag, and Pb are present in trace amounts. The unetched sample shows no deformation and globular $Cu_{2-x}Fe_2S$-inclusions, indicating a total deformation < 10. Etching the sample with ferric chloride revealed heavy coring with underlying slightly deformed polyhedric twinned crystals with strain lines, suggesting a low-level final deformation took

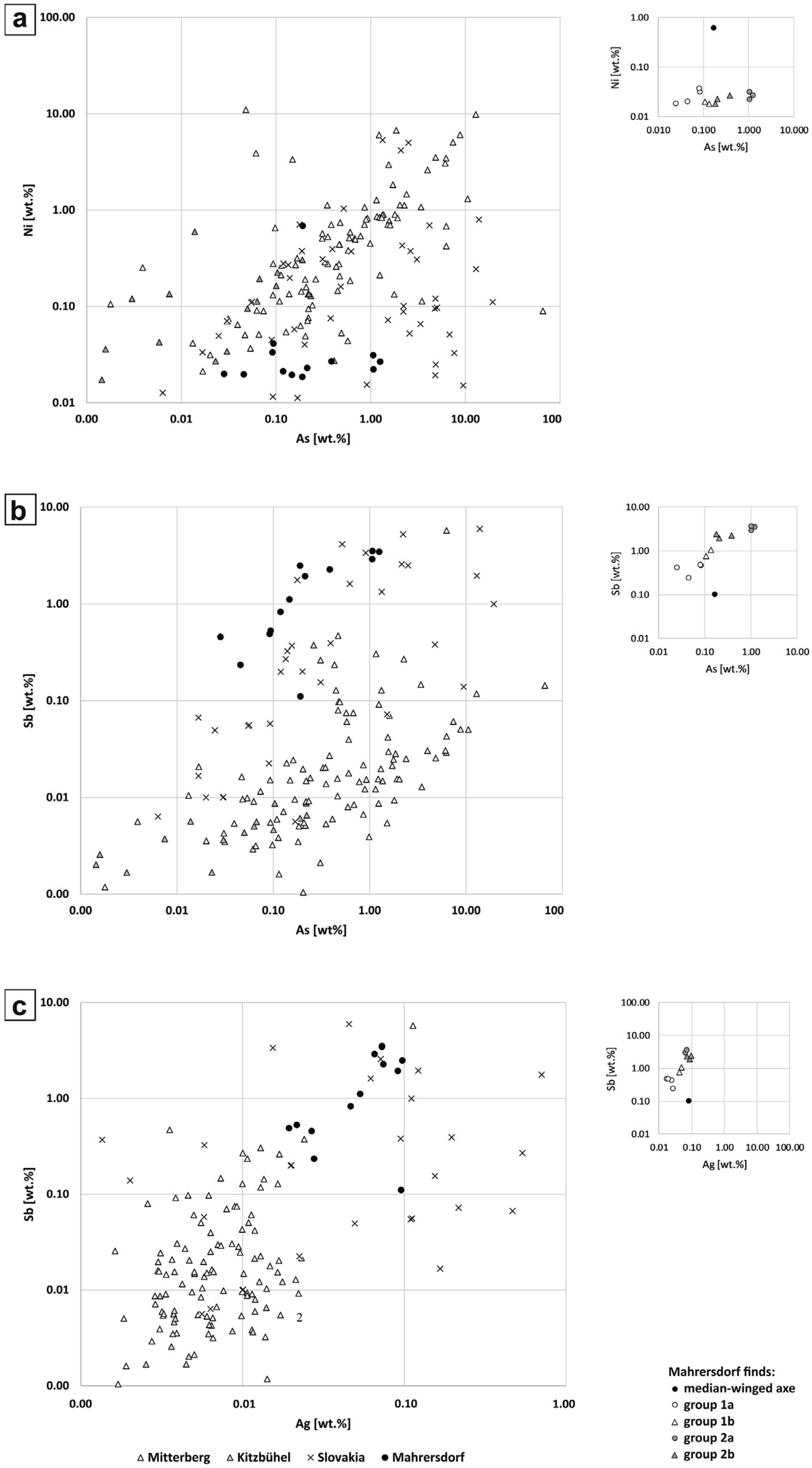

Fig. 7. Logarithmic plots of trace elements: As-Ni, As-Sb, and Ag-Sb. Ore values are normalized to copper and based on regional, interdisciplinary investigations of the specific mining regions (Pernicka et al., 2016; Modarressi-Tehrani et al., 2016; Schreiner, 2007). In the small graphs, the details of the Mahrersdorf finds: the median-winged axe (34.776), visible in the graphs as black point, clearly stands out. Finds from Group 1 (white; Group 1a: circles, Group 1b triangles) and Group 2 (grey; Group 2a: circles, Group 2b triangles) are easily distinguishable from each other. For the definition of the groups, see section 4.1.

