OREA 32

Bronze Age Metallurgy

Production – Consumption – Exchange

Mario Gavranović
Mathias Mehofer (Eds.)

Austrian Academy of Sciences Press

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AUSTRIAN ACADEMY OF SCIENCES

Austrian Archaeological Institute
Department of Prehistory & West Asian / Northeast African Archaeology

Oriental and European Archaeology

Volume 32

Series Editor: Barbara Horejs

Publications Coordinator: Ulrike Schuh

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Proceedings of the Workshop "UK-Gespräche"
at the Austrian Academy of Sciences:
20th Anniversary of the Archaeometallurgical Laboratory at VIAS,
University of Vienna, May 2019

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PRESS

Published with the support of the Austrian Science fund (FWF): PUB 1150
https://doi.org/10.55776/PUB1150

and the Faculty of Historical and Cultural Studies of the University of Vienna.

This publication was subject to international and anonymous peer review.
Peer review is an essential part of the Austrian Academy of Sciences Press evaluation process. Before any book can be accepted for publication, it is assessed by international specialists and ultimately must be approved by the Austrian Academy of Sciences Publication Committee.

The paper used in this publication is DIN EN ISO 9706 certified
and meets the requirements for permanent archiving of written cultural property.

Language editing: Meghan Crnjak
Graphics and layout: Andrea Pancheri, Absam
Coverdesign: Mario Börner, Angela Schwab

ISBN: 978-3-7001-9483-5

Printing: Print Alliance, Bad Vöslau

https://epub.oeaw.ac.at/9483-5
https://verlag.oeaw.ac.at
Made in Europe

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Preface by the Series Editor

The 32nd volume is dedicated to a long-term research focus of our OREA series in both respects, namely the research topic and the focus region. "Bronze Age Metallurgy. Production, Consumption, Exchange", edited by Mario Gavranović and Mathias Mehofer, represents one result of the long-term collaboration between our institute (the former Institute for Oriental and European Archaeology, now the Austrian Archaeological Institute at the Austrian Academy of Sciences) and the Vienna Institute for Archaeological Science (VIAS) at the University of Vienna, which was intensified around a decade ago. The 'UK Gespräche' (Urnfield Culture Talks), initiated by Michaela Lochner in the late 2000s at the Austrian Academy of Sciences with a focus on the Late Bronze Age of Central Europe, have been expanded to include Southeast Europe since Mario Gavranović joined the team in 2015. His systematic approach to the study of central and southeastern European Bronze Age societies has resulted in a new dynamic within his research group, characterised by the development of new case studies, international projects and long-term collaborative partnerships. The fruitful joint projects with Mathias Mehofer, who heads the Archaeometallurgical Laboratory at VIAS, showcase such a successful collaboration, and I am pleased to host their edited volume in the OREA series as an outcome of the 'UK Gespräche' and the 20th anniversary of the VIAS Archaeometallurgical Laboratory. The list of cooperation partners, who have facilitated the research process and provided valuable insights that have enhanced the work of both editors, is a testament to the collaborative nature of this endeavour.

The examination of the role of metals in Bronze Age societies represents a well-established and long-term research approach within the field of European archaeology. This has resulted in a significant body of research, encompassing a multitude of archaeometallurgical studies of artefacts and metal sources which have been conducted over the past decades. The creation of a standardised research framework on metals has been spearheaded by former and current scientists, facilitating the generation of a new level of quality and quantity of data. The Archaeometallurgical Laboratory at VIAS made a substantial contribution to the advancement of analytical techniques, with the potential for further significant outcomes in the future. The contextualisation of old and new analytical data within a wider socio-cultural framework, the opportunity of sampling newly excavated and securely dated objects, surveying potential unknown sources in underestimated areas and the compilation of all these complex data to create new models are the focus of Gavranović's research group and many of the authors in this volume. The contributions and socio-culturally related results, as summarised by the editors in their introduction, have not only produced exciting new data, published for the first time, but also offer new interpretations of Bronze Age communities, their networks, lifeways and wider connectivity. The evaluation of the newly presented models and narratives by future research has the potential to create a new dynamic in southeastern and central European metallurgical research.

I would like to express my sincerest gratitude to Mario Gavranović and Mathias Mehofer for organising the workshop and editing this volume and for their compilation of 19 contributions by 21 authors. The editors' introduction provides a good overview of the general outcome and of current research in the focus regions. Special thanks go to all contributors for sharing their expertise, data and models. I would also like to thank the Austrian Science Fund and the University of

Vienna for their financial support to realise this volume, and I sincerely thank Ulrike Schuh for managing the entire publication process. The Austrian Academy of Sciences Press is also to be commended for its continued support of the OREA series.

Barbara Horejs
Scientific director of the Austrian Archaeological Institute
Fujairah, 12 November 2024

Preface by the Rector of the University of Vienna

In 2019, on the occasion of the international conference, 'Bronze Age Metallurgy: Production – Consumption – Exchange', the 20th anniversary of the Archaeometallurgical Laboratory of the Vienna Institute for Archaeological Science (VIAS) at the University of Vienna was celebrated. The meeting was part of the 'UK-Gespräche' series, graciously organised by the Institute for Oriental and European Archaeology (now Department of Prehistory & West Asian/Northeast African Archaeology, Austrian Archaeological Institute) of the Austrian Academy of Sciences.

From May 22nd through 24th, 20 international experts in mining archaeology and archaeometallurgy came to Vienna to discuss ground-breaking transdisciplinary research centred around Bronze Age metal use in Europe. The primary focus of the meeting was on the mining, smelting, distribution, and use of copper. The symposium opened new perspectives on the manifold interactions between humans and their complex use of metal in both sacred and profane contexts.

This interdisciplinary approach has a long history within the University of Vienna. In 1998, the Archaeometallurgical Laboratory at VIAS was installed by Univ.-Prof. Dr Falko Daim. He recognised, with great foresight, the potential of archaeometric analysis for archaeology. The laboratory aims to develop and integrate methods from the natural sciences in a dynamic relationship with cultural history frameworks of archaeology. In 2000, Dr Ing. Mathias Mehofer, one of the editors of the present conference proceedings, was appointed as director and has successfully managed the laboratory ever since. As a result, numerous scientific collaborations have been initiated, and many substantial publications have been completed. This work has focused not only on outstanding archaeological objects, such as the famous gold treasure of Vălčitrăn (National Archaeological Museum Sofia), but also on prehistoric exchange systems, technology transfers, and their impact on the environment. Dr Ing. Mathias Mehofer is to be warmly congratulated for these impressive achievements.

Finally, I would like to extend my heartfelt gratitude to the two editors – Dr Mario Gavranović and Dr Mathias Mehofer – for their invaluable contributions to this volume. Their dedication and expertise have made this publication a true testament to the advancements in our field. I am confident that this is just the beginning of many more productive research cooperations between scholars at the University of Vienna and the Austrian Academy of Sciences, a future that we all are integral to.

Univ.-Prof. Dr Sebastian Schütze
Rector of the University of Vienna

Introduction

Mario Gavranović[1] *– Mathias Mehofer*[2]

The volume presented here contains contributions from the international workshop 'Bronze Age Metallurgy. Production – Consumption – Exchange', held in Vienna in May 2019. The conference, as a part of 'UK-Gespräche' annual meetings, was organised by the former OREA Institute (now Department of Prehistory & West Asian/Northeast African Archaeology, Austrian Archaeological Institute) of the Austrian Academy of Sciences and VIAS (Vienna Institute for Archaeological Science, University of Vienna) on the occasion of the 20th anniversary of the Archaeometallurgical Laboratory at VIAS. The main goal was to gather renowned experts in Bronze Age mining archaeology and archaeometallurgy and to discuss recent developments and results concerning copper production and use, trade and exchange of raw materials, and alloying practices in areas of central and southeastern Europe. Altogether, 19 conference papers were presented, reporting on research achievements and new results on Bronze Age Metallurgy in the territories of present-day Austria, Bosnia-Herzegovina, Croatia, Hungary, Germany, Italy, North Macedonia, Poland, Serbia, Slovenia, and Switzerland. Nine submitted contributions in this volume cover most of this area.

In 2014, our joint research on Bronze Age Metallurgy with a focus on the Balkan Peninsula started in the frame of the cooperation between the Austrian Academy of Sciences and the University of Vienna with a small pilot project. The first promising results on Late Bronze objects from Bosnia[3] motivated us to extend to adjacent regions, enlarge our dataset, and tackle open questions regarding metals' production, exchange and consumption. Over the years, we established a sustainable network of collaboration partners spanning the western and central Balkans, including archaeology, geology and metallurgy experts. Thanks to the numerous colleagues from the local museums and collections and their interest in participating in our joint research projects, we were able to build up a large dataset with currently over 1000 metal, ore, and slag samples from different Bronze and Iron Age contexts in an area between the Adriatic Sea, Southeast Alps, Carpathian Basin and Lower Danube.

When we started our investigations, little was known about the Bronze Age metallurgical networks in the Balkans.[4] The assumptions about the use of the local copper ore sources, particularly in Serbia and Bosnia, were part of the archaeological narrative but were not based on analytical results. The intensive use of local ore resources during the Copper Age (Majdanpek, Rudna Glava, Belovode) led to the hypothesis that local Bronze Age communities continued exploiting mineral deposits and producing raw material copper.[5] In addition, the rising number of metal workshops (with moulds, crucibles, casting waste and clay cores) in the archaeological record during the Middle and Late Bronze Age supported the idea of intensive copper ore mining on a

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3 Gavranović – Mehofer 2016.

4 Radivojević et al. 2018.

5 Gavranović 2012; Kapuran 2014.

regional scale.[6] Under these premises, we began our systematic sampling to explore the flow of metals in the Bronze Age Balkans.

Within the sampling strategy, the archaeological information (context, dating, typology, distribution, etc.) formed the essential criteria for the choice of objects. These included ores, slags, ingots, casting remains, and semi-finished and finished objects, covering the entire production chain. The subsequent analyses with a scanning electron microscope (SEM-EDS), energy dispersive-X-ray fluorescence (ED-XRF) and lead isotope analyses (LIA), as well as neutron activation analysis (NAA), were carried out at the archaeometallurgical laboratory at VIAS (University Vienna), at the Curt-Engelhorn Centre of Archaeometry Mannheim and the Johannes Gutenberg University of Mainz. In the first step, the results of SEM-EDS and ED-XRF provided an overview of the chemical composition, allowing us to get the first diachronic insight into the alloying practices and to compare them with already presented data from neighbouring regions (e.g., Slovenia, Italy or Carpathian Basin). Based on the SEM-EDS and ED-XRF results, in the second step, we selected samples for LIA as the most reliable tool for narrowing down the copper provenance. A particular focus was set on the possible use of abundant domestic ore sources. However, prior to our work, some of these copper deposits (e.g., in Central Bosnia) were not determined in terms of geochemistry, requiring some pioneering work and the involvement of local geological and mineral experts.

The research in eastern Serbia, where previous investigations led to the discovery of a few sites with traces of Bronze Age copper processing,[7] elucidated the importance of this area and provided new knowledge about metal production and the societies involved in copper production. Although initially assigned to the Late Bronze Age (14^{th}–11^{th} centuries BC), the series of radiocarbon dates unmistakably confirmed that copper production sites in eastern Serbia were active between the late 20^{th} and 17^{th} centuries BC (Early to Middle Bronze Age)[8] and thus slightly preceded the beginning of the copper production in the Alps (e.g., Hochkönig-Mitterberg in Austria or Trentino in northern Italy) that started around the 19^{th}/18^{th} century BC and intensified in the following centuries.[9] The analytical results clearly demonstrated the use and exploitation of local sulfidic copper ore sources from surrounding deposits in eastern Serbia. However, Bronze Age mining traces were not detectable due to the intense exploitation of copper ores in all later historical periods, including modern times. The detailed analyses of the smelting remains revealed that copper was extracted in at least three steps, each with a characteristic slag shape. They confirm that sulfidic ores were converted to copper within a matte smelting process.[10]

According to the available data, copper production was widely practised in eastern Serbia during the Early and Middle Bronze Ages, with traces of smelting in most of the registered settlement sites around the ore deposits. Burial practices of societies engaged in copper production included exclusive cremation with urns deposited in circular stone construction and with very few grave goods, mainly pottery.[11] The urn cemeteries investigated thus far do not reveal any distinct social differentiation or accumulation of wealth and prestige objects. In fact, despite the evident and well-spread copper extraction in the area, there is only a small number of bronze objects in the entire archaeological record, indicating that the local population was not much involved in casting. Due to the current absence of any finds that could be interpreted as indicators of social hierarchy, the question about the beneficiaries of copper extraction in terms of the increase in wealth remains open. Following chemical and lead isotope analyses, copper from eastern Serbia is attested in Middle Bronze Age objects from the central Balkans. These objects are likely cast in

6 Wanzek 1989; Gavranović 2013.
7 Kapuran 2014.
8 Kapuran et al. 2020; Mehofer et al. 2021.
9 Pernicka et al. 2016.
10 Mehofer et al. 2021.
11 Gavranović et al. 2020; Kapuran et al. 2020.

some regional workshops, indicating the circulation of copper raw material from eastern Serbia, at least on a regional scale.

From the late 17th century BC onwards, the archaeometallurgical data indicates crucial changes in the metal supply of the central and western Balkans. Copper production in eastern Serbia ceased for reasons that still need to be explained entirely. The depletion of local copper sources can be ruled out as a possible cause, and the archaeological record suggests the continuity of human occupation in the area, but apparently without significant involvement in copper processing. In addition, the analytical results of a few Middle Bronze objects showed the presence of copper with a geochemical signature corresponding to deposits in the Trentino area of northern Italy, indicating a fundamental change in the metal supply (networks) in the Balkans.[12] Particularly surprising were the analytical results of more than 250 Late Bronze Age objects from different regions of the western and central Balkan, dating between 1400 and 900 BC. They clearly emphasise the predominance of copper from the South Tyrolean and Trentino mining regions.[13] The metal from these regions was detected in metal types with supra-regional distribution tendencies but also in strictly local types, which are with certainty produced in regional workshops. This corresponds well with the already published data for Italy from the same period, showing that the Apennine Peninsula was a part of the same copper supply networks.[14] The significance of the copper mining and smelting districts in northern Italy for understanding the Bronze Age metallurgy in Europe has been recently highlighted by an increasing number of analyses. They show the presence of this raw material in Italy, the eastern Mediterranean and even Scandinavia.[15] Now, we can assume that the same mining region also supplied the areas of western and central Balkan for most of the Middle and Late Bronze Ages. The exchange networks through which the copper from the Trentino and South Tyrol entered the Balkans will be the focus of future research. In principle, we can describe two possible routes: along the Adriatic Sea and the river system of the Danube, with the Drava, Sava and Morava as the primary communication ways.

According to the current state of research, copper from other sources had a subordinate role in the Late Bronze Age metallurgy in the western and central Balkans (see Mehofer et al. in this volume). Noteworthy exceptions are ingots from hoards in Bosnia and Serbia with copper chemically and isotopically corresponding to the mining areas in Hochkönig-Mitterberg in Austria. Three samples, including one Mycenaean rapier from North Macedonia (Tetovo) and two ingots deposited in LBA hoards in Serbia and Bosnia, contained copper with a geochemical signature falling in the area of the Cypriot copper ores. None of the Late Bronze Age objects analysed thus far contained copper that could be associated with local deposits in Bosnia or Serbia. Due to the state of research, other European copper ore deposits, like in the Slovakian ore mountains or Bulgaria, cannot be entirely excluded, even though it is unlikely that they deliver metal to the regions under study.

The contributions in this volume provide an excellent frame for integrating and contextualising the new results on Bronze Age Metallurgy in the Balkans and most of the neighbouring regions. The results of new analyses, excavations, and systemic studies presented here extend our understanding of metallurgical processes on regional and supra-regional levels reflected in the archaeological record.

The first part of the conference proceedings includes papers discussing mining and smelting activities in Switzerland, Austria, and northern Italy.

The first paper by Rouven Turck and Philippe Della Casa presents the living conditions of prehistoric miners in a settlement in the Oberhalbstein Valley (Graubünden, Switzerland). It describes the local ore deposits, the possible organisation of mining and smelting and, connected

12 Mehofer et al. 2021.
13 Gavranović et al. 2022.
14 Mehofer et al. 2020; Jung et al. 2021.
15 Ling et al. 2019; Nørgaard et al. 2021.

to this, the econometric, technological and social factors showing that the mining and smelting communities did not gain a substantial benefit from their activity, which is comparable to the situation in eastern Serbia.

Markus Staudt and Gert Goldenberg focus on the Late Bronze to Early Iron Age mining and smelting from fahlores at Schwaz-Brixlegg, North Tyrol, Austria. Their article describes the 'chaîne opératoire' of prehistoric copper production in this mining district. It presents all process steps of copper extraction, from the extraction to the production of finished objects, in detail and is supported by several new data.

The contribution by Thomas Koch Waldner gives an overview of the first results of a previously unknown Late Bronze Age mining landscape in the upper Vinschgau region, South Tyrol (IT). The discovery of smelting slags provides evidence for local copper production and consumption. In addition, the archaeological finds from the area suggest contact with the eastern Mediterranean and the Balkans.

The three following papers deal with the regions of northern Italy and the Balkans in the Late Bronze Age with a particular focus on newly revealed and intensive connections regarding the copper supply.

The contribution by Elisabetta Borgna and Caterina Canovaro considers the social organisation and practices of communities in northern Italy during the Late Bronze Age with regard to metallurgy and deposition of metal objects. Some hoards from the northern Adriatic regions serve as case studies to discuss archaeometallurgical and archaeological questions on metal provenance, as well as the relationship between northern Italy, Urnfield areas in the Alps, and parts of the western Balkans.

The article by Mathias Mehofer et al. presents the first insights into the Late Bronze Age distribution of raw metal in the western and central Balkans. Copper from northern Italy (South Tyrol and Trentino), the Hochkönig-Mitterberg region in Austria and Cyprus was found in various hoards and settlements, giving a first indication of the supra-regional exchange patterns of copper raw metal.

The paper by Mario Gavranović et al. discusses two Late Bronze Age hoards from the Požarevac area in Serbia (Klenje und Kličevac-Rastovača). The analytical results indicate the presence of copper raw material mainly from Trentino (IT) and other distant areas such as Cyprus and Mitterberg, Austria. Although situated in an area with abundant copper ore deposits, none of the results from the Požarevac area point to the possible use of domestic sources.

The last three contributions of the volume bring new results on metal supply networks, metallurgical practices and non-invasive archaeometallurgical methods in central and eastern Europe.

In their contribution, Bianka Nessel and Claes Uhnér investigate different distribution patterns of copper ingots during the Bronze Age and regard these objects as early forms of the metal commodity in the interwoven and wider-reaching exchange. Thanks to the thorough analysis of ingot fragments, focusing on so-called bun ingots, the authors can identify multi-layered circulation networks with several regional clusters from a diachronic perspective.

In their contribution, Kamil Nowak et al. present new results on metal provenance in Lower Silesia, which was part of Lusatian Culture and, thus, the large Urnfield complex of the Late Bronze Age. Focusing on a particular type of bracelets, the authors bring new data showing the influx of copper from northern Italy into this region during the 12th and 11th century BC and valuable information on Bronze Age metalwork.

The paper by János Gábor Tarbay et al. describes various non-invasive and non-destructive analyses (X-ray fluorescence spectroscopy, Prompt Gamma Activation Analysis, and Neutron Imaging) on one specific Late Bronze Age object. Furthermore, it discusses the intentional addition of the lead to the bronze alloy in the transregional perspective of the time between Ha A2 and Ha B1 and the regional frame of Transdanubia in western Hungary, known for intensive deposition activities.

Our work would not be possible without the participation and collaboration of colleagues from different museums and institutions from Austria (Natural Historical Museum, Vienna), Bosnia-Herzegovina (National Museum of Bosnia and Herzegovina, Sarajevo; Regional Museum Travnik; Regional Museum Doboj; City Museum Zenica), Croatia (The Institute of Archaeology Zagreb, Archaeological Museum Zagreb; Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb; Museum of Slavonia, Osijek; Museum of Brodsko Posavlje, Slavonski Brod), North Macedonia (The Archaeological Museum of the Republic North Macedonia, Skopje; National Museum Veles; Museum of City Gevgelija) and Serbia (Institute of Archaeology, Belgrade; National Museum of Serbia, Belgrade; Museum of Mining and Metallurgy, Bor; Museum of Vojvodina, Novi Sad; City Museum Sombor; National Museum Požarevac; Museum of Krajina, Negotin; National Museum Niš; County Museum Aleksinac). In particular, we thank our colleague and friend Aleksandar Kapuran from the Institute of Archaeology in Belgrade for his generous support in field works and sampling campaigns. We also want to thank Meghan Crnjak for her assistance with proofreading and editing. Special thanks go to Ulrike Schuh for her editorial support and Andrea Pancheri for her layout work.

Finally, our sincere thanks go to all authors for their valuable contributions to this conference volume and talks. We want to thank Barbara Horejs and the former OREA Institute (now Department of Prehistory & West Asian/Northeast African Archaeology, Austrian Archaeological Institute, Austrian Academy of Sciences) for supporting the pilot phase of our research in 2014 and 2015. A further set of analyses in 2018 was accomplished with the help of Dr. Anton-Oelzelt Newin'sche Stiftung of the Austrian Academy of Sciences. From 2019, the Austrian Science Fund (FWF) supported our research in the framework of the project 'Bronze Age metal producing societies in the western and central Balkans' (P32095-G25, 2019–2024, PI M. Gavranović). We are also grateful for the financial support of the Vienna Institute for Archaeological Science, University of Vienna, provided since the beginning of the research in 2014, and to the Faculty of Historical and Cultural Studies, University of Vienna, for co-organising the workshop. Rector Univ.-Prof. Dr Sebastian Schütze gave us the honour to contribute with an opening speech and preface to this volume. It is our pleasant duty to acknowledge the financial support for this publication provided by the Faculty of Historical and Cultural Studies, University of Vienna, and the FWF book publication project no. PUB 1150.

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Mining and Smelting Activities in the Alps

Living in High Alpine Conditions: Living between Ice and Ores

Rouven Turck[1] – *Philippe Della Casa*[2]

Abstract: This paper discusses the living conditions of prehistoric miners and smelters based on current research on primary copper metallurgy in the Oberhalbstein Valley (Graubünden, Switzerland). Topics discussed are the settlement history of the Oberhalbstein, local ore deposits, possible organisation of mining and smelting, econometric, technological and social factors, and the copper trade network. Particular focus is given to the discussion of metal-age settlement activity, which was almost certainly temporary and seasonal at elevations above 1400 m. Based on this, socio-economic models of the significance of Iron Age copper mining are developed.

Keywords: Copper metallurgy, Alpine/mountain archaeology, living conditions, copper as a socio-economic tracer

Settlement History/Colonisation

The prehistoric settlement history of the Oberhalbstein has been a topic of study since the 1930s and 1940s. Amateur researcher Walo Burkart[3] explored sites in all of Graubünden and the Oberhalbstein valley, which led to the discovery of the metal-age site Motta Vallac (Fig. 2).[4] He also discovered Bronze Age sites such as the significant settlement Savognin-Padnal,[5] and the sites Savognin-Rudnal and Cunter-Caschligns (Fig. 1).[6]

The long-term research carried out by Jürg Rageth on the Padnal hill in Savognin has allowed a discussion of settlement activity in the valley from the later stages of the Early Bronze Age onward, based on archaeological evidence and absolute ^{14}C data.[7] Archaeological finds from the valley suggest the continuous presence of people. However, due to the complex stratigraphy of the sites, one or more intervals in settlement cannot be ruled out. Recent ceramic analyses confirm significant settlement activity at Motta Vallac in the Middle Bronze Age.[8] All sites mentioned here show activity in the Late Bronze Age.

The use of the inner Alpine regions can certainly be explained by the 'prime mover' agriculture.[9] Numerous animal bones in settlement contexts suggest local animal husbandry in the form of Alpine farming.[10] The valley must also have played an important role as a link between north and south and as a transit route through the Alps.[11] A third factor is the local resources, namely

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2 Universität Zürich, Institut für Archäologien, Switzerland.
3 Burkart 1939.
4 Zürcher 1982, 20–51; Wyss 1977; Bradler 2018; Jäger 2018; Roffler 2018; Turck et al. in press.
5 Rageth 1986. J. Rageth's excavation reports were published yearly between 1972 and 1986 in the Jahrbuch Archäologie Schweiz.
6 Nauli 1977; Wyss 1993.
7 Rageth 1986; Fasnacht 1999 with newly calibrated ^{14}C data.
8 Roffler 2018.
9 Della Casa 2002; Reitmaier et al. 2018.
10 Bopp-Ito 2012.
11 Della Casa 2002.

Fig. 1 Map of the Oberhalbstein Valley with mentioned sites (graphics: O. Bruderer, R. Turck)

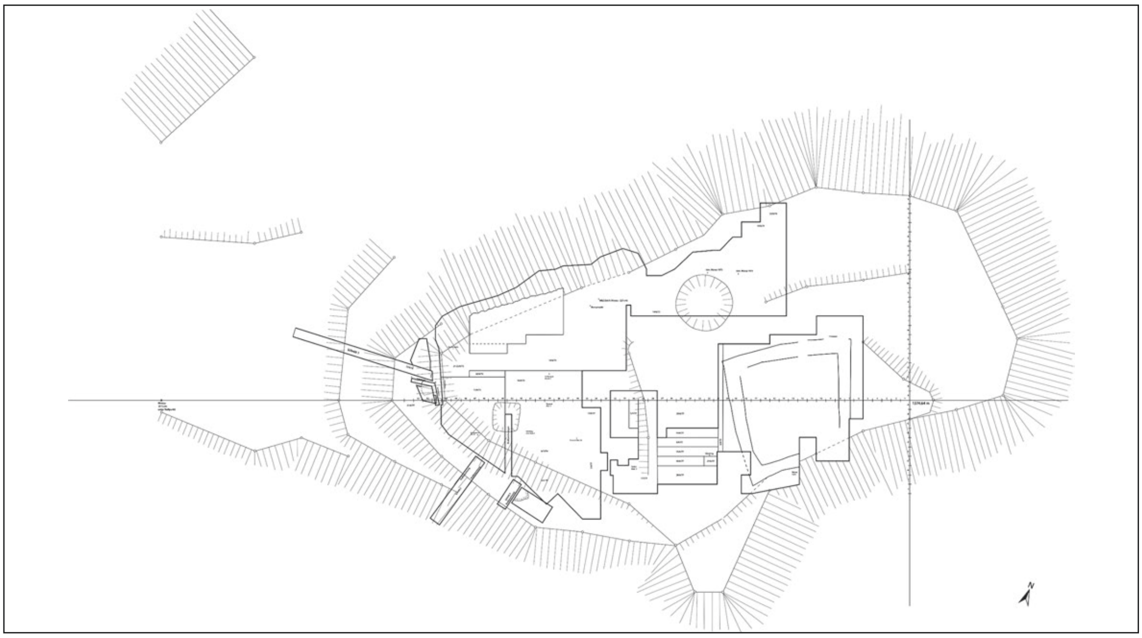

Fig. 2 Plan of the settlement Motta Vallac, Salouf/Surses (drawing: M. Bradler)

copper. Archaeological evidence in the form of bronze casting residues and casting moulds confirms the practice of bronze working and copper casting.[12]

Possible interpretations of slag and ore found in settlement contexts[13] have been the subject of debate[14] and must be revised in light of recent slag analyses from smelting sites in the valley.[15] A casting mould has also been found at Cunter-Caschligns,[16] and non-ferrous remains of secondary metalworking and tools, such as stone hammers,[17] have been found at Motta Vallac. This suggests that metalworking played an important role in the valley during the Bronze Age.[18] Studies of Bronze Age artefacts indicate the use of fahlore copper,[19] which does not occur in the Oberhalbstein. Research is currently underway to determine whether Bronze Age metalworkers used local copper in the bronze casting process. A detailed chronological overview of metallurgical activities in the settlements is still pending.

Activity in the Early Iron Age has rarely been discussed due to the scarcity of finds. However, these finds, predominantly pottery, have been the topic of recent research.[20] Single finds suggest that these potsherds can be associated with Taminser pottery,[21] named after the eponymous burial ground,[22] and thus date to Hallstatt D. A permanent settlement of the valley – as is the case in the Bronze Age – cannot be ascertained based on current evidence and is a factor in ongoing research on prehistoric mining in the valley.[23]

12 Rageth 1979a, figs. 27.1; 50.1–2; Rageth 1982, fig. 39.1–4; Rageth 1984, figs. 21.13–21; 23. 3–6; 24. 3–11; 35.6–27.
13 E.g., Rageth 1979a, fig. 54–57; Rageth 1982, fig. 58.
14 Rageth 1986; Fasnacht 1999.
15 Reitmaier-Naef 2019.
16 Keller-Tarnuzzer 1944, tab. VII, fig. 1–2.
17 Wyss 1993, fig. 3; Jäger 2018.
18 O'Brien 2015, 105.
19 Fasnacht 1991; 1999.
20 Turck 2016, 17; Roffler 2018, 32–34.
21 Schaer 2003, 44.
22 Conradin 1978; Schmid-Sikimić 2002.
23 Turck 2015; Della Casa et al. 2016, based on the work of Fasnacht 1991 and Schaer 2003.

For the Late Iron Age, there were very few finds from the valley,[24] making any activity in the La Tène period difficult to reconstruct.

The situation changed in the Roman period, as archaeological evidence of activity is well documented both in the systematic fortification and use of the Septimer Pass between the Bergell Valley and southern Oberhalbstein Valley[25] and through the presence of Roman auxiliary troops and settlements.[26]

There is evidence of metalworking during the High Middle Ages at Marmels Castle.[27] Modern mining activity in the area has been researched and published by Eduard Brun.[28]

Ore Deposits and their Accessibility

The Oberhalbstein Alps lie in the Central Alpine border zone where the East Alpine nappe obducts the West Alpine Penninic. The Penninic nappes originated in the Tethys Ocean, while the East Alpine sequences form part of the former South Adriatic Margin.

Between the two lies the upper Pennine Platta nappe, with rocks composed primarily of oceanic crust such as ophiolites, pillow lavas and radiolarites. This obduction zone shows a complex interaction of tectonic sedimentation, which makes the geological map of the area very unclear.[29]

The Platta nappe comprises many small, scattered ore deposits. Larger deposits are found in only a few places, for example, east and west of the Marmorera Lake in the outcrop and mining areas Cotschens and Gruba. The numerous small and larger mineralisations were researched and published by Volker Dietrich.[30] They are exclusively sulphide mineralisations, often recognisable by a distinctive red oxidation zone. The copper usually occurs here in chalcopyrite ($CuFeS_2$) associated with iron sulphides and iron oxides like pyrite (FeS_2), pyrrhotite (FeS) or magnetite (Fe_3O_4).[31]

These iron-rich ores and an analytical misunderstanding led to the assumption that Alpine archaeological finds in the Oberhalbstein Valley were associated with iron production.[32] This error was corrected in the 1980s and supported by later research.[33]

A German-Austrian-Swiss project has overseen renewed prospecting, sampling, and mineralogical and geochemical analyses of many of these sites. It has also allowed the development of a geochemical and lead-isotope characterisation of the ore deposits in the Oberhalbstein, which can be used as the basis for origin analyses in the future.[34]

To date, the project has been able to secure evidence of prehistoric mining at three sites. In Cotschens and Vals, underground mining was carried out with the help of fire-setting. At the third site, Avagna-Ochsenalp, the entrance to the mine is obstructed, and the mining method can no longer be ascertained.[35]

Two of the prehistoric mines and most of the ore deposits are found at over 2000 m above the (current) tree line. Supplying the (pre)historic mines with the wood and other resources needed for mining must have demanded considerable effort. Some sites, such as Vals, also lie in relatively

24 Rageth 1979b, fig. 2.1; Deschler-Erb 2013.
25 Rageth et al. 2013; Sele 2013.
26 Rageth 1979b.
27 Eschenlohr 2012.
28 Brun 1987.
29 Nievergelt 2001.
30 Dietrich 1972.
31 Dietrich 1972.
32 Burkart 1949; Zindel 1977; Rageth 1979b.
33 Geiger 1984; Fasnacht 1991; Schaer 2003.
34 Reitmaier-Naef 2018.
35 Reitmaier et al. 2015; Reitmaier et al. 2020.

steep and difficult-to-reach areas. In these environmental conditions, it can be assumed that mining activities took place exclusively in the summertime.

Mining Districts and their Structural Elements

The Oberhalbstein mining district can be divided into two areas: the lower valley around the village of Savognin and the upper valley around the modern-day Marmorera reservoir. A few sites associated with mining have also been found in the neighbouring valleys of Avers, Bergell and Oberengadin.[36]

In contrast to the six known prehistoric mines, there are approximately 80 known smelting sites. This imbalance is particularly evident in the lower valley, where there is a considerable distance between the prehistoric mining area Avagna-Ochsenalp on the east side of the valley and the majority of the smelting sites on the valley's west side. It is unlikely that the ores from this mine were transported up to 10 km across the valley for smelting. It is more likely that mining also took place on the west side of the valley and that the current state of research inadequately depicts the area. The soil cover thickness, vegetation, and agricultural and residential density make it difficult to localise ore deposits and archaeological sites in this part of the valley. The relationship between the Late Bronze and Early Iron Age smelting sites and the mostly Bronze Age settlements in the lower valley will be the subject of future research.[37]

Far more archaeological sites are known in the upper part of the valley (Fig. 1). They date almost exclusively to the Early Iron Age.[38] A clear accumulation of smelting sites is noticeable around the modern-day Marmorera reservoir. This is where the largest ore deposits and the prehistoric mines of Cotschens and Vals are found.[39] The smelting sites tend to be located at heights around 2000 m or slightly above. This suggests that the sites were intentionally established at or directly below the forest line in order to secure the wood supply, while the corresponding mine could be found above the forest line, as is the case with Cotschens.

Small-scale interrelations between single smelting sites, ore deposits and mines can be inferred based on the natural topography of a site. The smelting site Gruba I and the mining depressions Gruba II lie in close proximity to one another,[40] while another, much younger mine can be found at a few hundred metres distance.[41] A direct connection can also be assumed between the most extensive mining area, Cotschens/Val Starschagns, and the smelting sites located immediately below in the areas of Alp La Motta, Pareis and Clavè d'Mez. Based on geochemical data, an explicit connection between a deposit and a smelting site can currently only be posited for the mineralisation at Muttans and the smelting site Val Faller Plaz.[42]

The proximity of the smelting site at Gruba I to the deposits and mining depressions at Gruba II and that of the ore deposit at Val Natons to the smelting site at Alp Natons is evident.[43] The numerous smelting sites in areas further south, such as Bivio Plaz, Bivio Barscheinz or Bivio Brüscheda, which are found singly or in small groups, suggest the exploitation of smaller copper deposits that have since been lost. In an interesting contrast, several relatively copper-rich deposits have been found in the southwestern area of Oberhalbstein; however, with the exception of Radons, no smelting sites have been found.[44]

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36 Schweizer 1982; Reitmaier et al. 2016; Turck et al. 2017; Wenk et al. 2019.
37 Rageth 1986; Bradler 2018.
38 Oberhänsli et al. 2019.
39 Reitmaier et al. 2015; Reitmaier et al. 2020.
40 Turck 2019.
41 Brun 1987; Turck et al. 2018
42 Reitmaier-Naef 2018.
43 Turck 2019, fig. 1.
44 Reitmaier-Naef 2018.

Fig. 3 High plateau Drauscha, Bivio/Surses (photo: Ph. Della Casa)

Fig. 4 Abri Murtèr, Bivio/Surses (photo: Ph. Della Casa)

So far, no evidence of permanent settlement or agricultural activity during the Late Bronze Age and Early Iron Age has been found in the upper valley. The role copper production played in settlements and subsistence strategies in this area remains unknown.

Mining Districts and Temporary Camps Sites

Recent field surveys at rock shelters and high plateaus suggest the use of temporary campsites by miners and smelters. ^{14}C dates (Tab. 1) from charcoal found at the Drauscha high plateau (Fig. 3) and the Abri Murtèr (Fig. 4), both in Bivio, and from Abri III in Val Faller, Mulegns

Fig. 5 Val Faller, Abri III, Mulegns/Surses (photo: A. Bahß)

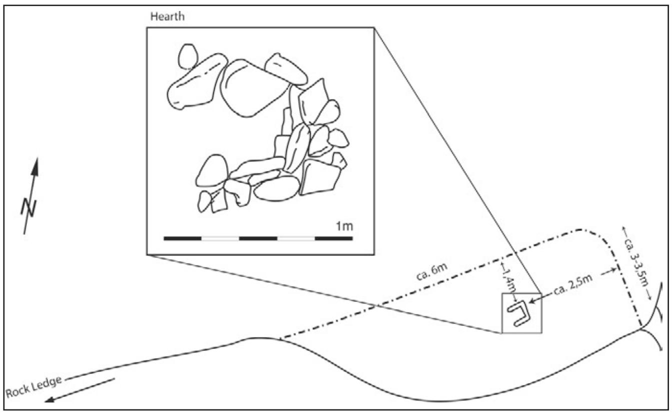
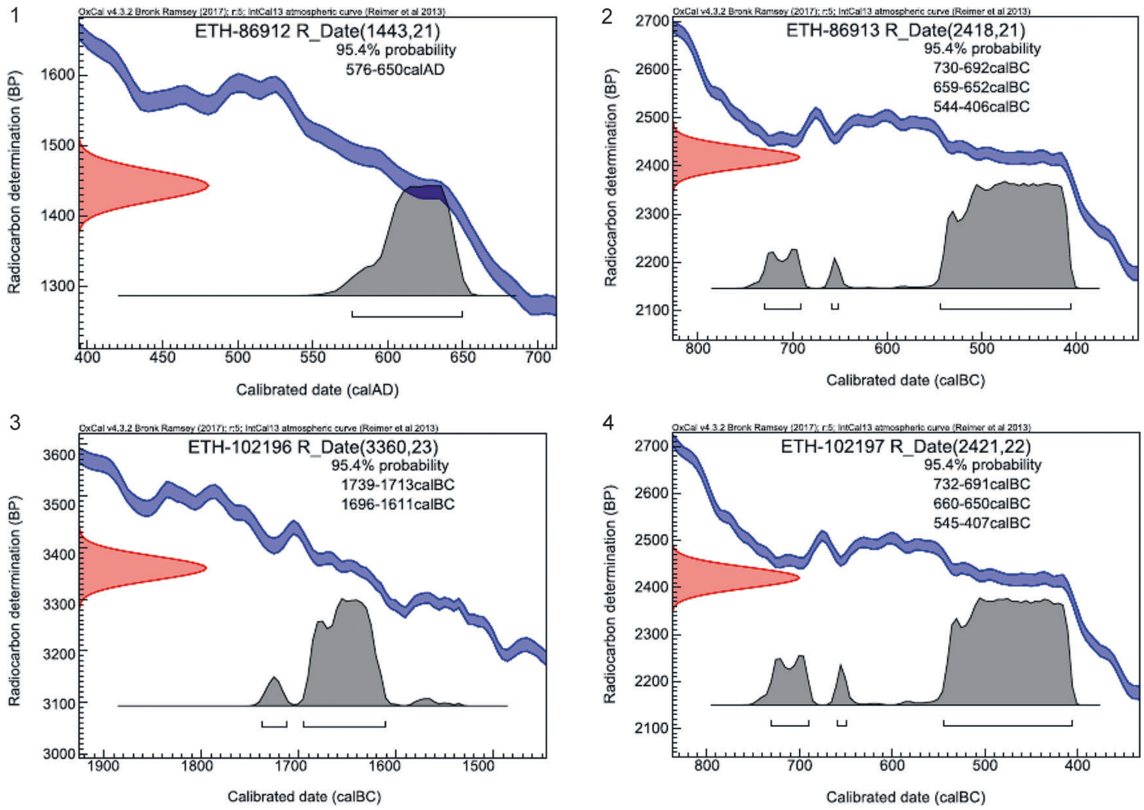


Fig. 6 Abri Las Mottas, Sur/Surses (drawing: A. Bahß, R. Turck)

(Fig. 5), confirm the use of these temporary spaces since the 2nd millennium BC, as well as during the height of copper mining and smelting in the valley. At the site Abri Las Mottas, Sur, a preserved hearth was discovered (Fig. 6). The site was documented by J. Rageth on 22.09.1976. Charcoal from this hearth was dated in Bern in 1976 (sample number B-2976). The newly calibrated date falls between 1123 and 802 BC in the 2-sigma range. This is a similar timeframe to the ^{14}C dates from Ofen I at the smelting site Gruba I.[45] Unfortunately, despite several attempts, the site Abri Las Mottas could not be relocated. While this shelter was located only a few hundred metres from the smelting site Gruba I, at an elevation of between 1850 and 1900 m, Abri III lies within sight of the smelting site Val Faller, Plaz,[46] at approximately 100 m distance, at an elevation of 1800 m.