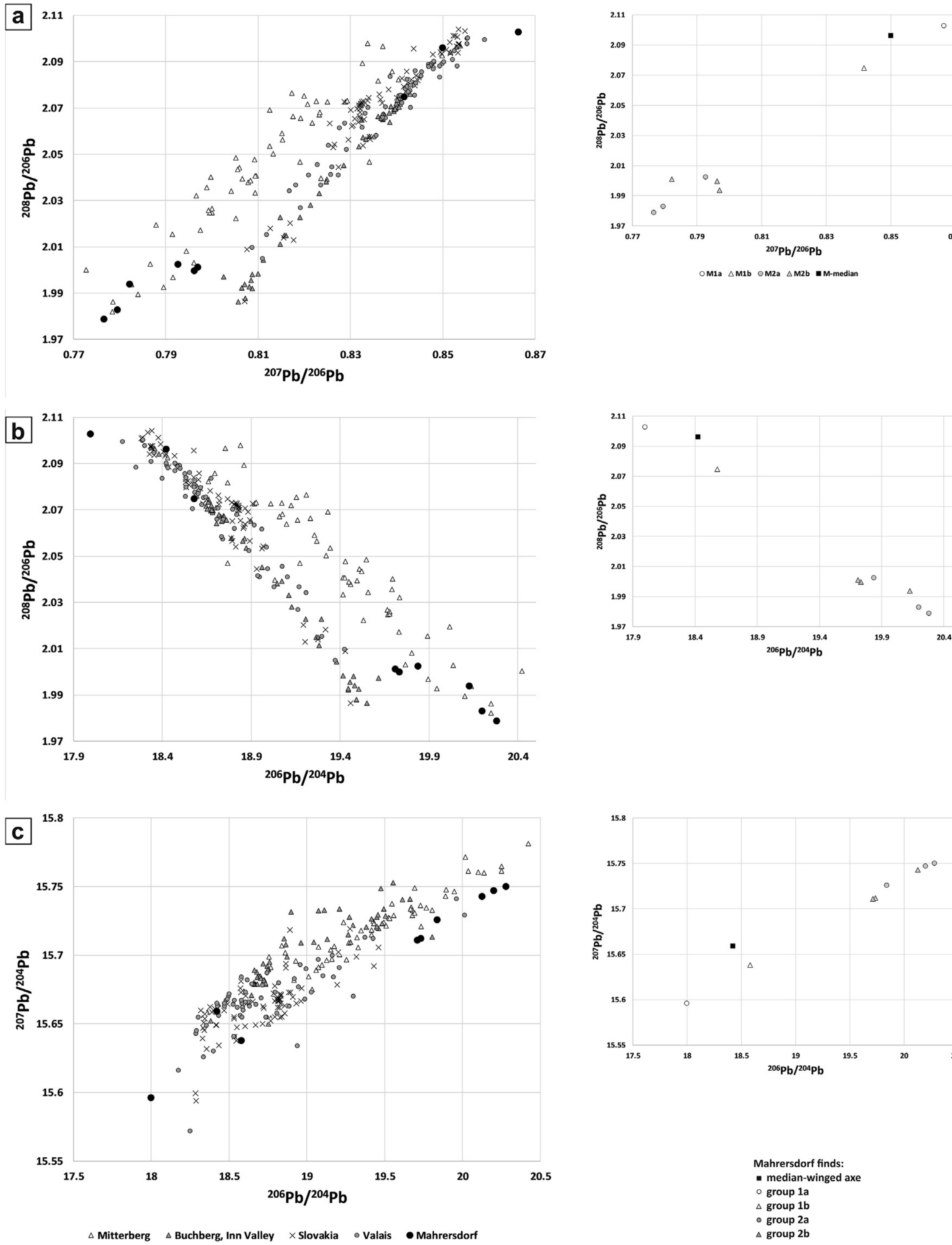

Fig. 8. Lead isotope ratios of the Mahrersdorf artifacts compared to possible ore sources. The analytical uncertainties are comparable with the size of the symbols. The ore data are from: Cattin et al., 2011; Höppner et al., 2005; Modarressi-Tehrani et al., 2016; Pernicka et al., 2016; Schreiner, 2007; and Schubert, 2005.

place after short annealing (Fig. 5, e). In polarised light, no copper oxides are visible, but a thick layer of copper carbonates covers the surface of the sample. Hardness measurements are ~ 160–199 HV with no significant difference between the extreme edge of the axe and the core of the sample.

A sample was taken from the centre edge of socketed axe 34.779 A and contained 2.2 wt% Sb, 1.1 Sn, 0.4 As, 0.7 S, and 0.5 Fe. Sulfur and Fe are mainly present in the $Cu_{2-x}Fe_2S$-inclusions, and Ni, Ag, and Pb are present in trace amounts. The inhomogeneous α-solid solution contains inclusions of $Cu_{2-x}Fe_2S$ (dark grey) and relatively brittle δ-phase from the Cu-Sb system (light grey). These inclusions are found in the more Sb-rich zones of the alloy and contain about 31 wt% Sb, 2 Sn, and 1 As. The sample shows cracking, which was likely caused by tension during deformation, indicating insufficient or late annealing. Etching the sample's surface with ferric chloride and Klemm II revealed a slightly deformed dendritic casting structure. There was no indication of annealing (Fig. 5, f). The corrosion products were mainly copper oxides and carbonates that follow the dendritic structure into the core