Drauscha and Abri Murtèr sites cannot be assigned to a specific smelting site. However, some sites in the southern Bivio region, for example Barscheinz I, are found at elevations between 1900 and 2050 m, and date to the Late Bronze Age and Early Iron Age (Tab. 1). Considering the proximity of these sites, it is conceivable that local miners established mobile campsites in protected

45 Turck et al. 2014.
46 Turck 2019.



Sample no.	ER	FK	Site name	Place	Munici-pality	Material	^{14}C age	±1σ	±1σ	$\delta^{13}C$	±1σ	mg C	C/N	East	North	Eleva-tion
ETH-86912	67168	118	Drauscha	Bivio	Surses	charcoal	1443	21	0.0022	-24.1	1	0.99	338.92	768258	150223	1950
ETH-86913	67168	115	Abri Murtèr	Bivio	Surses	charcoal	2418	21	0.0019	-24.7	1	0.86	238.27	770600	150696	2136
ETH-102196	69431	4	Val Faller, Plaz, Abri III	Mulegns	Surses	charcoal	3360	23	0.0019	-24.3	1	1.00	436.82	766134	153725	1794
ETH-102197	69431	30	Barscheinz I	Bivio	Surses	charcoal	2421	22	0.0024	-24.3	1	0.99	274.02	770574	148679	1910

Tab. 1 ^{14}C samples cited in the text. 1. High Plateau Drauscha (Bivio); 2. Abri Murtèr (Bivio); 3. Val Faller, Abri III (Mulegns); 4. Smelting place, Barscheinz I (Bivio) (charts: I. Hajdas, R. Turck)

locations in the short summer months. This would have allowed them to work efficiently with the smelting sites and resources. The permanent settlement, as it is found in the lower valley at 1300–1400 m, seems unlikely in the upper valley over 1700 m.

Temporal and Econometric Patterns

The temporal reconstruction of the mining activities is the main focus of the current research project. Material for absolute dating was gathered through field surveys, test pits and probes, and larger excavations. The preservation of charcoal in prehistoric smelting contexts often allows dendrochronological dating. Additionally, old data must be questioned, recalibrated, or remeasured.[47]

47 Rageth 1986; Wyss 1993, summarised in Schaer 2003.

^{14}C data yields absolute dates for mines and smelting sites between the Middle Bronze Age and the Middle Ages.

Copper smelting in the region seems to have reached its peak in the (late) 7th century BC, based on the fact that smelting activity was concentrated in the Iron Age. However, a phase of small-scale production in the Bronze Age can be assumed, as the mining activity on the Ochsenalp dates to the 11th century BC.[48] Some charcoal from test pits and drilling samples also yielded Bronze Age ^{14}C dates, especially for the lower valley. It is possible that the old wood effect may influence these results.

The smelting sites Gruba I and Val Faller Plaz excavated stratigraphically, and the mines in Vals and Cotschens have been dendrochronologically dated to the Early Iron Age.[49]

The current state of research does not allow any conjecture about the extent of mining and copper production. It can be assumed that the amount of copper produced during the Bronze Age in this area was much smaller than in the southern and eastern Alpine regions.

Technological Knowledge and Transfer Techniques

The explicit transfer of technology, for example, from regions further to the east, has not been determined thus far. Prospectors and miners could have reached the area via the Engadin and the Inn Valley to the east, Vinschgau to the southeast, and Maloja Pass or the Bergell and Avers Valleys to the southwest.

The mining gallery at Vals and Grube 1 at Cotschens confirm the use of fire-setting in Iron Age underground mining.[50] There is plentiful archaeological evidence for the use of this technique in the eastern Alpine mining regions of the Bronze Age.

Open-pit mining for ores is also likely but difficult to confirm archaeologically. A pit at Gruba II is currently being researched and may be of prehistoric origin.[51]

Stone tools in the main heap at Cotschens indicate ore beneficiation in the immediate vicinity of the mines.[52]

To date, there is no clear archaeological evidence in the Oberhalbstein of ore beneficiation using mechanical techniques (possibly involving water), which may be due to the limited extent of the excavations to this point.

There are apparent differences in the organisation and application of smelting processes compared with other mining areas. The smelting sites differ significantly from those in the Mitterberg and Inn Valley regions.[53] This influences the reconstruction of the smelting process.[54] While slag sand and tools are found at smelting sites further to the east,[55] their absence here is striking. The mass of clay tuyère fragments found in Oberhalbstein[56] suggests that the smelting ovens in this area were far more elaborately ventilated than those in the Eisenerzer Ramsau, the Inn Valley or the Trentino, where only a few examples of tuyère fragments have been found.[57]

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48 Oberhänsli et al. 2019.
49 Oberhänsli et al. 2019.
50 Reitmaier-Naef et al. 2015, 41–44; Reitmaier-Naef et al. 2015, 47–48; Reitmaier-Naef et al. 2020.
51 Reitmaier Naef et al. 2015, 44–45; Turck et al. 2018.
52 Reitmaier-Naef et al. 2020.
53 Turck 2019.
54 Reitmaier-Naef 2019.
55 Tomedi et al. 2013, 62.
56 Nüssli 2018; Nüssli 2019.
57 Klemm 2004, fig. 11.1–5; Cierny 2008, tab. 1, 11; Tomedi et al. 2013, fig. 10.

Exchange of Copper

It is currently not possible to say anything about the intended use of Oberhalbsteiner copper or the significance of the Oberhalbstein Valley as a copper supplier, as no research has been carried out on these questions to date.

A comparison of recently published ^{14}C data from the early burials in Singen[58] to early dates from Savognin-Padnal[59] rules out contemporaneous development. The earliest evidence of metallurgical activities in the Oberhalbstein is several hundred years younger than the copper from Singen. Additionally, the Singen copper consists of fahlore, which does not occur in the Oberhalbstein.[60] The Oberhalbstein mining region can thus be ruled out as a potential source of the Singen copper.[61]

Valentin Rychner and Niklaus Kläntschi's study[62] of mostly Late Bronze Age artefacts in Switzerland suggests the use of differing types of copper. The question remains whether ores from the Oberhalbstein were circulated in the Bronze Age and how this developed in the Iron Age. Future research on secondary metallurgy (alloying, casting, distribution of objects) will focus more on these issues. Walter Fasnacht's suggestion that Early Bronze Age copper is evidence of fahlore copper and bronze imports into the valley[63] must also be reviewed: current comparative studies from the eastern Alpine region indicate that fahlore was dominant in the Early Bronze Age, while chalcopyrite gained importance in later periods.[64]

Copper exchange networks were likely in existence in the Iron Age. Exchange to the south could have taken place via the Bergell Valley to Tessin. To the north, the Oberhalbstein connects to the Hinterrhein Valley, through which the Lake Constance region is easily accessible via the northern Bündnerland and Sankt Gallen. The settlement at Montlinger Berg (Oberriet SG) could have functioned as a market centre in the Alpine Rhine Valley.[65]

To the south, there are many settlements that may have some connection with copper from the Oberhalbstein, such as Arbedo (TI) or Giubiasco (TI), Castaneda (GR) or settlements in the Lower Engadin (GR).[66] To the north, Early Iron Age settlements such as Tamins (GR)[67] and Chur Markthallenplatz (GR)[68] are contemporary with the mining activities in the Oberhalbstein.

Further research will allow these suppositions to be investigated based on the characterisation of the copper produced in the Oberhalbstein.

Social Aspects

The lack of reliable Iron Age settlements and detailed agricultural and historical environmental data means there are more questions than answers about the social organisation of copper mining and its economic significance in the Oberhalbstein Valley and further afield.

One important aspect is the interrelationship between primary, subsistence economy activities such as agriculture and animal husbandry and secondary economies such as resource use or Alpine trade routes.

58 Stockhammer et al. 2015.
59 Fasnacht 1999.
60 Dietrich 1972.
61 Krause 1988.
62 Rychner – Kläntschi 1995.
63 Fasnacht 1999.
64 Grutsch et al. 2019; Möslein – Pernicka 2019.
65 Steinhauser 1989.
66 Primas 1972; Tori et al. 2004; Pernet et al. 2006; Tori et al. 2010; Nagy 2012; Zürcher 1982.
67 Conradin 1978; Schmid-Sikimić 2002.
68 Rageth 1992.

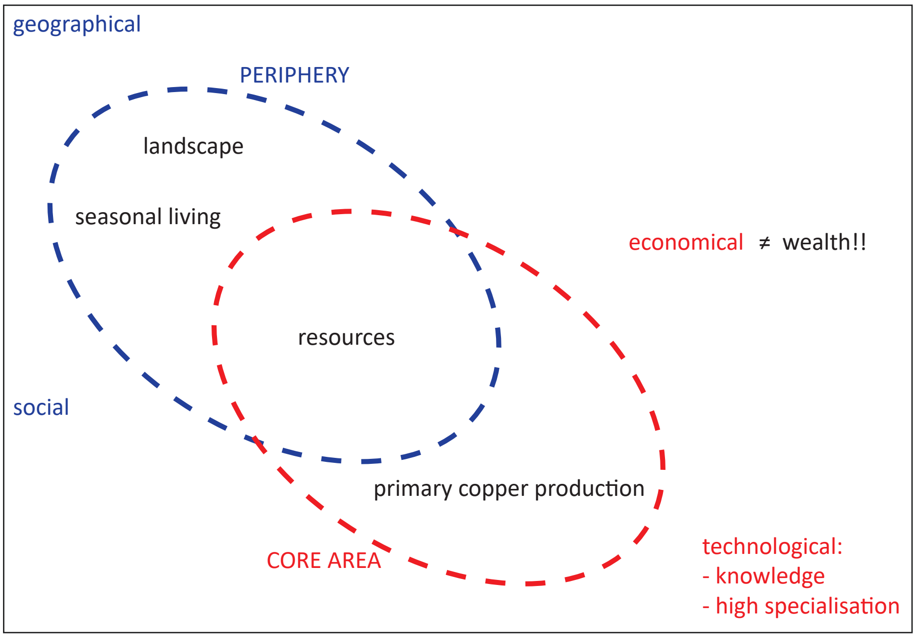

Fig. 7 Socio-economic significance of copper mining and smelting in the Oberhalbstein/Surses (graphics: R. Turck)

In one possible model of this interrelationship, a portion of the population undertakes mining and smelting work seasonally. Another model allows for specialised work, suggesting that a part of the population is occupied exclusively with copper production, thus relying on the rest of the population for their livelihood. A 'mobile' version of this model is also conceivable, in which specialised miners and smelters come to the Oberhalbstein Valley seasonally, for example, from the Inn and Rhine Valleys. The question of a systematic hierarchy can also be raised: was there a social division between the part of the population occupied with the subsistence economy and those involved in mining? If so, what form could this have taken?

It is certain that the activities associated with copper production – prospecting, mining, smelting, and transport – required the acquisition of specialised knowledge. This must have occurred in an open, social interaction space, as Philippe Della Casa and Biljana Schmid-Sikimić suggested for the contemporaneous transalpine trade network.[69]

Similar to the discussion of Bronze Age elites reliant on Alpine mining,[70] an approach to defining potential Early Iron Age Alpine mining hierarchies may be useful. Due to the lack of data needed for comprehensive and transdisciplinary analyses,[71] a definition can be suggested based on archaeological characteristics of social inequality.

Iron Age centres with exceptional architecture or burials with rich grave goods have not been found in the Oberhalbstein or in the valleys adjoining to the south and north. Exceptions are small settlements in Unterengadin[72] and the small burial ground of Tamins am Vorderrhein.[73]

There is archaeological evidence of contact between the north and south: to the north through Taminser pottery[74] and to the south through Laugen-Melaun pottery.[75] The pottery also contained

69 Della Casa 2002; Schmid-Sikimić 2002.
70 Kienlin – Stöllner 2009; Krause 2011; Bartelheim 2013.
71 Scholz et al. 2017.
72 Zürcher 1982.
73 Conradin 1978; Schmid-Sikimić 2002.
74 Rageth 1992; Roffler 2018.
75 Roffler 2018.

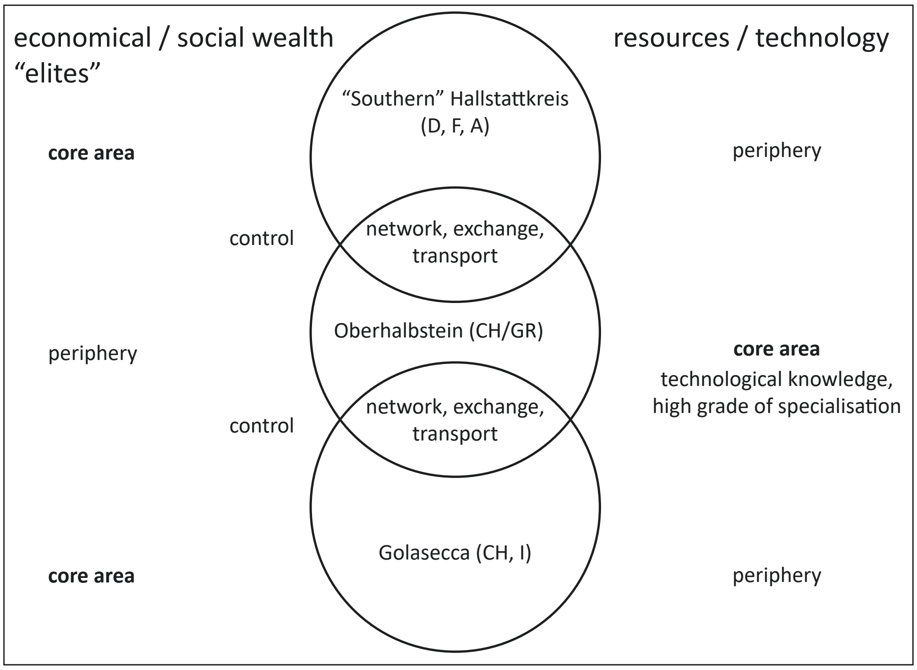

Fig. 8 Core Area vs Periphery Model, Early Iron Age primary copper production (graphics: R. Turck)

tempers stemming from southern rock formations.[76] Although there has been no analysis of Early Iron Age copper and bronze artefacts, it can be conjectured that the consumers of the raw material may have been the Golacecca groups south of the Alps and the Late Hallstatt groups to the north. The analysis of richly furnished burials and complex transport networks in southern Alpine regions[77] suggest a highly organised, stratified community. Elites and social stratification also characterise the Hallstatt culture.[78]

The socio-economic significance of the Oberhalbstein valley as a mining area is shown in Fig. 7. Although the primary reason for land use in the first half of the 2nd millennium BC was not based on the raw material copper, it seems to have become the 'second mover' during the Late Bronze Age, gaining importance in the Early Iron Age. The mining landscape lies in a geographical periphery. It's difficult to access, and the high elevation allows only seasonal work. At the same time, a technological, highly specialised 'Core Area' emerged, where specialised knowledge around ores, mining, beneficiation and smelting, and associated tasks such as procuring wood and food for the workers, was acquired and practised. However, archaeological evidence from the area suggests that these specialists were not privileged economically. There are no indications of social elites in the immediate vicinity of the mining areas. Potential consumers who profit from copper as a resource and control the copper network seem to be found in the distant regions to the north and south of the Alps, in the Hallstatt and Golasecca groups (Fig. 8).

Summary

This paper assesses the social impact of local mining activities in the Early Iron Age in the Oberhalbstein Valley, using recent research on mines and smelting sites, as well as a re-evaluation of the metal-age settlement landscape in the Oberhalbstein, which takes into account the accessibility

[76] Nüssli 2019.
[77] Schmid-Sikimić 2002, 217–237; De Marinis 2007.
[78] Veit 2000; Verger 2006.

of the raw materials in their peripheral, high Alpine location. In the geographical periphery of the high Alpine region, a technological centre of primary metallurgy was established around local raw materials. Specialised knowledge and craftsmanship were concentrated at an elevation between 1300 and 2500 m. However, there is no archaeological evidence of local elites or elites in neighbouring valleys. Climatic conditions only allowed settlement in the lower valley.

Archaeological finds from this period are rare and poorly preserved compared to Bronze Age artefacts. This may be due to taphonomic processes and possibly because mining activities were carried out seasonally in the valley. Some evidence of this was found in campsites in rock shelters at elevations over 1800 m.

The metallurgical network must have been organised from the centres north and south of the Alps. Here, in the Hallstatt culture and the Golasecca groups, consumers of copper and bronze objects may be found, as these regions have elites or social 'core areas'. The knowledge and craftsmanship associated with primary metallurgy in the Alpine region did not result in higher social status in Early Iron Age society.