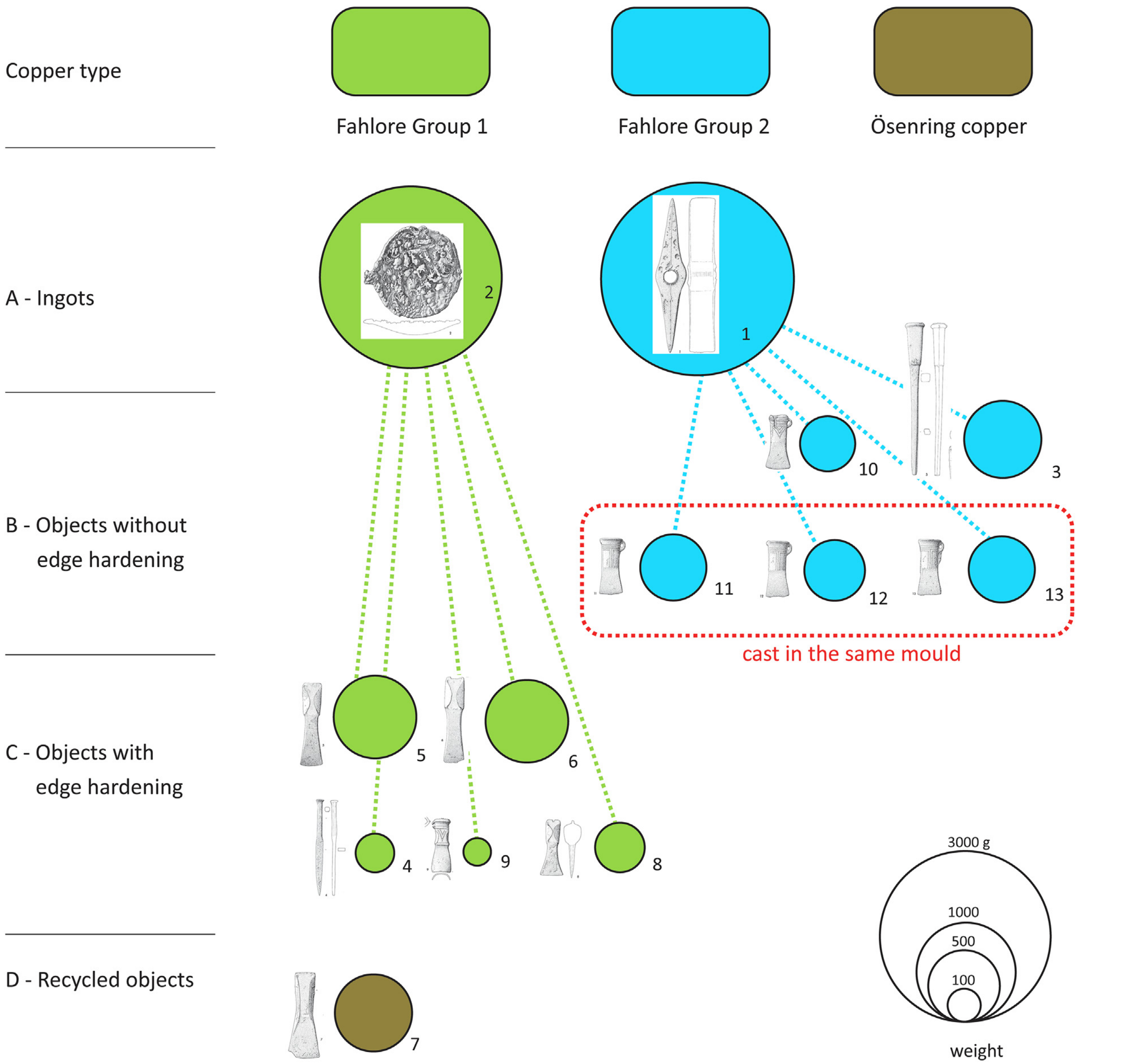

Fig. 9. The production stages and copper grouping present in the Mahrersdorf hoard.

Table 1
Overview of the archaeometallurgical samples from the Mahrersdorf hoard. All objects are stored in the Natural History Museum Vienna (NHM). Their old inventory numbers are in brackets. Samples chosen for metallographic study were taking on the edge or rim (for casting cakes) of the objects (see Fig. 3).

No.	object	type	inv. no.	chem.	metallogr.	Pb isotope	Chronology	Reference (Mayer 1977)
1	double-axe shaped ingot	–	34.784	x		x	Ha B1	no. 35, pl. 125/1
2	casting cake	–	34.785	x	x	x	Bz D – Ha B	pl. 125/2
3	socketed pickaxe	type Mahrersdorf	34.782 (2128)	x	x	x	Ha B1	no. 1341, pl. 125/3
4	lancet-shaped chisel		34.783	x	x		Bz D – Ha B	no. 1263, pl. 125/4
5	end-winged axe	type Bad Goisern	34.777 B (2120)	x			Ha B1	no. 725, pl. 125/5
6	end-winged axe	type Bad Goisern	34.777 A (2118)	x	x	x	Ha B1	no. 724, pl. 125/6
7	median-winged axe	(special form)	34.776	x	x	x	Bz C – D	no. 918, pl. 125/7
8	end-winged axe	variant Bad Aussee	34.778	x			Ha B1	no. 759, pl. 125/8
9	socketed adze	with broad edge	34.781	x	x		Ha B1	no. 1076, pl. 125/9
10	socketed axe	with V-decoration	34.780	x	x	x	Ha B1	no. 1070, pl. 125/10
11	socketed axe	with T-decoration	34.779 C	x		x	Ha B1	no. 1067, pl. 125/11
12	socketed axe	with T-decoration	34.779 A	x	x	x	Ha B1	no. 1069, pl. 125/12
13	socketed axe	with T-decoration	34.779 B	x	x	x	Ha B1	no. 1068, pl. 125/13

Table 2
The elemental composition of the objects in the Mahrersdorf hoard are given in wt%. Manganese, Se, and Te were detected in all objects at < 0.005 wt%, and Zn at < 0.1.

No.	object	inv.no.	Cu	Fe	Co	Ni	As	Ag	Cd	Sn	Sb	Pb	Bi
1	double-axe shaped ingot	34.784	94	0.28	< 0.01	0.02	0.184	0.094	< 0.005	2.76	**2.41**	< 0.005	0.025
2	casting cake	34.785	98	1.21	< 0.01	0.02	0.045	0.027	< 0.002	0.007	0.232	< 0.005	< 0.005
3	socketed pickaxe	34.782	96	0.19	< 0.01	0.02	0.209	0.089	< 0.005	1.95	**1.90**	< 0.005	0.029
4	lancet-shaped chisel	34.783	88	0.67	< 0.01	0.04	0.083	0.019	< 0.01	**10.7**	0.47	< 0.005	< 0.005
5	end-winged axe	34.777 B	91	0.12	< 0.01	0.02	0.109	0.043	< 0.005	**8.0**	0.76	< 0.005	0.011
6	end-winged axe	34.777 A	91	0.33	< 0.01	0.02	0.136	0.049	< 0.005	**7.3**	**1.03**	0.011	0.018
7	median-winged axe	34.776	88	< 0.05	0.06	0.61	0.170	0.085	< 0.01	**10.9**	0.099	0.025	< 0.005
8	end-winged axe	34.778	90	0.21	< 0.01	0.02	0.026	0.024	< 0.005	**9.4**	0.41	< 0.005	< 0.005
9	socketed adze	34.781	92	0.24	< 0.01	0.03	0.085	0.018	< 0.005	**6.9**	0.46	< 0.005	< 0.005
10	socketed axe	34.780	94	0.09	< 0.01	0.02	**1.06**	0.072	< 0.005	0.98	**3.5**	0.005	0.082
11	socketed axe	34.779 C	94	0.10	< 0.01	0.03	**1.25**	0.072	< 0.005	0.57	**3.4**	0.005	0.093
12	socketed axe	34.779 A	96	0.46	0.01	0.03	0.38	0.073	< 0.005	1.12	**2.24**	< 0.005	0.031
13	socketed axe	34.779 B	95	0.11	< 0.01	0.03	**1.05**	0.065	< 0.005	0.47	**2.9**	0.006	0.071

of the sample that usually avoid the $Cu_{2-x}Fe_2S$-inclusions. Hardness measurements show a slightly harder edge of 139–156 HV compared to the core of the sample at 92–105 HV.

Socketed axe (34.779 B) was sampled on its edge and contained 2.9 wt% Sb, 1 As, 0.5 Sn, 0.6 S, and 0.1 Fe. Iron is present as $Cu_{2-x}Fe_2S$ inclusions, and Ni, Ag, and Pb in trace amounts. The unetched sample shows a slightly deformed dendritic structure with relatively low Fe globular dark grey $Cu_{2-x}Fe_2S$ and slightly pointy light grey δ-phase (Cu-Sb system) inclusions. Both types are in the more Sb-rich zones of the alloy. The latter contain ~ 31 wt% Sb, 2.4 As, < 1 Ag, and some traces of Fe. The white dots inside the δ-phase inclusions contain, apart from Cu, mostly Bi (~12 wt%), Sb (~9), and As (~2.3). The globular shape of the $Cu_{2-x}Fe_2S$ inclusions indicates total deformation of < 10%. Etching the sample with Klemm II revealed large grains with curved boundaries, indicating light annealing and some deformation. Corrosion products, mainly copper oxides and carbonates, follow the dendritic structure into the core of the sample while mostly avoiding the $Cu_{2-x}Fe_2S$ inclusions. The hardness measurements for the sample ranged from 110 to 143 HV with lower values on the very edge (110–122 HV) compared to the core (135–143 HV).

Socketed axe 34.780 was sampled on its edge and found to contain 3.5 wt% Sb, 1 As, 1 Sn, 0.8 S, and almost 0.1 Fe. Iron is present in $Cu_{2-x}Fe_2S$-inclusions with Ni, Ag, and Pb in trace amounts. The unetched sample shows a slight deformation dendritic structure with globular dark-grey $Cu_{2-x}Fe_2S$ inclusions. Pointy light-grey inclusions in the more Sb-rich zones of the alloy contain ~ 31–32 wt% Sb and 2 Sn and As each. The inclusions are relatively brittle δ-phase from the Cu-Sb system. Smaller white dots at the edge of these inclusions most likely consist of Cu, Sb, and some Bi; XRF analysis showed ~ 0.08 wt% of Bi in the alloy. After etching the sample with Klemm II, ca. 60 × 60 µm large grains with curved boundaries and twinning were revealed, indicating light annealing and some deformation in the sampled area. Corrosion in the sample follows along the dendritic structure and consists mainly of copper carbonates (azurite and malachite) and oxides (mainly cuprite). There were few small reddish copper oxide, or Sb or As oxides, usually present at trioxides, inclusions in the matrix. Hardness measurement values of 128–160 HV showed no significant difference between the very edge of the axe and the core of the sample.

Socketed adze 34.781 was sampled on its edge and found to contain 7 wt% Sn, 0.5 Sb, and 0.8 S, and 0.2 Fe. Sulfur and Fe are mainly present in $Cu_{2-x}Fe_2S$ inclusions with Ni, As, Ag, and Pb in trace amounts. The unetched sample shows a slightly deformed dendritic structure with globular dark grey inclusions of $Cu_{2-x}Fe_2S$. The inclusions are in the more Sn-rich zones of the alloy. Their globularity indicates that the total deformation of the metal in the sampled area was less 10%. Etching the sample with ferric chloride and Klemm II revealed dominant coring, indicating that the alloy was not homogenised. Equiaxed grains of α-solid solution show twinning and strain lines. The grains themselves, and the twins themselves, are only slightly deformed on the edge. The corrosion consists of a surface layer of predominantly copper carbonates and some small copper oxide inclusions (cuprite) in the metallic matrix. As noted in the other object samples, $Cu_{2-x}Fe_2S$ inclusions are corrosion resistant. Hardness measurements show rather high values on the edge (143–206 HV) and in the core of the sample (160–181 HV).