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Prehistoric Copper Production in the Fahlore Mining District Schwaz-Brixlegg: Transfer and Development of Technologies

Markus Staudt[1] – *Gert Goldenberg*[2]

Abstract: This article deals with the 'chaîne opératoire' of prehistoric copper production in the mining district of Schwaz-Brixlegg in the Lower Inn Valley, North Tyrol, Austria. All steps are briefly discussed, from the extraction of raw materials, ore processing and smelting to the finished metal and its dissemination in the region and beyond. In addition to the consideration of older findings, the results of the tri-national research project, 'Prehistoric copper production in the Eastern and Central Alps – technical, social and economic dynamics in space and time', funded by the Austrian Science Fund (FWF), are also included.[3] The Austrian subproject carried out at the University of Innsbruck focused on the Late Bronze Age to Early Iron Age copper production from fahlores from the Schwaz-Brixlegg ore deposits and on the geochemical characterisation of prehistoric copper and bronze artefacts.[4] Combining the results of archaeological investigations in the field with material analyses, conclusions can be drawn about the beginning, duration and intensity of mining periods as well as their economic significance.

Keywords: Copper mining, Late Bronze Age, Early Iron Age, fahlore, chaîne opératoire, dendrochronology, smelting site, slag beneficiation

Research Questions and Research Concepts for Early Copper Extraction in the Alpine Region

The research centre HiMAT (History of Mining Activities in the Tyrol and Adjacent Areas – Impact on Environment and Human Societies), established at the University of Innsbruck in 2007, is investigating the mining history of Tyrol and its neighbouring regions within the framework of interdisciplinary studies. The research centre started with a special research programme (SFB HiMAT) funded by the Austrian Science Fund (FWF) from 2007 to 2012.[5] Meanwhile, manifold and complex results are available from various smaller and larger research projects, which impressively prove a very extensive and multi-phase copper ore mining and metal production in the prehistory of North Tyrol.[6]

With regard to early copper mining and metal production, some of the most important research questions are as follows:

- Which copper ore deposits in the Alpine region were used in prehistory (raw material sources, traces of mining, ore processing, smelting, etc.)?
- Which technological, economic and social developments connected to mining activities can be reconstructed (production chain, infrastructure, supply, working and living conditions of the mining society, added value, trade)?

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3 I 1670-G19, 2015–2018, trinational DACH-project, funded by the FWF, the DFG and the SNF.
4 Staudt et al. 2019a; Staudt et al. 2019b; Grutsch et al. 2019.
5 F 31-G02, project part F 3106, 2007–2012.
6 Projects funded by the Tiroler Wissenschaftsförderung, the Austrian Academy of Sciences, the University of Innsbruck and the Federal Monuments Office of Austria (BDA).

- How can mining activities be dated (beginning, duration, and end of mining activities, as well as high-resolution dating)?
- How can the relationship between raw materials and finished products be established (provenience studies for the reconstruction of trade routes, significance of Alpine copper for the prehistoric European market)?
- What effects did copper ore mining and extractive metallurgy have on the early society and the environment (up to the present day)?

In order to find answers to these questions and to understand and reconstruct the developments in early mining, systematic field prospections and archaeological excavations have been undertaken. The documented findings provide information about the individual production steps from mining to ore processing and smelting, the infrastructure in the mining districts and the working and living conditions of the miners' communities. By integrating numerous scientific and engineering disciplines, it is possible to investigate special aspects on the basis of the material promoted by the archaeological investigations, and as a result decisively expands our knowledge on this special subject. With the interdisciplinary approach, the complex of early copper production provides valuable source material for the reconstruction of the technical, economic and social history on a local, regional and supra-regional scale.

The Change of Copper Types during Prehistoric Periods

Evidence of a first copper ore mining boom in the Early Bronze Age in North Tyrol (Lower Inn Valley) could be indirectly provided from settlement sites like Buchberg (Wiesing),[7] Mariahilfbergl (Brixlegg),[8] Tischoferhöhle (Ebbs)[9] and Kiechlberg (Thaur).[10] These sites yielded metallurgical remains of copper production based on local fahlores with simple smelting techniques (slags and tuyères, crucible smelting with blowpipes). During this period, 'fahlore copper' was widely spread over central Europe, as it is indicated by geochemical analysis of copper and bronze artefacts (trace element characteristic of fahlore copper, Sb, As, Ag …).[11] Traces of Early Bronze Age fahlore mining, however, are still a desideratum in the Schwaz-Brixlegg mining district due to the massive extraction activities in younger periods (Late Bronze Age, Early Iron Age, Medieval and Modern times).

In 2018 and 2019, the excavation company TALPA carried out a large-scale archaeological excavation at Kundl-Wimpissinger.[12] Early Bronze Age features[13] – a tiny battery of four pit-shaped furnaces which are directly linked to a larger roasting hearth[14] – suggest smelting activities with sulfidic fahlores. The relatively small size of these furnaces would fit well with the dimension of the well-known and widespread homogeneous plano-convex 'casting cakes',[15] which are considered to have played an important role in the distribution of raw copper from the Alps.[16] There seems to be further evidence of Early Bronze Age copper production from the Kropfsberg castle hill.[17]

7 Martinek – Sydow 2004.
8 Huijsmans – Krauß 2015.
9 Kneußl 1969.
10 Töchterle 2015.
11 Junk et al. 2001.
12 Bader 2020; Bader 2021.
13 An interdisciplinary research project at the University of Innsbruck (DOC-team, funded by the Austrian Academy of Sciences) will provide new insights into this site: 'Kupfer und Eisen im 1. Jahrtausend v. Chr. Montanarchäologische Untersuchungen zur Metallverarbeitung und Wirtschaftsstruktur eines Werkareals im Unterinntal'. ÖAW DOC-team, 2021–2024. Project leader: Peter Trebsche.
14 Staudt et al. 2021.
15 Modl 2010, 128; Lutz 2016, 339; Lutz et al. 2019b; Modl 2019.
16 Lutz et al. 2019a, 323.
17 Staudt – Trebsche in press.

From approx. the 17th century BC onwards, a new type of copper captured the metal market of the Bronze Age in central Europe. It is characterised by a relatively high level of purity with a low content of trace elements and can thus be distinguished geochemically from fahlore copper. Research has identified the mining region at Mitterberg near Bischofshofen in the province of Salzburg not only as one of the main sources of this new type of copper but also as the starting point of the systematic exploitation of chalcopyrite ores ($CuFeS_2$) in the Eastern Alps.[18]

The spectacular dimensions of the Bronze Age Mitterberg copper production become manifest in the extensive pit fields and processing areas above ground, as well as in impressive underground traces reaching a depth of up to 200 m. A large number of around 200 localised smelting sites in the wider vicinity of the mining relics confirms the extraordinary intensity of mining.[19] After the large-scale production in the Mitterberg region with a focus on the 15th and 14th centuries BC, further mining districts with similar ore deposits were able to establish themselves over time.[20] The fact that mining activities in the Kitzbühel Alps are concentrated in the 13th century BC, according to well-dated archaeological sites,[21] is of particular interest for the dynamics of metal production in space and time. A comparison of the archaeological features and findings clearly shows that proven technologies from the Mitterberg district concerning mining, ore processing and smelting were adopted by the districts in the Kitzbühel Alps, indicating a systematic transfer of knowledge and technology from east to west during the later phase of the Middle Bronze Age and the beginning of the Late Bronze Age.[22]

A significant turning point in East Alpine copper production took place in the 12th century BC. The fahlore deposits of Schwaz-Brixlegg in the Lower Inn Valley, which had previously been forgotten for several centuries, regained outstanding importance. The reasons for this development are probably of an economic nature but unknown in detail until now. According to archaeological findings and dating, fahlore mining has experienced a renaissance since the 12th century BC with a second heyday, which is reflected in the large number of mining relics from this epoch that are still preserved today. Also, in the analyses of copper and bronze artefacts from this period, the increasing use of fahlore copper can be seen in the trace element contents of antimony, arsenic and silver.[23] Since the 1990s and especially in the frame of the RC HiMAT research projects, extensive and sometimes spectacular features have been uncovered and documented, which provide an insight into the Late Bronze Age to Early Iron Age production chain of copper extraction (mining, ore processing and smelting).

Prehistoric Mines

The first proof of prehistoric fahlore mining in the area Schwaz-Brixlegg was published by Peter Gstrein.[24] In the 1990s, the first research projects with systematic archaeological prospections and excavations, conducted by the University of Innsbruck and funded by the FWF,[25] provided numerous further proofs in the field.[26] During the same period, mineral collector and amateur mining archaeologist Hanspeter Schrattenthaler was able to explore an extensive number of prehistoric sites during his surveys.[27] The archaeological research on prehistoric fahlore mining and

18 Lutz – Pernicka 2013; Pernicka et al. 2016; Stöllner 2015.
19 Stöllner 2011; Thomas 2018.
20 Stöllner et al. 2016.
21 Preuschen – Pittioni 1956; Pichler et al. 2009; Koch Waldner – Klaunzer 2015; Neuninger et al. 1970.
22 Goldenberg et al. 2019; Staudt et al. 2022; Staudt et al. 2024.
23 Lutz – Pernicka 2013; Rychner – Kläntschi 1995; Grutsch et al. 2019.
24 Gstrein 1981.
25 P 08738 und P 12049-GEO.
26 Goldenberg 1998; Goldenberg – Rieser 2004.
27 Rieser – Schrattenthaler 1998/1999; Rieser – Schrattenthaler 2002; Rieser – Schrattenthaler 2004.

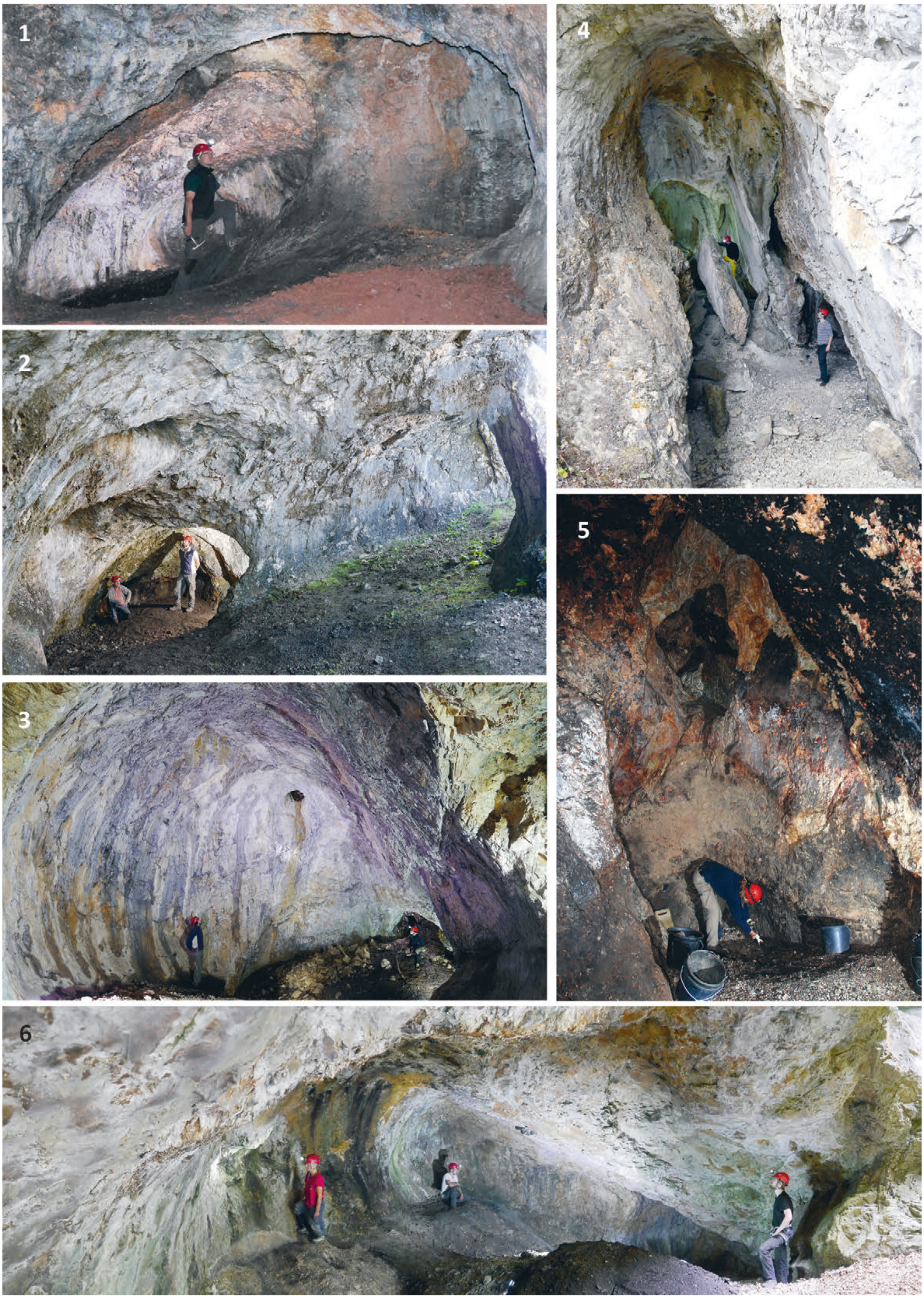

Fig. 1 Dendrochronologically dated mines in the fahlore district Schwaz-Brixlegg. 1. Mauk B; 2. Gratlspitz 1; 3. Moosschrofen East; 4. Schönbieglerbau; 5. Mauk E; 6. Bauernzeche lower mine (photos: M. Staudt, G. Goldenberg, M. Scherer-Windisch)

extractive metallurgy was expanded and intensified beginning in 2007 and continuing within the framework of the special research programme (SFB HiMAT[28])[29] and the succeeding tri-national DACH project 'Prehistoric copper production in the Eastern and Central Alps – technical, social and economic dynamics in space and time' (Austrian project part funded by the FWF, I1670-G19, 2015–2018).[30] In the synopsis of all results from site surveys and archaeological excavations below and above ground, the fahlore mining district of Schwaz-Brixlegg presents itself as an important and large-scale supra-regional copper production centre between 1200 and 650 BC.[31]

The excavations from 2015 to 2018 concentrated on underground mining sites, pit fields, processing sites and one smelting site.

Plans and three-dimensional models[32] were generated for numerous mines that have been investigated. Archaeological excavations took place in the backfill material remaining inside the mines and yielded valuable information on the stratigraphy and their dating.[33] The artefacts (stone tools, bone tools, ceramic fragments, lightning sticks, food waste in the form of animal bones[34], charcoal remains from fire-setting and fireplaces) not only provide information about the technologies used in mining, but they also give insight into the working and living conditions of the mining communities (infrastructure, supply, way of life, eating habits, etc.). In addition to numerous radiocarbon dates, dendrochronological analyses of wood and charcoal finds enable a high-resolution dating accurate to a year (logging years of timber) and thus can estimate periods of operation, driving rates and timber management.

Dome-shaped cavities in the fahlore bearing 'Schwazer Dolomit' are typical mining relics resulting from fire-setting. Such characteristic traces are still visible at many places in the Schwaz-Brixlegg mining district (Fig. 1). The method of fire-setting was preferably used in prehistoric times to mine the very hard dolomitic host rock. According to previous observations, mining seems to have been limited to a maximum depth of approx. 65 m, which can probably be attributed to ventilation reasons.[35] In some mines, ventilation shafts were laid in, which also worked out with the fire-setting technique. Nice examples that are still well preserved today can be seen at the Knappenkuchl (Kleinkogel), inside the Schönbieglerbau (Burgstall; Fig. 1.3) and in the underground of the Kropfsberg Castle.

By clarifying the stratigraphic sequence of the overlapping fire-set cupolas, it is possible to reconstruct the strategy of driving. For the specialists applying the fire-setting technique, it was possible to advance in every direction (upwards, forwards, sideward, downwards).[36] Crater-like structures in the Wilde Kirche (sub-district Kleinkogel) and in the Bauernzeche (sub-district Großkogel), resulting from a huge number of fire-setting operations represent the most impressive relics of this practice and show the dimensions in which mining was already carried out in prehistoric times. The scale of these mining cavities gives an idea of how great the motivation and need must have been for manpower as well as for materials such as wood, stone tools, food, etc.

So far, within the framework of the research activities of the RC HiMAT, it has been possible to investigate and survey a total of 13 prehistoric mines.[37] Excavations were carried out where the remaining backfill material inside the mines promised good chances for the uncovering of stratigraphic sequences with datable finds. The excavation results in the Bauernzeche (upper mine;

28 Funded by the FWF, F 3106-G02, 2007–2012.
29 Goldenberg et al. 2012; Goldenberg 2013; Goldenberg 2015; Schibler et al. 2011.
30 Goldenberg et al. 2019; Staudt et al. 2019a; Staudt et al. 2019b; Grutsch et al. 2019.
31 Goldenberg et al. 2019, fig. 7.
32 Scherer-Windisch 2017; Brandner 2018; Staudt 2024.
33 Staudt et al. 2017; Staudt et al. 2018a; Staudt et al. 2019a.
34 Saliari et al. 2020.
35 Rieser – Schrattenthaler 2002, 32.
36 Scherer-Windisch 2017, Taf. 9; Ancel – Py 2008.
37 Mauk B & E (district Sommerau), Moosschrofen East & West (Zimmermoos), Gratlspitz 1–3 (Thierberg), Bauernzeche upper & lower mine (Großkogel), Knappenkuchl (Kleinkogel), Schönbieglerbau North & South (Burgstall), Gut Wetter Bau (Burgstall), Sagzeche (Palleiten) and Kropfsberg.