4. Discussion

4.1. Chemical composition

The chemical composition of the median-winged axe (34.776) corresponds to typical Ösenring-copper with As, Sb, Ag, Ni, no Bi (see Krause 2003, Cluster 10), and relatively low amounts of Fe compared to the other objects in the hoard. It also contains 10.9 wt% Sn; the highest percentage of Sn measured in the hoard. Generally, the As content correlates to Ag with As > Ag for every find analysed. Low amounts of As correlate with lower amounts of Ag. The median-winged axe 34.776 shows notably less Sb than any other of the finds. Notable are the high amounts of As in the three socketed axes (inv.no.s 34.779 B-C, and 34.780). The As content corresponds to the Sb composition with over

Table 3
Lead isotope ratios of the Mahrersdorf artifacts.

No.	Object	inv.no.	$^{208}Pb/^{206}Pb$	2σ	$^{207}Pb/^{206}Pb$	2σ	$^{206}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ
1	double-axe shaped ingot	34.784	2.001	0.0001	0.79704	0.00003	19.711	0.003	39.442	0.019	15.711	0.002
2	casting cake	34.785	2.1026	0.0001	0.86652	0.00002	17.998	0.003	37.843	0.015	15.596	0.003
3	socketed pickaxe	34.782	1.9997	0.0001	0.79621	0.00001	19.733	0.003	39.46	0.017	15.712	0.002
6	end-winged axe	34.777 A	2.0747	0.0001	0.84174	0.00001	18.579	0.001	38.545	0.001	15.638	0.001
7	median-winged axe	34.776	2.096	0.0001	0.85	0.00001	18.423	0.003	38.613	0.013	15.659	0.003
10	socketed axe	34.780	1.9787	0.0001	0.77667	0.00001	20.28	0.001	40.126	0.005	15.75	0.001
11	socketed axe	34.779 C	1.9828	0.0001	0.77955	0.00003	20.199	0.001	40.051	0.008	15.747	0.001
12	socketed axe	34.779 A	1.9937	0.0001	0.78219	0.00002	20.127	0.003	40.127	0.008	15.743	0.001
13	socketed axe	34.779 B	2.0024	0.0001	0.79269	0.00003	19.839	0.001	39.725	0.007	15.726	0.001

Table 4
Overview on selected metallographic features of the Mahrersdorf artifacts.

No.	object	inv. no.	CuS/$Cu_{2-x}Fe_2S$	CuSb δ	def. in %	strain lines	twins	coring	comments	max. HV
2	casting cake	34.785	$Cu_{2-x}Fe_2S$	–	0	–	–	–		97
3	socketed pickaxe	34.782	$Cu_{2-x}Fe_2S$	–	0	–	–	–	as-cast with Cu-Sn-Sb inclusions	206
4	lancet-shaped chisel	34.783	$Cu_{2-x}Fe_2S$	–	c. 90	x	x	x		206
6	end-winged axe	34.777 A	$Cu_{2-x}Fe_2S$	–	< 10	x	x	x		199
7	median-winged axe	34.776	CuS	–	10–20	x	x	x		193
9	socketed adze	34.781	$Cu_{2-x}Fe_2S$	–	< 10	x	x	x		206
10	socketed axe	34.780	$Cu_{2-x}Fe_2S$	x	< 10	–	x	x		143
12	socketed axe	34.799 A	$Cu_{2-x}Fe_2S$	x	< 10	–	–	–	no annealing	160
13	socketed axe	34.799 B	$Cu_{2-x}Fe_2S$	x	< 10	–	–	–	light annealing; beginning formation of grains from dendrites	156

3 wt% for every axe, and relatively low amounts of Sn (0.5–1 wt%).

The composition of the other twelve objects generally aligns with Trampuz Orel's Cluster 6 (Trampuž Orel, 1996, 204-209 Tab. 16), the dominant cluster among Slovenian Ha B bronze finds, and Krause's Cluster 12 with high amounts of As and Sb, but no Ag, Ni, or Bi, which is a composition that has been associated with Eastern Alpine copper (Krause, 2003, Figs. 40–41; 90–91). The objects associated with Cluster 12 can be further divided into two distinct groups. Group 1 is comprised of the casting cake, the three end-winged axes, the socketed adze, and the chisel. This group is characterised by higher amounts of Fe (≥0.12 wt%), significantly lower amounts of As (< 0.15), Sb (≤1), Bi (< 0.02), and Ag (< 0.05). The two end-winged axes, 34.777 A and B, can be placed into a separate sub-group (1a), as their As, Sb, and Bi values are slightly higher in comparison to the other objects of Group 1. All of the objects in Group 1, apart from the casting cake, were alloyed with 7–11 wt% Sn.

Group 2 is comprised of the socketed axes (34.779 A-C and 34.780), the socketed chisel (34.782), and the double-axe shaped ingot (34.784). Iron characterises the chemical composition of the objects in Group 2 (< 0.12 wt%, with the exception of socketed axe 34.779 A), As (≥0.18), Sb (≥1.9), Bi (≥0.025), and Ag (> 0.06). Noteworthy in this Group is the relatively low amount of Sn (< 1 wt%). Group 2 can be further subdivided into groups 2a and 2b with ∼ 3.5 wt% Sb and > 1 As (socketed axes 34.779B-C, and 34.780) and 1.1–2.8 wt% Sn (socketed chisel (34.782), the double-axe shaped ingot (34.784), and socketed axe 34.779 A), respectively. Interestingly, the amount of Sb (1.9–2.4 wt%) is slightly lower, and their As significantly so (0.2–0.4 wt %).

The chemical composition, in particular the amounts of As and Sb, indicates that all thirteen objects from the Mahrersdorf hoard were made from fahlore (see also Fig. 7). Comparing the As-Ni, Sb-Ni, Ag-Ni, As-Sb, and Ag-Sb logarithmic diagrams of the Mahrersdorf hoard objects with the eastern Alpine sources, it is evident that only the median-winged axe matches the concentrations of Ag and Sb in LBA (Ha A-B) seen in contemporary bronze objects from Tyrol, Salzburg, and southern Bavaria (see Pernicka et al., 2016, Figs. 8 and 14). However, the Ag-Sb logarithmic diagrams of the eastern Alpine and Slovakian (see Wrobel Nørgaard et al., 2019, Fig. 11) also matches the median-winged axe, indicating a more likely association with Slovakian ores (Fig. 7c).

To the contrary, all of the other finds show more Sb and Ag – except those in Group 1a – and less Ni than is characteristic of the Mitterberg ores. The Sb and Ag amounts are also higher than those of LBA (Ha A-B) black copper/fahlore copper and contemporary bronze objects from Tyrol, Salzburg, and southern Bavaria (Pernicka et al., 2016, Fig. 14). Comparing the data to the Ag-Sb logarithmic diagrams that include eastern Alpine and Slovakian ore sources, it is clear that the objects from Groups 1b and 2 match the Slovakian ores. Only the objects in Group 1a can be associated with both Mitterberg and Slovakian ores. The Ni-Ag and As-Sb logarithmic diagrams (Fig. 7) indicate an association with Slovakian ores for all of the Mahrersdorf finds.

4.2. Metallography

All of the tin bronze axes and chisels show coring, indicating that the duration and annealing temperature was not sufficient to homogenise the alloy. However, because of this deficiency, all of these objects show equiaxed grains of α-solid solution with twinning and strain lines; the latter indicates that cold deformation was the final working step. Copper sulfide (CuS) inclusions were found in the median-winged axe 34.776, with all other tin bronze axes containing $Cu_{2-x}Fe_2S$.

The microstructures of the Cu-Sb-Sn axes and chisel in the samples differ significantly. The edge of the socketed pickaxe (34.782) shows a dendritic as-cast microstructure. Similarly, on axe 34.799 A, no annealing and only a slight amount of total deformation was applied. Axe 34.799 B shows large grains with curved boundaries, indicating light annealing and some deformation. Axe 34.780 shows large grains with curved boundaries and twins, indicating light annealing and some deformation. All Cu-Sb-Sn axes and chisel also contain $Cu_{2-x}Fe_2S$ inclusions and brittle δ-phase, and only three of the Cu-Sn axes and one chisel show (α + δ) eutectoid (34.799 A-B and 34.780) indicating that the later three underwent sufficient annealing above the eutectic point at c. 520 °C to dissolve the eutectoid into the α-solid solution.

The total amount of deformation – usually below 10% and about 10–20% in axe 34.776 – is overall astonishingly low in edges of these objects compared to other axes from the same period. The lancet-shaped chisel (34.783), however, shows a significant amount of deformation (c. 90%). It also has about 12 wt% Sn and the highest hardness value of all the sampled objects. The hardness is directly related to the alloy choice and the total amount of deformation. The Cu-Sn axes and the adze (34.776, 34.777 A, 34.781), and the Cu-Sn lancet-shaped chisel (34.783), have a hardness of ∼ 200 HV, which is significantly higher than the Cu-Sb-Sn axes (34.799 A and B, 34.780) and socketed pickaxe (34.782). Concerning the latter, one should note that due to high segregation, the Sn-rich areas reach up to 200 HV while the Sn-poor drop to about 160 HV.

The casting cake consists of as-cast copper with consistent hardness values at around 90 HV. It has low porosity and $Cu_{2-x}Fe_2S$ inclusions. Other elements, such as Sb and Bi (in combination with Cu and sometimes low amounts of Ag and As), form globular inclusions.

4.3. Lead isotope analyses

The Pb isotope signatures of the Mahrersdorf finds form three separated clusters that correspond to chemical groups 1 and 2, and the median-winged axe (Figs. 7 and 8). These clusters support the chemical analyses that suggest at least three different ore sources were used to make the objects. The Pb isotope signatures from the Mahrersdorf finds were compared to several major European ore sources in Austria, Bulgaria, Cyprus, Germany, Ireland, Italy, Slovakia, Spain, Switzerland, and United Kingdom, in order to identify the most probable source of the metal used in their production. The Eastern Alpine region, excluding Kitzbühel, and Slovakian and Valais ore sources were also included. The Eastern Alpine and Slovakian deposits contain radiogenic Pb that does not conform to their geological ages. Notably, the Mitterberg main lode is also more radiogenic than the syngeneic ore from other veins (Pernicka et al., 2016, Fig. 10). The Pb isotopic patterning for the Mitterberg ores are scattered significantly, as they also contain Uranium.

Interestingly, the isotopic signatures of the casting cake from Mahrersdorf does not match any of the major European ore sources (Fig. 8). The median-winged axe ratios, however, point to the Slovak Ore Mountains with another possible match being the Valais-region. The end-winged axe (34.777 A) is more difficult to attribute to any one source, as it plots in an area where the ratios of Buchberg, Inn Valley, and the Valais Region overlap with the Slovak Ore Mountains. However, a more likely connection to the Slovak Ore mountains is indicated by the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram. The other finds from Mahrersdorf hoard instead seem to be more closely related to the Mitterberg ores even though they plot near the borders of the distribution area (Fig. 8a–b); Fig. 8c shows a more distinct separation and the likelihood of a different ore source.