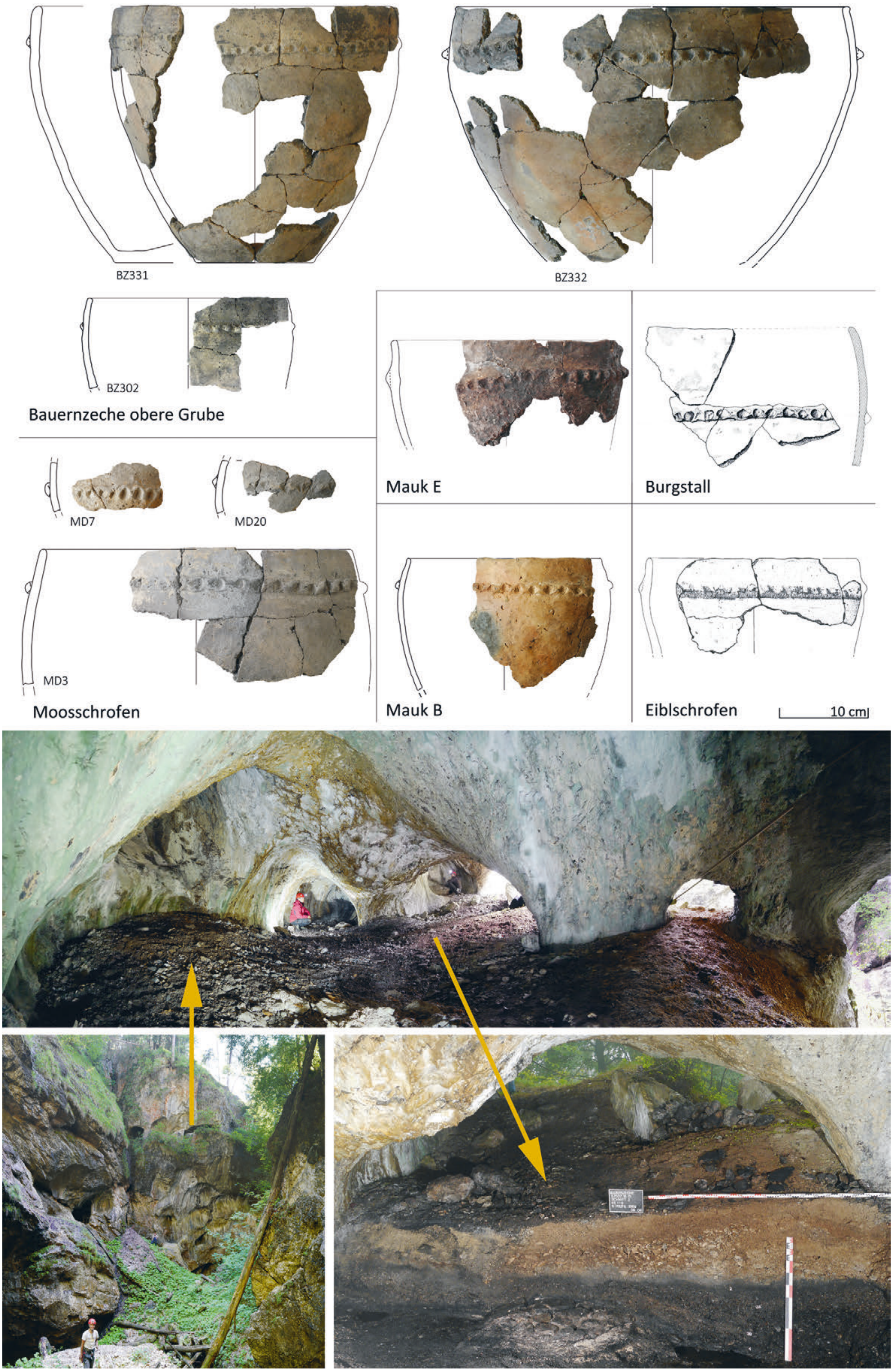

Fig. 2 Pottery from the miners' shelter inside the upper mine Bauernzeche (picture below) and comparable ceramic finds from Early Iron Age mines (graphics: M. Staudt, B. Rieser, H. Schrattenthaler, P. Gstrein)

Fig. 2, below) were quite spectacular, as the investigated mining cavity was used as a 'miners' shelter' contemporaneously with ongoing extraction activities nearby. Here, a multiphase fireplace at the base of an occupation layer up to 30 cm thick filled with waste material could be uncovered and documented underneath the backfill. The excavation supplied large quantities of pottery fragments (a total of approximately 33 kg) and animal bones (food waste, a total of approximately 6 kg) as well as stone tools and a few bones as well as antler tools.[38] The majority of the pottery dates chronologically into the time stage Ha C1 (possibly also Ha C2),[39] a period with very little archaeological evidence in Tyrol so far. Dendrochronological analyses on charcoal could indicate activities in the 7th century BC (youngest end year 665 BC).[40] Due to the unfavourable course of the ^{14}C calibration curve ('Hallstatt plateau'),[41] radiocarbon dating can only provide inaccurate data for this period. The pottery fragments recovered in the other investigated mines (Ivanuslauf, Moosschrofen, Mauk B, Mauk E, Eiblschrofen) show very comparable shapes and decorative elements (Fig. 2).[42] After evaluation of all of the dendrochronological data, these mines (Mauk B, Mauk E, Gratlspitz 1, Moosschrofen East, Bauernzeche lower mine, Schönbieglerbau North and South) can be dated essentially into the 8th century BC (Early Iron Age) with one exception. The mine Knappenkuchl (Kleinkogel, Fig. 7)[43] is the only underground mine dated to the Late Bronze Age, according to 14C analysis (12th/11th century BC).

In 2020, archaeological excavations at the Kropfsberg mine revealed evidence of Early Iron Age copper mining (7th century BC). The Romans later visited this site to perform ritual acts (sacrifices).[44] On the castle hill Kropfsberg, additional Hallstatt period settlement activities that are directly related to copper production from fahlores could be explored.[45] Due to the similarities in the pottery from the settlement and the Bauernzeche, it is assumed that the miners from the Bauernzeche had settled in the nearby Kropfsberg hill.

Prehistoric Mining Pits/Pit Fields

Besides the impressive and well-preserved prehistoric underground mines, numerous pit fields are also known from the Schwaz-Brixlegg mining district. Most of these structures are considered to be of prehistoric origin. This can be concluded after three excavations carried out at three different locations thus far.[46] The funnel-shaped or furrow-shaped structures are well recognisable in the terrain model (laser scan), as well as their strike direction. Expanded mining pit fields can be found in the sub-districts Sommerau, Weißer Schrofen, Rotenstein, Burgstall and Reither Kopf. Stone tools (hammer and crushing stones as well as anvil stones) are often found in slope cuts and during archaeological excavations connected to the pit fields. These stone tools are essentially assigned to the surface work of ore beneficiation (crushing and grinding) and are often accompanied by greenish animal bones (food waste) and ceramic fragments. In contrast, the prehistoric backfill layers below ground yielded only a few fragments of stone tools so far. The stone tools, therefore, are considered to have played only a minor role in driving and mining. Underground, they were probably used only to remove the rock slabs loosened by the effect of heat during fire-setting and for a first crushing of the mined rock.

38 Staudt et al. 2018a; Goldenberg et al. 2019; Staudt et al. 2019a.
39 Zetzmann 2019.
40 Kurt Nicolussi and Thomas Pichler carried out the dendrochronological analyses.
41 Staudt et al. 2019a, 126.
42 Goldenberg et al. 2019, fig. 6.
43 Goldenberg et al. 2019, fig. 7.
44 Staudt – Goldenberg 2022; Goldenberg et al. in press.
45 Staudt – Trebsche 2022; Staudt – Trebsche in press; Trebsche – Staudt in press.
46 Goldenberg 2013, 102–103; Goldenberg 2015, 154–156; Staudt et al. 2018b; Staudt et al. 2019a.

An indication of the use of bronze picks for mining in the Schwaz-Brixlegg district has so far only been provided by two individual finds, one fragment of a pick tip from the Gratlspitz and a Late Bronze Age socketed pick fragment with a horizontal strip from the pit field Weißer Schrofen.[47] As discussed above, fire-setting was the most important mining method performed in the dolomitic hostrock (Schwazer Dolomit) in prehistoric times. This fact may explain the very rare finds of metal tools. In contrast, finds of pick points or bronze socketed picks are much more frequent in the mining districts at the Mitterberg[48] and in the Kitzbühel Alps[49]. Here, the dominant chalcopyrite ores usually occur in softer rocks (e.g., phyllites), which are less or not at all suitable for extraction with fire-setting because of their inner structure. Nevertheless, the method of fire setting was applied to the hard and quartz-rich veins of the Mitterberg.[50] It is obvious that the choice of the mining technique – fire-setting or metal tools – was essentially dependent on the type of host rock and was, first of all, aimed at the highest possible efficiency and, thus, the profitability of the ore extraction.

The pits in the Burgstall, Weißer Schrofen, Rotenstein, Reither Kopf, and Sommerau mining sub-districts that have been investigated so far date back to the Late Bronze Age on the basis of radiocarbon analyses and/or ceramic finds. The most recent prehistoric mining activities took place in the second half of the 8th century BC. This can be shown by the results of dendrochronological analysis of charcoal remains (felling date of firewood) from fire-setting in the Early Iron Age mines. If one summarises all archaeological findings and a large number of absolute dates from mines, pit fields and ore beneficiation sites, it becomes evident that the copper production based on fahlores from the Schwaz-Brixlegg mining district lasted at least 550 years from the beginning of the 12th to the middle of the 7th century BC.

Prehistoric Smelting Sites

Until the Early Bronze Age, crucible smelting techniques were in use for copper production and performed in simple pit hearths. For this process, the necessary temperatures (in the range of 1200 to 1350°C) were relatively easy to achieve with blowpipes.[51] With this technology, mainly oxidic copper ores (malachite, azurite and others), as well as fahlores (also in combination), were processed in settlements in the Lower Inn Valley as well as in other Alpine regions. In the period from the late Early Bronze Age to the early Middle Bronze Age, the innovation of the 'shaft furnace process' took place in the Mitterberg mining districts, where chalcopyrite was the dominant copper ore occurring in large quantities. From this moment on, the eastern Alpine mining 'industry' experienced a fundamental change that was accompanied by further technological innovations in many areas of the production chain.

This change was mainly based on the possibility of processing the abundant chalcopyrite ores ($CuFeS_2$) with an important economic benefit, which previously was almost impossible to do with the older technology. The large-scale copper production from chalcopyrite requires systematic slagging of the iron content in the ore. With quartz as an additive (already abundant in the gangue in general), the iron could be separated from the valuable copper in the form of an iron silicate slag. For this multi-stage process, different 'early industrial-like' structures were set up in the mining districts. These include the characteristic 'roasting hearths' as well as 'low shaft furnaces', which in archaeological excavations frequently occur in the form of 'twin furnaces' or 'furnace batteries' (Fig. 3).[52] In the roasting hearths (Fig. 4), the sulphur

47 Goldenberg et al. 2019, 163, fig. 2.
48 Stöllner – Schwab 2009, 151–154; Thomas 2018, 225–223.
49 Goldenberg et al. 2019, fig. 2; Staudt et al. 2024.
50 Thomas 2018, 420–421.
51 Töchterle et al. 2013.
52 Goldenberg 2004; Koch Waldner – Klaunzer 2015.

content of the ore was partially removed by oxidation (SO_2) in open wood fires and the ore was thermally broken down and prepared for the smelting process. The smelting took place in low shaft furnaces and initially aimed at enriching the copper in the form of a 'copper matte'. The furnaces were run with charcoal and/or wood[53] along with the aid of tuyères and bellows. This process yielded the formation of iron silicate slags, which were deposited as waste material on slag heaps or – in younger periods – recycled by crushing, grinding and washing in order to recover a maximum of small inclusions of copper-bearing phases. The process of roasting and smelting had to be repeated several times to obtain an iron-free and copper-rich matte. Reports on traditional smelting techniques in Nepal, as well as our own experimental work, show that, in principle, the chalcopyrite ore can also be smelted first and then roasted with similar efficacy.

The general opinion that has been published for decades, that roasting is always the first step of extractive metallurgy (of sulfidic copper ores), may be relativised in future discussions. At least in the fahlore district, the last production step (transformation from matte to copper) probably took place at the smelting site.[54] The transformation of the copper matte into raw copper – was carried out.

The new combined process of multiple smelting and roasting has considerably increased the scope of production, as evidenced by countless slag heaps with a remarkable cubature in the mining areas of the Southern and Eastern Alps during the Middle and Late Bronze Age to the Early Iron Age.[55] The innovation in extractive metallurgy was successfully applied, further developed and improved, and the mining of chalcopyrite bearing ore deposits dominated the East Alpine mining industry for several centuries. From the 12th century BC onward, the technology was modified and adopted for the smelting of fahlores.

In the fahlore district of Schwaz-Brixlegg, only two Late Bronze Age smelting sites[56] could be localised so far, and they have been investigated extensively and in detail.[57] According to radiocarbon analyses and one dendrochronological analysis, both sites date into the Late Bronze Age (12th/11th century BC) and show typical structures such as multi-phase roasting hearths and furnace batteries. Thus, they correspond appropriately to the well-known smelting sites from the Eastern Alps (Mitterberg, Kitzbühel region and others) as well as from the Southern Alps (South Tyrol, Trentino), with very similar structures and features.

Four furnaces from the smelting site in Rotholz (Gem. Buch i. T.; Fig. 3, middle) and two from the Mauken Valley (Mauk A, Gem. Radfeld; Fig. 3, top) – all placed into glacial loam sediments – could be excavated and documented in detail. They show a rather longitudinal orientation and were probably about one metre high in origin, according to the documented stone collapse. The furnace constructions at Rotholz were built almost exclusively with blocks of reddish sandstone, which occur in the vicinity of the site. The bottoms of these furnaces were lined with flat stone slabs. The interior furnace walls were originally covered with clay during the operation. This is evidenced by numerous fragments of burned furnace clay at Rotholz and Mauk A, most of them showing one-sided scorification. It can be assumed that because the iron content of the local fahlores and the quartz content of the gangue is generally too low to form a self-fluxing melt, there was an addition of quartz (locally available in the form of quartz sandstone)[58] and probably iron minerals (like limonite, available from nearby deposits)[59]. Some

53 Hanning 2012; Hanning et al. 2015.

54 Staudt 2024.

55 Stöllner 2015; Trebsche 2015; Klemm 2015; Waldhart et al. 2021; Nothdurfter 1993; Koch Waldner et al. 2020; Cierny 2008; Silvestri et al. 2015; Bellintani – Silvestri 2021; Turck et al. 2014; Turck 2019; Naef 2015; Reitmaier-Naef et al. 2015; Reitmaier-Naef 2019; Reitmaier-Naef 2022.

56 Early Iron Age smelting activities have recently been documented on the Kropfsberg castle hill. Staudt – Trebsche in press.

57 Goldenberg et al. 2012; Goldenberg et al. 2019; Goldenberg 2013; Goldenberg 2015; Staudt et al. 2017b; Staudt et al. 2018b; Staudt et al. 2018c; Staudt et al. 2019b.

58 The presence of red sandstone is known to occur in the immediate vicinity of both smelting sites.

59 Pirkl 1961.

Fig. 3 Late Bronze Age furnaces from Mauk A (top) and Rotholz (below) (photos: G. Goldenberg, M. Staudt)

indications support these assumptions; however, they must be followed up through further investigations.

The roasting hearths, which could be uncovered next to the furnaces at both smelting sites, show very similar and characteristic features. They are usually around two metres long and one metre wide (Fig. 4), in general, multiphase and sometimes repositioned. In such cases, a younger roasting hearth was simply turned by 90 degrees (Fig. 4.3, 7) or displaced by half a metre (Fig. 4.1, 7). In Rotholz, 'Kellerjoch Gneiss' was the preferred stone material for the curbstones of the roasting hearths. The reuse of broken grindstones made of the same material could be observed in one of these constructions. Between the upright-orientated stones of the roasting hearths from Rotholz, a layer of slag sand (up to 5 cm thick) and laid stone slabs were regularly placed at the base of the hearths (Fig. 4.1, 3–6) and covered carefully with a layer of clay up to 10 cm thick, on which the roasting fires were ignited. As a result of multiple roasting processes with open wood fires, the originally yellowish-brown clay layer took on an intensive red colour (oxidising burning), which is characteristic of the excavated roasting hearths.

Fig. 4 Roasting hearths from Mauk A (1–2) and Rotholz (3–7) with the substructure construction made of flat stones and slag sand (1, 3–6) (photos: G. Goldenberg, M. Staudt)

Special constructions remain to level out the sloping terrain for the installation of the metallurgical units, which could be partly excavated and documented at both smelting sites Rotholz and Mauk A. A substructure in the form of a stone wall had either been dug into the loamy slope (Rotholz) or erected on the loamy soil (Mauk A).

Process Optimisation and Recycling

Since the Middle Bronze Age, wet-mechanical processes have been systematically applied to optimise the process of ore beneficiation. This is evidenced by the many ore washing installations ('sluice boxes') excavated on the Troiboden at Mitterberg,[60] as well as by the mighty ore processing dumps at the Kelchalm site near Kitzbühel[61], Jochberg[62] and at Götschen in the Brixen Valley (Brixental).[63] At the end of the Middle Bronze Age/beginning of the Late Bronze Age, a systematic crushing, grinding and washing process was also introduced for the beneficiation of slags. The aim of this innovation was to recover as much as possible of the copper-rich inclusions remaining in the smelting slag and feed them back into the process. Evidence of this systematic recycling of copper-bearing slags is documented in the form of extensive slag heaps, which consist predominantly of tiny crushed slag ('slag sand'). The separation of the metal-rich inclusions for the purpose of improving and optimising the metal output was carried out by wet-mechanical treatment (gravity separation with water, similar to gold washing). It can, therefore, be assumed that the positioning of the smelting sites was geared not only to the proximity to the ore deposits, topographical factors and wood resources but also to the availability of water (source areas, streamlets). Although most of the wet-mechanical processing work at the two investigated smelting sites in the Lower Inn Valley was concentrated on slags, subordinated remains of ore crushing, grinding, and subsequent washing could also be observed. In the case of Rotholz, a few finds of pure fahlore, which did not require any mechanical processing, indicate the potential of high-quality ores from nearby mines. A Late Bronze Age beneficiation site where only ore was exclusively processed could be excavated and documented in the upper part of the Mauken Valley at Schwarzenbergmoos.[64]

In the 1990s, well-preserved remains of a wooden structure that had been used for wet mechanical processing of the finely ground slag were revealed at the smelting site Mauk A in the Mauken Valley in the middle of a massive slag heap (Fig. 5.1, 3). The wooden planks of this 'sluice box' had been partly sealed with leftover textiles.[65] There was even a preserved wooden slat that had served originally to regulate the water flow. Dendrochronological investigations date this board after 1010 BC and are more likely to indicate younger smelting activities.[66] At the Late Bronze Age smelting site in Rotholz, the remains of two wooden washing troughs or sluice boxes (which were not as well preserved) could be documented, filled with fine-grained and strongly-baked slag sediments (Fig. 5.2, 4). The associated slag heap (slag sand) had been deposited directly next to these slag beneficiation structures.

On the smelting site Rotholz, eight circular trough-shaped pits, each about 50 cm in diameter and arranged in a row, were discovered during the excavation. These pits can probably also be associated with some wet processing of slag (Fig. 6.1–4), as indicated by a distinct content of 'slag sand' in the remaining sediment residues in two of these pits. These look quite similar in consistency to the slag sediments in the nearby washing troughs. One hypothesis that can be discussed is

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60 Stöllner 2015.
61 Koch Waldner – Klaunzer 2015.
62 Staudt et al. 2022.
63 Neuninger et al. 1970.
64 Goldenberg et al. 2012; Goldenberg 2013; Goldenberg 2015.
65 Grömer et al. 2017.
66 Nicolussi et al. 2015, 242.

Fig. 5 Wooden constructions (sluices) for slag beneficiation. 1, 3. Mauk A; 2, 4. Rotholz (photos: G. Goldenberg, M. Staudt)

that hot slag cakes were removed from the furnaces and directly quenched in these shallow water basins in order to break down the slag cake by thermal shock. In some of these pits, slight traces of an impact of heat in the form of thin marks of burned clay at the bottom were recognisable (Fig. 6.4), which might originate from the deposition of several hundred-degree hot slag cakes. The eight pits were positioned along a north-south oriented wall of stones that appeared to be associated somehow with the pits.

Because the documented features in Rotholz and the Mauken Valley (smelting site Mauk A) were quite similarly arranged, the question was raised whether such pits for slag processing like in Rotholz could also be expected at the smelting site Mauk A. For this reason, a small excavation campaign was conducted at the Mauk A site in 2019 to prove whether or not these special structures existed. For this purpose, a former and refilled excavation section '7' (2008) was enlarged at its northern end (section '11'), where an accumulation of stone blocks similar to what had been observed at the Rotholz smelting site could be documented in 2008. During the excavation work in 2019, it could be clarified that a stone substructure for a roasting hearth had been constructed there. In front of this stone wall, another shallow pit of the same size and shape as those from Rotholz could be uncovered. The content of the pit filling has not been analysed so far, but a similar function of the structure, like in Rotholz as part of the process chain, can be assumed. (Fig. 6.5–6). Approx. 80 cm west of this structure, a second pit filled with a large number of slag fragments (mainly from heterogeneous slag cakes) was revealed. This shallow pit ends on the top of a huge erratic block cached in the glacial loam, which was obviously used for the breaking of slag cakes and possibly iron minerals as well (Fig. 6.5). So, two of the assumed pit structures could be localised by a well-directed excavation, both of them connected obviously to the systematic processing of slags.