5. Conclusions

As indicated by the results of the Pb isotope analyses, possible ore sources for comparison to the Mahrersdorf finds are the Mitterberg region, the Inn Valley (including Buchberg near Wiesing), the Valais region, and the Slovak ore mountains. Before concluding, however, it should be emphasized that among the copper ore deposits next to the Mahrersdorf hoard, almost no chemical or Pb isotope data exists. Unfortunately, the only one contemporaneous and geographically nearest copper mine, located at Prigglitz-Gasteil, where a predominantly chalcopyrite ore deposit was exploited in the LBA, can be eliminated as a possible source for the fahlore copper type alloys present in the Mahrersdorf hoard (unpublished project analyses). More data is sorely needed in this regard in the easternmost Alps and the Kőszeg-Güns-Mountains. Several ore deposits in this region were likely mined during the LBA, as evidenced by numerous smelting sites (Prein an der Rax; Hampl, 1953; Hampl and Mayrhofer, 1963; Trebsche, 2015a; Klemm, 2019, 48-50 Fig. 2) and hoards containing raw copper and semi-finished products (hilltop settlement Gelände bei Grünbach: Trebsche et al., 2019; hillfort Velem-Szentvid: Czajlik et al., 1995; Czajlik, 2013).

Bronze Age smelting sites in Upper Styria, that are connected to the Vienna Basin via the Schwarza, Mur, and Mürz rivers (Kraus et al., 2015; Preßlinger and Eibner, 2013/2014, 2017), have also not been studied. At present, there are no archaeometallurgical analyses or chemical or Pb isotope studies for objects found at the sites. Furthermore, Cu deposits near Trattenbach in southeastern Lower Austria (Hackenberg, 2003) have scarce evidence for Bronze Age activity, but should nevertheless also be included in future data acquisition.

5.1. Stages in the life cycle of bronze objects and chemical composition groups

Within the complex working processes and stages in the life of bronze objects, such as casting the object, its thermomechanical treatment, usage, recycling, remelting, and final deposition, several are present in the Mahrersdorf hoard. Interestingly, these stages are in line with the chemical grouping of the objects (Fig. 9). Among the analysed objects, the first stage in the production of a bronze object is the casting of ingots (stage A). Two copper ingot types can be distinguished: the plano-convex bun ingot ("casting cake" 34.785) and the double-axe shaped ingot (34.784). The plano-convex bun is as-cast and most likely the first cast directly from the furnace. In contrast, the double-axe shaped ingot, made of fahlore, and containing about 2.8 wt% Sn, indicates that Sn was intentionally added or mixed with another tin-bronze object during casting. Hence, it was not made out of fresh copper like the plano-convex bun, but instead out of fresh or remelted copper to which fresh Sn or a tin-bronze was added. Despite the double-axe shaped ingot belonging to a group of ingots concentrated around the Caput Adriae, its chemical composition does not match any of the specimens analysed from the Kanalski Vrh II hoard from Slovenia, which are characterized by very high Pb content with an average of 17.4% (Trampuž Orel, 1996, 229–230 analyses no 717–769). In contrast to earlier interpretations (Teržan, 1996, 252), the northernmost specimen of this ingot type found in Mahrersdorf, cannot be regarded as an import from the southeastern Alpine region or product of the same copper production area.

In stage B, the object is cast and is not worked further. Objects in this stage are represented by the four socketed axes (34.779 A-C and 34.780) and the pickaxe (34.782). All of the objects show casting seam remnants and/or signs of miscasting. Macroscopic studies of the objects also did not show any traces of use-wear. Three metallographic samples taken from the edges of the axes (34.799 A-B, 34782) confirm that they were not cold worked, and one (34.780) was mildly annealed only. The same is true for the miscast socketed pickaxe. Interestingly, all five objects belong to Group 2 and could have been produced from the same alloy as the massive double-axe shaped ingot (34.784).

The three end-winged axes (34.777 A-B and 34.778), the socketed adze (34.781), and the lancet-shaped chisel (34.783) are finished products and belong to stage C. Each of these objects exhibited edge hardening on the surface in the form of hammering traces. Three of the five objects (34.777 A, 34.781, 34.783) were sampled for metallographic investigation and showed traces of annealing and work hardening. All of the objects in stage C were made from the same Group 1 Cu, which is different than the Cu in the objects in stage B. The objects in stage C could have been produced by adding Sn to the plano-convex bun ingot. One of the end-winged axes, no. 34.777 A, shows signs of use-wear and a part of the edge was broken off (Fig. 3/6). Comparably, the socketed adze shows consumed edges on both sides and the end-winged axe 34.778 a nicked edge.

Finally, in stage D the metal is recycled with edge hardening. The only object in this stage is the median-winged axe (34.776), which was also annealed and work hardened. From a typological point of view, the axe is considerably older (BZ C-D) than the other objects in the hoard (Ha B1). Its chemical composition and Pb isotopic signature is also an outlier among the other objects, belonging to the older Ösenring Cu grouping. This grouping corresponds with evidence for its secondary use. After its initial use, the neck was cut in order to adapt the median-winged axe to another type of hafting that belong to the end-winged axes that were predominant in the Late Urnfield Period.

The Mahrersdorf hoard contains two different types of axes: end-winged axes of the Bad Goisern type (including the Bad Aussee variant), and socketed axes with V-shaped or T-shaped decoration. These two types are typical of the Ha B1 period. Our analyses show that these two typological groups also reflect different Cu alloy groups. Both groups were produced from fahlores, but have distinct chemical and isotopic composition. There were likely at least two sources of fahlore Cu available in the Late Urnfield period (Ha B1) in the southern Vienna Basin situated between the easternmost fringe of the Eastern Alps, the Kőszeg-Güns-Mountains, and the Slovak Ore Mountains. Our analyses confirm earlier studies, of casting cakes from adjacent Western Hungary, that contemporaneously exploited mines produced the co-occurrence of different copper types during the preceding Early Urnfield Period. Along with these fahlore Cu alloys, older metal was still being circulated in the region. Some of the metal, for example, the re-worked median-winged axe from the Mahrersdorf hoard, was re-used some 150–200 years after their first appearance.

5.2. Scientific versus archaeological provenancing

The copper used in the production of the Mahrersdorf finds derived from different mineral sources. The re-worked median-winged axe was made of Ösenring-copper with As, Sb, Ag, Ni, and no Bi that most likely originated from the Slovak Ore Mountains. Their connection to the Slovak Ore Mountains is supported by the Pb isotope data and Ni-Ag logarithmic diagram.

For the objects in Group 1, the Pb isotope ratios of the end-winged axe (34.777 A) plot in the Buchberg, Inn Valley, and the Valais Region while overlapping with the Slovakian Mountains. However, a more likely connection to the Slovak Ore Mountains is supported by the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram and the chemical composition of the axe. The chemical composition of the casting cake also points to the use of fahlore, but the Pb isotope results do not match any European ore source. The remaining objects in Group 1, the end-winged axes 34.777 B and 34.778, socketed adze 34.781, and the chisel, were only chemically analysed; their composition points to a Slovakian ore source.

The objects in Group 2 are isotopically different than Group 1 and point to an Eastern Alpine ore source. The Mitterberg region is the closest, but not a perfect match, while the chemical analyses are more akin to the Slovak Ore Mountains. Since no perfect matches could be found among the currently available ore datasets, these two regions were not considered as possible sources of the Mahrersdorf Group 2 objects. Also, given the current lack of chemical data, we cannot trace the provenance of the alloys in Groups 1 and 2. These groups could correspond to a yet unstudied ore deposits in the surrounding region of southeastern Lower Austria, where there is evidence for copper mining in the LBA. Future research, therefore, should be prioritised on the copper deposits in southeastern Lower Austria, Upper Styria, and Burgenland. It would also be highly desirable to obtain relevant analytical data from adjacent Western Hungary and Slovenia, as noted already by Trampuž Orel 1996.

The occurrence of socketed axes with T-shaped decoration (Fig. 3/9–11) in the Mahrersdorf hoard, which were likely produced at the Velem-Szentvid hillfort in the LBA, is suggestive of the Cu and Sb ore deposits of Stadtschlaining in Burgenland. These deposits are thought to have contributed to the metal supply at Velem-Szentvid. Unfortunately, only the three specimens from this study have been analysed, and so there is currently insufficient data for comparison. In short, at this time, there are no unambiguous matches between the trace element profiles and Pb isotope patterns of the objects in the Mahrersdorf hoard and the large Cu ore deposits that have thus far been characterised. It is also possible that the related Cu ore deposits, which we presume to be in the vicinity of the Vienna Basin, have yet to be discovered and/or characterised. Another possibility is that different types of copper were, to a large extent, mixed so that the original patterns of the deposits are no longer evident in the final bronze products. The latter hypothesis may explain the difference in the high Sb content of planoconvex buns, such as those from the Schwechat hoard (c. 10–17.5 wt% Sb), and the finalized products in the Mahrersdorf hoard (1.9–3.5 wt% Sb in Group 2). Furthermore, it would follow that at least some casting cakes were the result of large-scale mixing of different ore types (chalcopyrite and fahlore copper). This scenario would have also prevented a simple match to an ore source. Still, to be certain, more effort should be made to investigate Cu ore deposits that are known to have been exploited in the Bronze Age (see also Killick et al. 2020), especially those in the Kőszeg-Güns Mountains near the metallurgical centre of Velem-Szentvid.

5.3. Tracing an individual metalworker

The Mahrersdorf hoard offers an interesting opportunity to glimpse into the working of a casting workshop by investigating the three miscast socketed axes with T-decoration. They were cast in the same mould, as can be seen by their almost identical dimensions, weight, and decoration. Assuming that a casting mould was only used by a specific metalworker or workshop, and had a limited life-span, the objects may be attributable to an individual and indicate the level of production standardization.

Every casting from a given mould is the result of a separate process involving the combination of metal sources and the ability of the metalsmith to produce a desired copper-based alloy. Of the three socketed axes from Mahrersdorf, two are nearly identical in their chemical composition (34.779 B and 34.779 C), while the third axe, 34.779 A, is very similar, but differs significantly in its Sn, As, Fe and Bi content. This difference suggests it was made using a different copper source than the first two. Comparison of these objects to sub-groups 2a and 2b, suggested that the metalsmith was capable of discerning slight differences in the Sb and As content and added less Sn as their concentration increased. The microstructures of axes 34.799 A and B show striking similarities, even in their hardness and total deformation.

It is highly desirable to study metal objects that were cast in the same mould. These studies yield valuable information about recycling, alloys choice, and their provenance. Socketed axes could provide an excellent starting point for those analyses, since several hoards with axes cast in the same mould have already been identified.

CRediT authorship contribution statement

M. Mödlinger: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Metallographic analyses, Analysis interpretation, Original draft, Writing of sections 2.3, 3, and 4, Writing of section 5. **P. Trebsche:** Conceptualization, Funding acquisition, Project administration, Writing of sections 1, 2.1, and 2.2, Writing of section 5.

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