The striking similarity of both of the investigated fahlore smelting sites, with multiphase roasting hearths, furnace batteries, wooden sluice boxes for wet-mechanical slag beneficiation and the described pit structures, reflects 'early industrial' smelting sites with well-established infrastructure and with highly skilled experts in extractive metallurgy in the $12^{th}/11^{th}$ century BC.

While the copper-bearing inclusions separated from the slag by wet-mechanical concentration were recycled in a further smelting process, the remaining slag sand was used for further purposes. For example, it was used as a temper material in ceramic production. The reason for this may have been the favourable properties of the slag grains (sharp-edged, partly bubbled and heat-resistant)

Fig. 6 The stone wall and the shallow pits for slag beneficiation. 1–4. Rotholz; 5–6 Mauk A (photos: M. Staudt)

and the easy availability (abundant, available without any additional manufacturing effort). Since slag temper also occurs in grave ceramics,[67] the heat-conducting properties of slag, as assumed for cooking ceramics, cannot have been the only reason for its use. Slag-tempered ceramics are mainly known around the Bronze Age copper mining centres of Mitterberg, Kitzbühel/Jochberg and Schwaz/Brixlegg.[68] In the Lower Inn Valley, the phenomenon of slag-tempered ceramics can be found in the Early as well as Late Bronze Age and, more rarely, in Early Iron Age ceramics. Slag temper appears in domestic ceramics, burial pottery, and technical ceramics. So far, the most recent stratified slag-tempered ceramic object comes from the Iron Age necropolis in Kundl and dates into the Ha D2 period.[69]

67 Krismer et al. 2012; Lang 1998, 366.
68 Sölder 1987/1988, Abb. 13; Töchterle et al. 2013, fig. 12; Kluwe 2013, fig. 21; Tropper et al. 2019; Staudt 2021.
69 Lang 1998, 366.

Several so-called 'casting cakes' and fragments of those from the immediate vicinity of the Late Bronze Age smelting site in Rotholz suggest that raw copper (large and heterogeneous flat casting cakes) made from fahlore had been produced at least to some extent close to the smelting site. In the 1970s, the remains[70] of Late Bronze Age smelting structures, slags, stone tools, tuyères and blowpipe fragments were discovered at the gravel quarry Kundl-Wimpissinger in the Lower Inn Valley.[71] Metallurgical investigations of the slags and the accompanying slag-tempered ceramics indicated the processing of sulphidic copper ores (fahlores) of the Schwaz/Brixlegg type.[72]

Technology Transfer and Specialisation in the Different Mining Areas

With the beginning of the Late Bronze Age, rapid population growth in North Tyrol – especially in the Lower Inn Valley – (influx mainly from Bavaria and Salzburg) – is reflected in the occupancy of excavated cemeteries. From the necropolises in Volders[73] and Vomp,[74] findings of copper ore, raw copper pieces, slags and tools prove that the partly foreign population groups were involved in copper ore mining and smelting and carried out a metal-working trade. Lothar Sperber assigns the mining districts of Mitterberg, Kitzbühel/Jochberg and the Lower Inn Valley to the Late Bronze Age 'Copper Association' of Salzburg, North Tyrol and Upper Bavaria.[75] Over time, the skilled workers who had immigrated due to the rich copper deposits had brought along their technical knowledge of mining, ore processing and smelting from the east (Mitterberg) to the west (Schwaz/Brixlegg). This is reflected in the similarity of the processing equipment (stone tools, bronze tools like socketed picks, wooden tools), the techniques, and the constructions in use (washing constructions, roasting hearths, smelting furnaces) In this context it is noteworthy also to mention the occurrence of slag-tempered pottery, whose distribution is concentrated in the vicinity of the Mitterberg, Kitzbühel/Jochberg and Lower Inn Valley mining districts. This regional phenomenon indicates a continuous interexchange with close cultural and economic connections between the North Tyrolean and Salzburg mining regions. This applies to the entire period from the beginning of the Early Bronze Age to the decline and end of copper production in the Early Iron Age. It is striking that this phenomenon has not yet been described from the simultaneously operated mining and smelting landscapes in the areas of South Tyrol, Trentino and Grisons. In these regions, however, a well-distinguishable type of pottery can be found, attributed to the so-called 'Laugen-Melaun' Culture. The geographical distribution of the Laugen-Melaun ceramic only marginally overlaps with the distribution area of slag tempered ceramics.[76] The slag-tempered pottery thus implies a population strongly related to mining in a geographically limited area, with independent techniques and traditions concerning ceramic production. However, prehistoric religious rituals show a rather uniform picture of the Eastern Alps.[77]

The bone material from four investigated sites in the mining district of Schwaz-Brixlegg indicates a remarkable change in the diet of the mining communities in the Lower Inn Valley from the Late Bronze Age to the Early Iron Age, which could be explained by the transition from a pig to cattle dominated animal husbandry. Cattle, sheep, goats, and pigs, the most important species for the meat supply of the miners and smelters, were mostly delivered to the working camps as whole animals. In some cases, however, there is evidence for additional meat packages (especially ribs in Bauernzeche upper mine). According to the age and sex structures obtained from the

[70] Unfortunately, most of the metallurgical finds were lost.
[71] Lang 1998, 11, fig. 6.; Tomedi et al. 2013; Staudt – Tomedi 2015; Patzelt – Weber 2015.
[72] Lang 1998, 11; Tropper et al. 2019.
[73] Sperber 1992.
[74] Sölder 2015.
[75] Sperber 2004.
[76] Goldenberg et al. 2019, fig. 10.
[77] Töchterle et al. 2018.

bone material, it seems that the miners consumed meat of high quality. The butchery marks noted on the bones from the Schwaz-Brixlegg sites point towards professional and systematic slaughter techniques, as can be observed on other prehistoric mining sites in the Eastern Alps as well.[78]

Summary

During the Bronze Age of central Europe, economic systems geared to high efficiency and profitability in terms of resource recovery and resource management became more apparent. In this context, not only access to the primary resources (ore deposits, wood supply) and the continuous development and improvement of the metallurgical process chain played an important role, but also the systematic recycling of valueless waste products (slags). This step is indicated by the rework of copper-bearing slags and the secondary use of slag sand as construction material (roasting hearths) or temper material for ceramic production. The supra-regional networks of producers, traders, and consumers must be very well-organised and highly functional in terms of the extraction, processing, and distribution of metal. This efficiency-oriented economic system, in connection with a well-established mining industry, comes along with a differentiation and specialisation of the connected society. The studies on the subsistence economy in the mining landscapes of the Eastern Alps also show a stringent picture.

In the prehistoric copper mining regions of the Eastern (and Southern) Alps[79] – especially during the Middle and Late Bronze Ages and Early Iron Age – the same technologies were applied, as documented by the results of numerous archaeological excavations of furnace batteries and roasting hearths in very similar arrangements and dimensions. This also applies to the tool sets in use (for instance, stone tools for mechanical ore and slag processing). It has become evident that prehistoric Alpine mining societies cultivated a vivid exchange of technological knowledge, especially between the regions of today's Salzburg and North Tyrol. Differences, however, can be observed with regard to underground mining techniques, which primarily had to be adapted to the geology or, rather, to the quality of the host rock in which the ore mineralisation occurred. Whereas the use of metal tools (bronze picks) was suitable for working in relatively soft schistous rocks (Kitzbühel, Mitterberg), the fire-setting technique was more efficient in hard and compact rocks like dolomite (Schwaz-Brixlegg).

The widespread and common use of slag tempered ceramic from the Early Bronze Age to the end of the Early Iron Age again demonstrates a continuous contact and interexchange of specific knowledge and traditions for the region between the Lower Inn Valley in the west, the Kitzbühel Alps in the Middle and the Mitterberg in the east. As a result, this formed a larger supra-regional economic area specialised (amongst others) in metal production and trade. In contrast, another such economic area becomes apparent for the Late Bronze Age/Early Iron Age with the copper production regions of Trentino, South Tyrol and the Grisons (Oberhalbstein, CH). This is indicated by the geographical distribution of the typical so-called 'Laugen-Melaun' pottery, in which slag temper has not been detected so far.

The close connection of this 'copper association' is also reflected in the time-related use of the different types of Alpine copper ('chalcopyrite copper', 'fahlore copper', 'mixed copper'), which were widely merchandised especially towards central Europe north of the Alps. Within the DACH-project continuous and extensive prehistoric fahlore mining and copper production from the Late Bronze Age to the Early Iron Age (12th–7th century BC; Fig. 7) could be demonstrated for the mining area of Schwaz-Brixlegg in the Lower Inn Valley.

78 Schibler et al. 2011; Saliari et al. 2020.

79 Lower Austria, Styria, Mitterberg, Viehhofen, Kitzbühel-Jochberg, Brixental, Unterinntal, South Tyrol, Trentino, Oberhalbstein (CH).

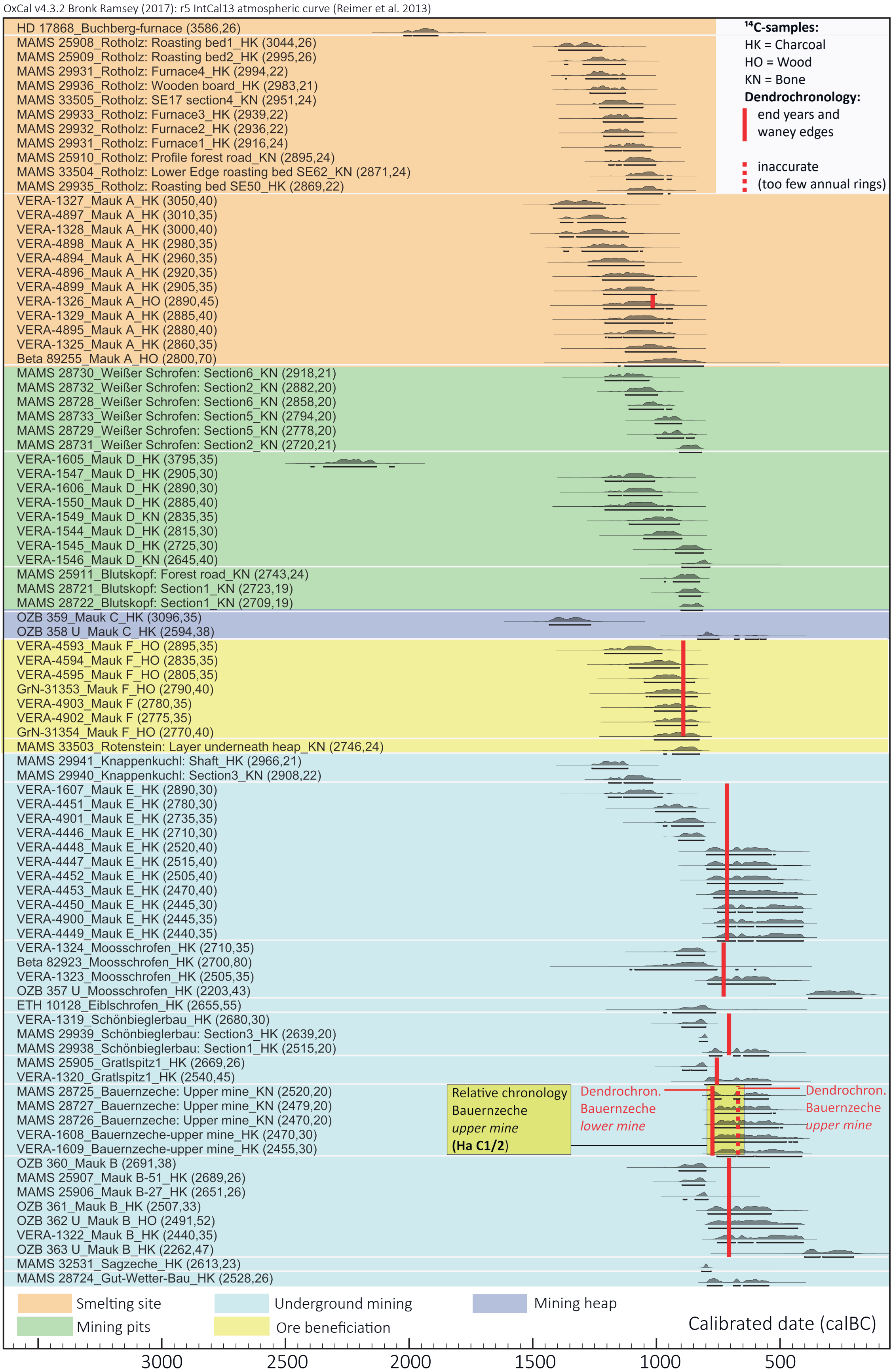

Fig. 7 Absolute and relative chronological dating from the mining district Schwaz-Brixlegg (graphics: M. Staudt)

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Bronze Age Copper Mining in the Vinschgau, South Tyrol: Discovery of a Mining Landscape in a Central Alpine Crossroad Area

Thomas Koch Waldner[1]

Abstract: At the foot of the Ortler Mountain, two settlements developed in the Middle Bronze Age at the chalcopyrite deposit of Stilfs in the Vinschgau (South Tyrol/Italy). It was the beginning of a long settlement history that was to last at least until the end of the Late Iron Age. The location of the sites, 'Kaschlin' and 'Weiberbödele', has given reason to believe that the prehistoric settlement traces, as well as the historic village of Stilfs, were connected to mining. Due to the discovery of prehistoric copper slags in the neighbouring municipality of Prad am Stilfserjoch, there are clear indications of Bronze Age mining in the Ortler Region. Based on ceramic finds of the Laugen-Melaun A period, the slag heap can be dated to the 13th/12th century BC. The discovery led to a research project carried out by the Deutsches Bergbau-Museum and funded by the Fritz Thyssen Foundation. In addition to its importance for metal extraction, the investigated region is an important point in terms of viability. In this area, the route to the Stilfser Joch (Lombardy), as well as to the Ofen Pass (Switzerland), branches off the path over the Reschen Pass (Danube–Adriatic Sea). The prehistoric finds in the upper Vinschgau bear witness to far-reaching contacts via these traffic routes. Some impressive examples of this are Eastern Mediterranean moulds and Eastern European spiral pendants found in a Middle Bronze Age house in the settlement at Ganglegg near Schluderns.[2]

Keywords: Copper smelting, Laugen-Melaun Culture, transfer of technology, slags, Bronze Age, Iron Age, settlements

Prehistoric Copper Mining and Smelting in South Tyrol – State of Research

South Tyrol lies between the largest known prehistoric copper mining regions of central Europe, Salzburg, North Tyrol and Trentino. The connection for the transfer of knowledge between the northern and southern Alpine mining areas had to be provided via this region. However, there are currently very few known traces from South Tyrol's prehistoric mining industry. Considering the various exploitable copper deposits in different parts of the country, the low number of mining archaeological sites is presumably due to a research gap. The recent discoveries in Vinschgau strongly support this assumption.

As early as 1940, the Viennese prehistorian Richard Pittioni, in his description of the state of research on the prehistory of South Tyrol, referred several times to the need for mining archaeological research in this region.[3] Until then, only a bronze axe from the copper mine of Prettau in the Ahrn Valley (Ahrntal), which was discovered in 1864, could be associated with prehistoric mining. The author of the first find report was certain that the discovery site of the bronze axe '… under the blasted ore rock…' ('…unter dem abgesprengten Erzgestein…') testifies to prehistoric underground mining in Prettau.[4] For Matthäus Much, a pioneer of mining archaeology, the axe was also the proof of prehistoric copper mining at Prettau.[5]

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[2] Steiner 2007, 140–149.
[3] Pittioni 1940.
[4] Schönherr 1864.
[5] Much 1879, 34.

It took more than a century for new evidence of prehistoric copper mining to be provided in the area of modern South Tyrol. In 1970, Viktor Welponer discovered the first Bronze Age copper smelting site in South Tyrol, near Reinswald in the Sarn Valley (Sarntal).[6] The high school teacher collected a variety of slags and wooden tools, including a wooden trough and various stone tools for crushing slag and/or ore. Lorenzo Dal Ri was the first archaeologist to examine the collected finds and the site itself.[7] He was aware of the results of the Austrian mining archaeological research at the Mitterberg,[8] Kitzbühel[9] as well as Trentino.[10] He recognised the close parallels to the smelting site in the Sarn Valley. Although this was an important discovery, no remains of the smelting facilities could be found at this site.

In addition to the discoveries near Reinswald, a smelting site on the side of the Eisack Valley (Eisacktal) in the same mountain range must be mentioned. At the location 'Kohlgruben' near Barbian, Erich Kofler from Bozen discovered the remains of prehistoric copper smelting activities. The archaeologist Dal Ri examined the surface finds. He describes an assortment of stone tools for the beneficiation of slag and/or copper ore,[11] and interestingly, slag sand was also documented at this site,[12] which clearly points to the recycling. According to this, the discovered stone tools were primarily used for slag processing. On the surface of the slag sand, pottery fragments were found that can be attributed to the period of Laugen-Melaun A or the 13th/12th century BC.[13] Unfortunately, no attempt was made to excavate the smelting facilities.

In the 1980s, another smelting site was discovered in South Tyrol. In the Etsch Valley (Etschtal) south of Bozen, at the site of Fennhals near Kurtatsch, well-preserved furnaces and a roasting bed were excavated.[14] For the first time, it was now possible to compare Bronze Age smelting facilities from South Tyrol with other regions. The structure of the Fennhals smelting site, as well as the smelting facilities, are comparable to the facilities in the Kitzbühel[15] and Mitterberg[16] regions. The present artefacts and findings of the smelting sites at Reinswald, Barbian and Kurtatsch show close parallels in copper processing technology between South, North and East Tyrol, Trentino and Salzburg.

The latest discovery of prehistoric copper production in South Tyrol is the slags from Prad am Stilfserjoch in Vinschgau, which the author identified in 2012 as Late Bronze Age copper slag.[17] This discovery eventually led to the current research. Since the beginning of the systematic research in 2019, three additional smelting sites have been localised in the area of Prad, Stilfs, and Laas (see Fig. 2).

The features from Milland[18] and Gufidaun[19] in the Eisack Valley from the Copper Age are significantly older than the sites described. The slag cakes (*Schlackenkuchen*) from Milland are among the oldest of this type in the Alps and beyond. The site was dated to the 3rd millennium BC. The use of sulfidic ores and smelting technologies from this period was detected only in a few

6 Dal Ri 1972a, 593.
7 Dal Ri 1972a; Dal Ri 1972b.
8 Zschocke – Preuschen 1932.
9 Preuschen – Pittioni 1937.
10 Preuschen 1968.
11 Dal Ri 1973, 237–238.
12 Dal Ri 1973, 237–239.
13 Dal Ri 1973, 238–239.
14 Nothdurfter – Hauser 1986.
15 Goldenberg 2004; Koch Waldner – Klaunzer 2015, 168–170; Koch Waldner 2017a, 230–405; Koch Waldner 2017b, 77–79.
16 Klose 1918, 27–33; Zschocke – Preuschen 1932, 73–107, pl. 3; Herdits – Löcker 2004.
17 See section 'Traces of Bronze Age copper production in the Vinschgau'.
18 Dal Ri et al. 2005; Tecchiati 2015.
19 Colpani et al. 2009.

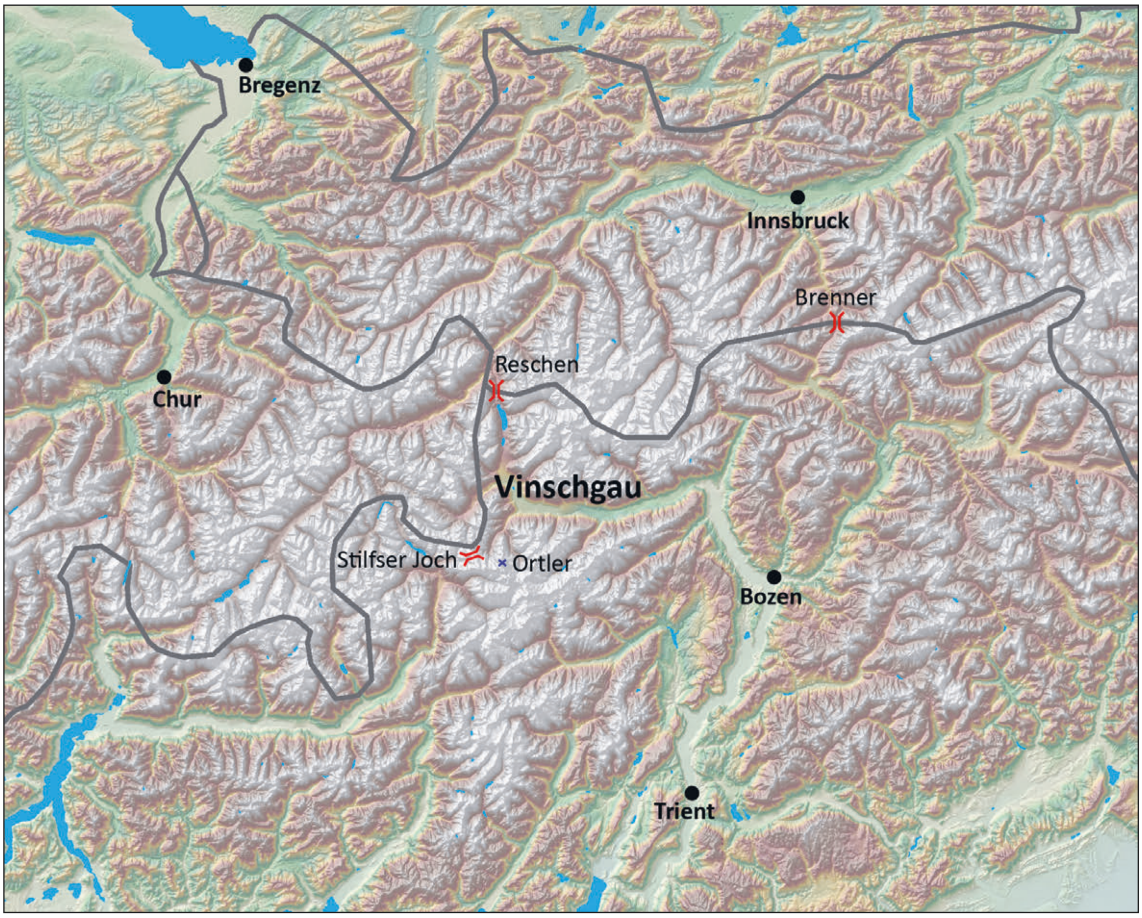

Fig. 1 Geographical location of the Vinschgau (graphics: T. Koch Waldner, map based on: EU-DEM Open TOPO DATA)

cases.[20] Regardless, there is a large chronological gap between these findings and the above-mentioned Late Bronze Age smelting sites in South Tyrol.

The Prehistoric Mining Landscape in the Vinschgau

Geographical and Geological Overview

The Vinschgau is situated on the upper reaches of the Etsch River and stretches from the Reschen Pass (1507 m a.s.l.) to the Schnals Valley (Schnalstal) (Fig. 1). In geographical terms, the valley basin of Nauders in North Tyrol, which is separated from the Inn Valley (Inntal) by the Finstermünz gorge, is also part of the Vinschgau. The geographical border in the east runs along the valley step at Töll (508 m a.s.l.) west of Meran. The mountains to the east and north of the Etsch River are part of the Ötztal Alps. To the west of the Etsch River lies the Sesvenna Group, separating the Vinschgau from the Lower Engadin in Graubünden (Switzerland). South of the Etsch are the Ortler Alps (also Ortler Group), with the Ortler (3905 m a.s.l.) being the highest mountain in South Tyrol. So far, the only evidence of prehistoric mining can be found in this mountain group.

20 Höppner et al. 2005; Merkl 2010.

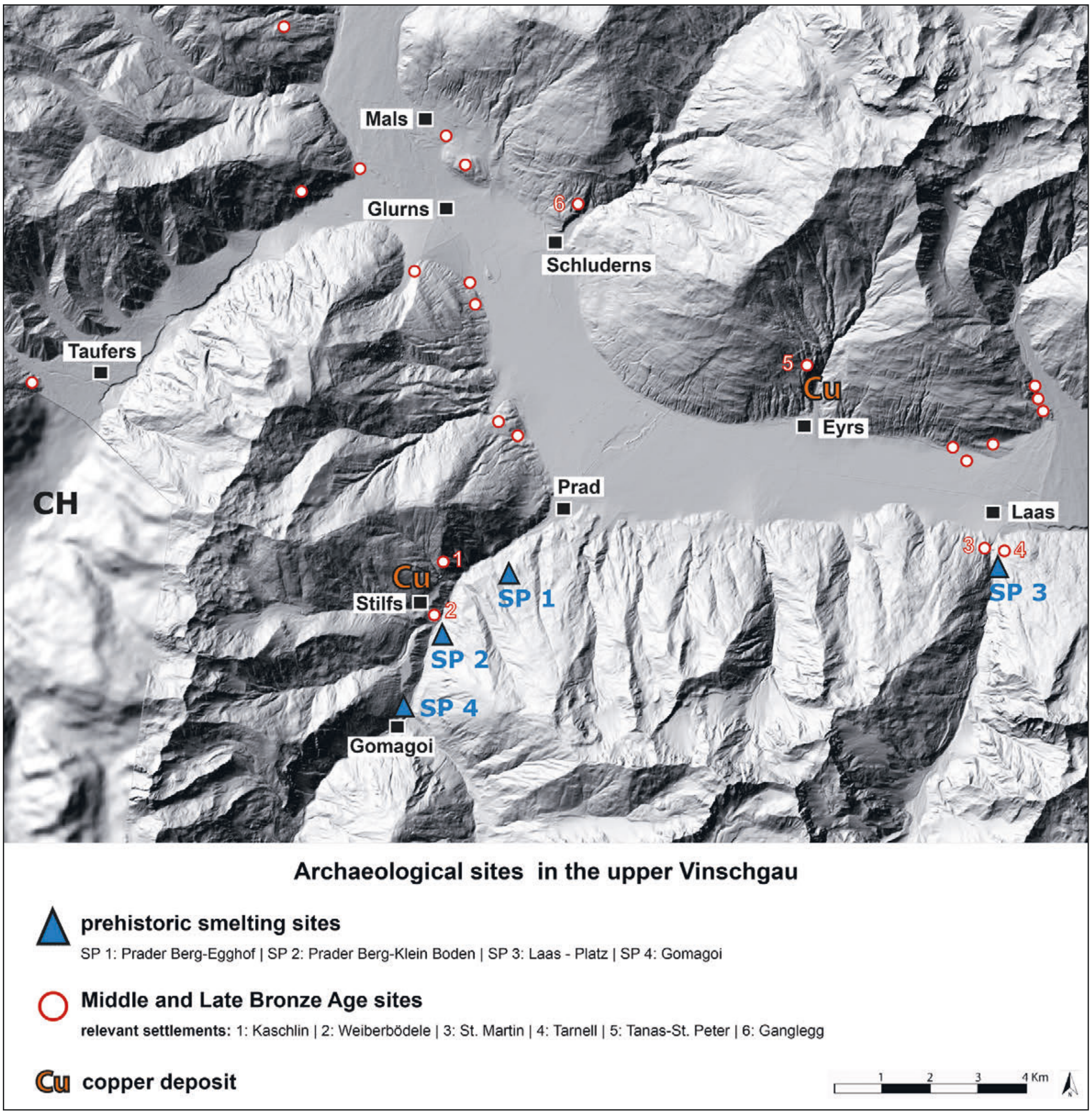

Fig. 2 Smelting sites and settlements of the second half of the 2nd millennium BC in the investigated area (graphics: T. Koch Waldner, map based on: Web-Gis-GeoBrowser, South Tyrol)

The central stock of the Ortler Alps consists mainly of dolomite and limestone rock on a crystalline base.[21] The dominant geological unit, however, is the Ortler-Campo nappe, in which metamorphic rocks – mica slate, quartz phyllites, orthogneiss, amphibolites and marbles – particularly occur. Ores or minerals mainly appear along tectonic lines.

Regarding copper mining in Stilfs, it is important to note that the mountain range in this area is characterised by a strongly folded, heterogeneous geological composition with a predominantly phyllitic slate.[22] The northwestern part of the Ortler area, as well as an area of the southern flank of the Ötztal Alps, is therefore considered an independent geological zone and is known as the Vinschgau shear zone.[23] The chalcopyrite deposits at Stilfs and Eyrs are located in this zone.

21 Keim et al. 2018.

22 Kind notice of Volkmar Mair and personal observations of the author during inspections as well as visiting the only still accessible mine gallery ('Arzloch') at Stilfs.

23 Keim et al. 2018.

Landscape and Settlement Development

The upper Vinschgau looks back on a long history of human occupation. The first sites were established in the Neolithic period.[24] In addition to several menhirs[25] and the settlement with the graveyard at Latsch,[26] the glacier mummy 'Ötzi' is particularly noteworthy among the finds of this period. Early Bronze Age sites can be found from the Sesvenna Group at Burgeis in the west to the Schnals Valley in the east.[27] Continuing from the Middle Bronze Age, the settlement pattern changed significantly. The number of sites and settlements doubled in quantity, suggesting a strong population increase in Vinschgau.

Stilfs and Prad

The first settlements in the area of the chalcopyrite deposit at Stilfs at the exit of the Sulden Valley (Suldental) were established during the Middle Bronze Age. In the immediate vicinity of this copper deposit, two hilltop settlements – 'Kaschlin' (Figs. 2–3, no. 1) and 'Weiberbödele' (Figs. 2–3, no. 2) – were founded in BA C. On the basis of the stray finds,[28] the larger, unexcavated settlement of 'Kaschlin'[29] (1400 m a.s.l.) can be dated from the Middle Bronze Age to the end of the Iron Age or from the 15th to the 1st century BC. Without closer archaeological investigation, it cannot be determined whether or notthe settlement was continuously inhabited during this long period. Most of the finds can be attributed to the Laugen-Melaun Culture or the Late Bronze Age and Early Iron Age (BA D/Ha A–Ha D). The site occupies a special position from both a mining archaeological perspective and a transport geographical point of view. The settlement area lies directly on a traffic route used since prehistoric times. The path leads from Agums (920 m a.s.l.) near Prad via Stilfs (1300 m a.s.l.) to the Stilfser Joch (2757 m a.s.l.). This pass connects the Vinschgau with the Valtellina (Veltlin), over which the Western Alps and northwestern Italy can be reached. With regard to prehistoric copper mining, the Stilfser Joch path, which rises only slightly, represents the fastest and safest access from the main valley of Vinschgau to the copper deposit at Stilfs. The Sulden Valley also offers a way to approach the deposit. When following the Suldenbach from Prad (915 m a.s.l.) upstream to Stilfserbrücke (1100 m a.s.l.), one reaches the foot of the mountain at Stilfs. Despite partially steep gradients and the danger of flooding, evidence of archaeological traces on the 'Weiberbödele' (1200 m a.s.l.) can be an indication that this path was also used. The site is situated on a hill 100 m above the valley bottom near Stilfserbrücke and has to be passed in order to access the copper deposit. The stray finds from the 'Weiberbödele'[30] reveal a similar picture to the settlement on 'Kaschlin'. Here, too, the beginning of human activities can be dated to the Middle Bronze Age, while most of the finds originate from the Late Bronze Age.

In addition to the prehistoric settlements near Stilfs, some stray finds should be emphasised, which show human activity in the entire area along the Sulden and Trafoi Valleys. These include a Late Bronze Age bronze axe (BA D)[31] from the Trafoi River and an Early Iron Age bronze axe (Ha C) from Stilfs.[32] The Late Bronze Age (BA D/Ha A) lance head[33] from the Prader Berg on the opposite side of the valley is lost today. Bronze Age pottery finds were discovered outside of

24 Steiner 2007, 25–27.
25 Pedrotti – Steiner 2014.
26 Steiner 2008.
27 Steiner 2007, 27–29.
28 Lunz 1997, 70–75.
29 Pardeller 1935; Alberti 1997; Steiner 2007, 136–207.
30 Lunz 1997, 70 no. 1–13.
31 Lunz 1997, 77 no. 2; Steiner 2007, 508 pl. 106 no. 3.
32 Lunz 1997, 77 no. 4; Steiner 2007, 508 pl. 106 no. 5.
33 Lunz 1997, 77 no. 3; Steiner 2007, 508 pl. 106, no. 4; Bruno 2012, 333.

Fig. 3 Stilfs with the prehistoric settlement sites at 'Kaschlin' (1) and 'Weiberbödele' (2) (photo: T. Koch Waldner)

'Kaschlin', and 'Weiberbödele' suggested that there were agricultural farmsteads in the vicinity of the hilltop settlements. These farms likely provided subsistence for the inhabitants of the exposed settlements.

Laas

A situation similar to that at Stilfs occurs at the exit of the Laas Valley (Laaser Tal). Here, as well, two settlements – 'Tarnell' (Fig. 2, no. 4) and 'St. Martin' (Fig. 2, no. 3) – were built directly at the valley exit in the Middle Bronze Age (BA C). Since the sites are still unexplored, it is not possible to determine the length of time in which they were inhabited. Recently, a few remains of a destroyed smelting site in the immediate vicinity of these settlements were localised.

Schluderns – Ganglegg

Ganglegg can be regarded as the central settlement of the upper Vinschgau during the Bronze Age. The site is situated at the exit of the Matsch Valley (Matscher Tal), in which the Schnals Valley and the North Tyrolean Ötz Valley (Ötztal) can be reached. It sits on a spur approximately 200 m above the valley at Schluderns and controls all traffic routes crossing the Glurns basin. It especially controls the Reschenpass route, with equally good visibility of the accesses to the Sulden Valley (Stilfser Joch Route) and the Müstair Valley (Münstertal/Val Müstair: Ofenpass Route – Switzerland). In addition to the strategically favourable position, the excavation results show that the settlement also played an important economic role. In this context, the production of bronze objects and the far-reaching contacts of metal craftsmen are of particular interest. Several

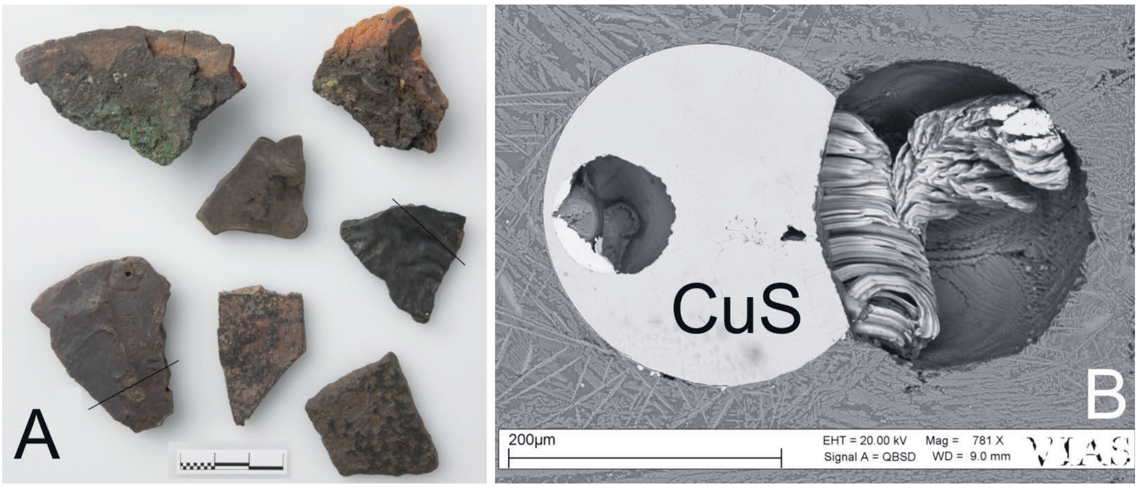

Fig. 4 a. Slags and fragments of crucibles from Stilfs-Kaschlin; b. Copper sulphide (grey) with metallic copper (white) in the slag matrix of a plate slag sample (photos: (a) G. Gattinger, IUHA, University of Vienna; (b) M. Mehofer, VIAS, University of Vienna)

mould fragments[34] and numerous hammer stones[35] testify to the importance of metalworking in this settlement. A particular feature is the house of a bronze caster from the 14th century BC. The spectrum of finds from 'Haus 10' range from central Europe to the Balkans and the eastern Mediterranean. While bronze tools such as an axe and a chisel are typical for the Alpine region,[36] the moulds in this house are comparable with specimens from the eastern Mediterranean.[37] Furthermore, bronze spiral pendants from the Balkans or the Carpathian region were found in the same building.[38] This shows how far-reaching the relations of metalworkers may have been during this period.

Traces of Bronze Age Copper Production in the Vinschgau

The moulds and crucibles from the Bronze Age settlement of Ganglegg near Schluderns, as well as from other hilltop sites in the Vinschgau, raised the question of the use of local ores.[39] The nearest copper deposits are located at Eyrs and Stilfs, in the phyllonitic slate of the Vinschgau shear zone. The described Bronze to Iron Age settlement sites near Stilfs gave reason to assume that the ore came from this deposit; however, no evidence was provided.[40] The assumption of Bronze Age copper mining was supported by scattered slag finds from the settlement area of 'Kaschlin' (Fig. 4.a).[41] In addition to the slags, crucible fragments were found, which couldn't be assigned with certainty to a prehistoric period. Consequently, it could only be speculated whether copper was extracted in Stilfs during prehistory.

In 2008, a large number of slags (Fig. 5) with several Late Bronze Age ceramic fragments of the Laugen-Melaun Culture were discovered during levelling works at Vellnair on the Prader Berg (SP 1), opposite Stilfs and the prehistoric settlement at 'Kaschlin'. As there is no known

34 Steiner 2007, 140–149.
35 Steiner 2007, 149–150.
36 Steiner 2007, 428 pl. 26.6,5.
37 Steiner 2007, 142–148 fig. 70.
38 Steiner 2007, 117–124 fig. 60.
39 Steiner 2007, 249–252.
40 Steiner 2007, 140–149.
41 Lunz 1997, 71.

Fig. 5 Plate slags (*Plattenschlacke*) from the smelting site SP 1 at Prader Berg-Vellnair (photo: G. Gattinger, IUHA, University of Vienna; T. Koch Waldner)

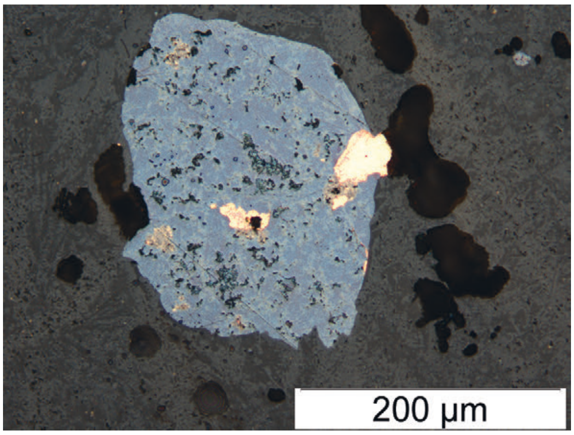

Fig. 6 Copper sulphide (matte) with metallic copper in a slag sample from SP 1 at Prader Berg-Vellnair (photo: M. Mehofer, VIAS, University of Vienna)

copper deposit on the Prader Berg, a secondary mixing of historical iron slags with Bronze Age pottery was suspected, so no further attention was paid to the discovery. After a re-appraisal of the slags in 2012, they could eventually be clearly attributed to prehistoric copper smelting. This discovery led to the first archaeological and archaeometallurgical mining investigations in 2013/2014. The first surveys and an interview with the archaeologists who examined the findings during the earthworks in 2008 confirmed that the discovered feature is the slag heap of a Late Bronze Age smelting site. The eyewitnesses reported that a stratigraphically well-defined layer was identified 50 cm below the surface. Numerous slags and some Late Bronze Age ceramic fragments were found in this layer. Initial archaeometallurgical analyses[42] have shown that the slags are the remains of the smelting of chalcopyrite (Fig. 6). The ceramics can be attributed to the Laugen-Melaun A period, dating the slag layer to the 13th/12th century BC.

42 Carried out by Mathias Mehofer at the archaeometallurgical laboratory of the Vienna Institute for Archaeological Science (VIAS), HEAS, University Vienna.

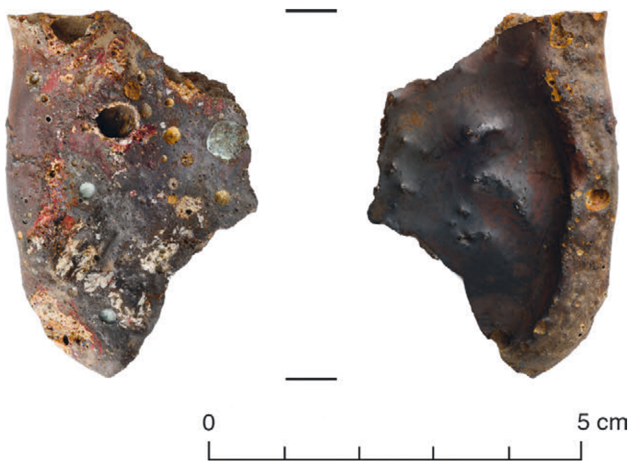

Fig. 7 Plate slags (*Plattenschlacke*) from the smelting site SP 3 at Laas-Platz, with drops of matte on the surface and an all-around elevation with an inner edge at the bottom (photo: G. Gattinger, IUHA, University of Vienna)

In the course of the surveys in 2019 and with the support of Hannes Pinggera from Stilfs, further smelting sites were localised at the Prader Berg above Stilfserbrücke (SP 2) and in Gomagoi (SP 4). The slags from these sites – plate slags (*Plattenschlacke*) and slag cakes (*Schlackenkuchen*) – are currently under investigation. Stray finds of copper slags from Fragges west of Stilfs and an area close to the settlement at 'Weiberbödele', show that further smelting sites in the Sulden Valley are to be expected.

One further site was also located outside the described area of Prad and Stilfs. As mentioned, the smelting site at Laas (SP 3) is situated close to the Bronze Age settlements of 'Tarnell' and 'St. Martin' at the exit of the Laas Valley. Alfred Gutweniger from Laas discovered the site during levelling works at the 'Platzer Wand' in 2011. Unfortunately, the site was heavily destroyed in the course of the earthworks. During a survey in the autumn of 2019, a few remains of two layers at the foot of the 'Platzer Wand', as well as some fragments of copper slags (Fig. 7), were documented. This discovery is the first evidence that the area of Laas – 12 km east of Stilfs – was also part of the prehistoric mining landscape in the Vinschgau. The origin of the ore used for copper smelting at Laas is currently being investigated. The use of ores from an unknown deposit in the Laas Valley or from the deposits at Eyrs and Stilfs could be possible.

Slags and Technology

The slag found in the different smelting sites shows close parallels. One characteristic is the frequency of plate slags (*Plattenschlacke*) and the amount of particularly thin (approx. 1–2 mm) fragments (Fig. 6). However, thicker plate slags (approx. 3–6 mm) were also observed at all smelting sites. The plate slag type, with thicknesses above 2.5 mm, has, in many cases, an all-around elevation with an inner edge at the bottom. This is probably the edge to the area where the valuable material (matte or metal) was separated from the slag and concentrated during the smelting process. Such elevations with hooked inner edges (Fig. 7) can also be observed at the Late Bronze Age to Early Iron Age smelting sites in Trentino.[43]

The slag cakes (*Schlackenkuchen*) from the Vinschgau (Fig. 8) have the same characteristics as specimens from other prehistoric mining regions in the Eastern Alps. Typically, they have no flowing structures and a relatively flat lower side. These features distinguish the slag cakes found in all prehistoric Alpine mining regions from the historical copper slags. During the Middle Ages and Early Modern period, a smelting process was used in which the slag flowed out of the furnace into an external pit, forming a flowing structure on the slag's surface. The morphological features of prehistoric slag cakes instead show that in the Bronze Age smelting process, the slags did not flow but were lifted out of the furnace and deposited on the ground or in a pit. The planned archaeological excavations at the smelting sites in the municipal areas of Prad and Stilfs will certainly provide further insights into prehistoric smelting technology.

[43] Herdits 2017, 187.

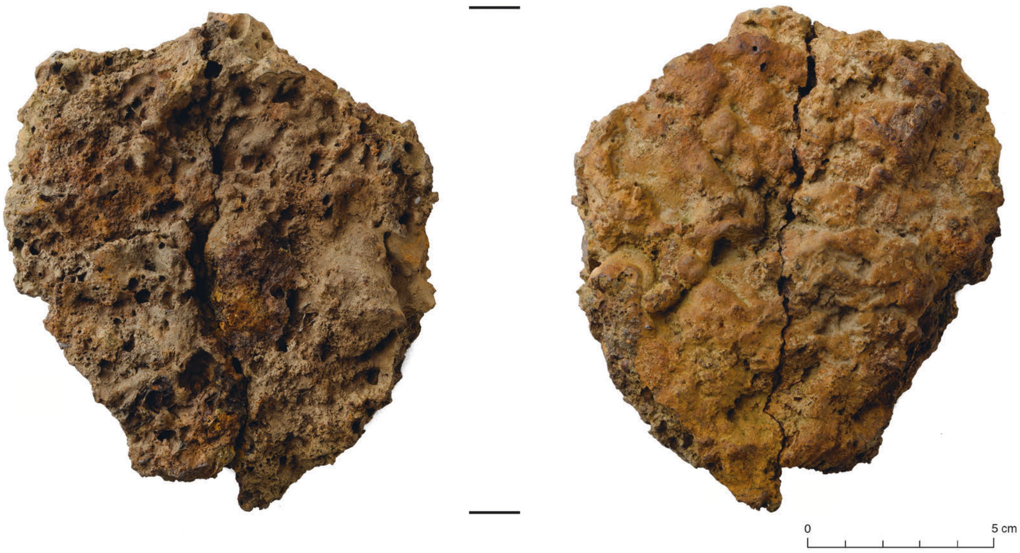

Fig. 8 Fragment of a slag cake (*Schlackenkuchen*) from the smelting site SP 2 at Prader Berg-Klein Boden (photo: G. Gattinger, IUHA, University of Vienna)

Technological Transfer and Metal Distribution

The mentioned Copper Age smelting site of Milland[44] in the Eisack Valley provides the earliest known evidence of copper extraction from chalcopyrite in South Tyrol and beyond. If the dating of the features is correct, the site at Milland is several hundred years ahead of its time in terms of technology. The slag cakes indicate an early phase of the development of a complex smelting technology that is actually typical for the Middle and Late Bronze Ages. The early technology can be clearly distinguished from the sophisticated smelting technology of the Middle and Late Bronze Age, especially by the blower nozzles. Blowpipe nozzles were also found in Milland,[45] which illustrates a primitive form of air supply, as it was common for the smelting of oxidic ores. It was not until the Middle Bronze Age that the tuyeres first appeared, which can be attributed to the use of simple bellows. These bellows replaced the blowpipes for the smelting of sulfidic ores and can be found in all mining regions of the Late Bronze Age in the Eastern Alps.[46] This supra-regional phenomenon demonstrates two stages of the development of smelting technologies and the transfer of knowledge between the Bronze Age mining regions.

The beginning of chalcopyrite smelting in the south bordering area of Trentino can also be traced back to the 3rd millennium BC.[47] At Montesei di Serso, the production of chalcopyrite copper with the early smelting technology lasted until the Early Bronze Age.[48] At the same time, co-smelting technologies (sulfidic fahlores mixed with copper oxides) were used in the Northern Alps.[49] The earliest evidence for the use of chalcopyrite north of the main Alpine ridge can be expected for the transition from the Early to the Middle Bronze Age in the Mitterberg region.[50] It is assumed that the development of sophisticated copper production technologies from chalcopyrite has taken place here. The reason for this assumption is the fact that the earliest evidence of large-scale production of chalcopyrite-copper by means of standardised work processes of mining, ore

44 Dal Ri et al. 2005; Tecchiati 2015.
45 Dal Ri et al. 2005, 10; Tecchiati 2015, 85 fig. 7.
46 Töchterle et al. 2013.
47 Perini 1992; Cierny 2008, 30.
48 Perini 1989; Cierny 2008, 31.
49 Martinek 1997; Höppner et al. 2005, 300–301; Schubert – Pernicka 2013.
50 Stöllner 2009; Stöllner 2015a.

beneficiation and smelting is attested for the Mitterberg region.[51] While this region was already a major producer of copper during the Middle Bronze Age, the traces of the techno complex – also known as 'Mitterberg Process' or 'East Alpine Copper Technology' – in other Alpine mining regions date back mainly to the Late Bronze Age and Early Iron Age.[52] In South Tyrol, there is a gap between the earliest evidence in the Copper Age and the heyday of the extraction of copper from chalcopyrite by means of highly developed technologies in the Middle and Late Bronze Age. The striking parallels between the smelting sites in the mining regions suggest a transfer of knowledge across the Alpine region. The question arises of whether sophisticated process technologies were imported from the Northern Alps during the second half of the 2nd millennium BC or if there was a parallel development south and north of the main Alpine ridge. Further research is needed to determine how the regional developments of mining and smelting technologies were connected.

Copper Production of the Laugen-Melaun Culture

With regard to copper distribution and the transfer of technological knowledge, the cultural background in the central Alpine region must be taken into account. During the 13th century BC, the Laugen-Melaun Culture emerged parallel to the Urnfield Culture in the area of today's South and East Tyrol as well as in Trentino. The majority of the Bronze Age copper production traces in this area date into the Laugen-Melaun period (13th–6th century BC). The smelting site at Klaunzerberg near Matrei[53] in East Tyrol and the bronze axe discovered in the copper mine at Prettau[54] are both the northernmost and easternmost signs of copper production in this cultural area. The proximity of these two mining districts to the northern Alpine mining regions of Kitzbühel, Viehhofen, St. Veit and Mitterberg is particularly noteworthy. The described smelting sites in the Eisack,[55] Sarn[56] and Etsch[57] valleys are in the centre, while those in Trentino[58] are on the southern edge of the territory of the Laugen-Melaun Culture. The newly discovered mining region in the upper Vinschgau represents the westernmost copper production within this context. The distribution of mining archaeological sites shows that copper was extracted in most parts of the Laugen-Melaun area and suggests that the mining economy had a major impact on this culture (Fig. 9).

Provenance studies of Late Bronze Age metal objects from Italy illustrate the supra-regional importance of the 'Laugen-Melaun copper'. The results demonstrate that the mining economy in Trentino played a key role in the Late Bronze Age metal supply of northern Italy due to the fact that copper from Trentino was detected in about 75% of the analysed bronze objects from northern Italy.[59] The significance of copper from the mining districts of South Tyrol for these distribution networks – which extended as far as southern Italy[60] – is currently being investigated by geochemical and lead isotope analyses of ores, slags and bronze objects. At this point, it should be emphasised that the geographical position of the Vinschgau made it possible to introduce the copper produced here into the exchange networks of southern and central Europe. With regard to provenance studies, the analytical results of bronze objects from the inner Alpine region as well as from the areas south and north of the Alps must, therefore, be taken into account equally.

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51 Stöllner 2015b.
52 Stöllner 2009; Stöllner 2015a.
53 Schernthanner 1893; Menghin 1949; Preuschen – Pittioni 1953; Kaltenhauser 1974.
54 Schönherr 1864.
55 Dal Ri 1973.
56 Dal Ri 1972a; Dal Ri 1972b.
57 Hauser 1986; Nothdurfter – Hauser 1986; Nothdurfter 1993.
58 Cierny 2008; Silvestri et al. 2015.
59 Jung – Mehofer 2013, 178–180.
60 Jung et al. 2011; Jung – Mehofer 2013.

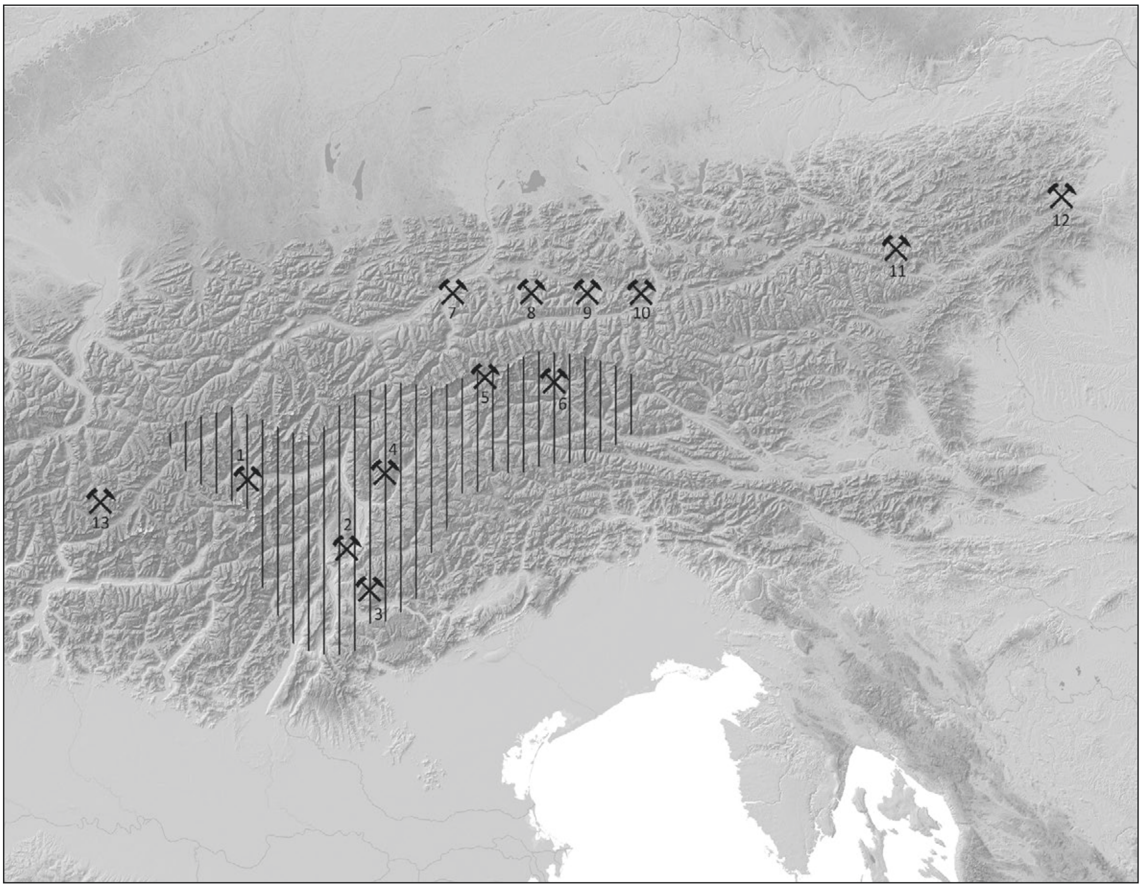

Fig. 9 Area of the Laugen-Melaun Culture and copper production regions of the second half of the 2nd millennium and the first half of the 1st millennium BC in the Eastern Alps: 1. Vinschgau; 2. Etsch Valley/Kurtatsch; 3. Trentino; 4. Eisack & Sarn Valleys; 5. Ahrn Valley/Prettau; 6. East Tyrol/Matrei; 7. Lower Inn Valley; 8. Kitzbühel; 9. Saalfelden Basin/Viehhofen; 10. Pongau/Mitterberg & St. Veit; 11. Eisenerzer Alps; 12. Neunkirchen District; 13. Oberhalbstein (graphics: T. Koch Waldner, map based on: EU-DEM Open TOPO DATA)

Although only a few prehistoric mining traces are known from East and South Tyrol, copper mining was apparently present in all parts of this area. This fact, together with the widespread distribution of copper from Trentino, illustrates the importance of mining and metal 'trade' within the area of the Laugen-Melaun Culture. It is, therefore, conceivable that this region played an important role in the transfer of technology.

Conclusion – Transfer of Knowledge to the West?

A significant phenomenon is the frequent presence of Laugen-Melaun pottery in eastern Switzerland, outside of the actual distribution area. Also, in other regions, such as neighbouring North Tyrol, Carinthia or the Lombardian Valtellina (Veltlin), ceramics indicative of Laugen-Melaun appear alongside the local pottery. However, the main area of distribution of Laugen-Melaun ceramics outside the core region is the Rhine Valley in Switzerland. Copper mining and metal exchange could be one of the reasons for the strong contact between eastern Switzerland and South Tyrol during the Late Bronze and Early Iron Ages.

The Laugen-Melaun Culture spread from the Vinschgau into the Müstair Valley – a side valley of the Vinschgau – and across the Sesvenna Group into the Lower Engadin. These two regions belong to what is now the Swiss Canton of Graubünden (Grischun) and represent the northwestern borderland of Laugen-Melaun. About 50 km southwest of this area lies the Oberhalbstein

(Surses), which is, in fact, the westernmost known copper mining region of the Eastern Alps. Right here, the Laugen-Melaun pottery was frequently found alongside local ceramics. As examples, the findings from the settlements of Savognin-Padnal[61] and Salouf-Motta Vallac[62] have to be mentioned. The earliest traces of copper extraction in this region date to the Late Bronze Age, while the majority can be attributed to the Early Iron Age.[63] Although only one smelting site in the Vinschgau has been dated so far (13th/12th century BC),[64] a chronological sequence of the beginning of mining between the two regions seems to be likely. The chronological approach combined with the frequent finds of Laugen-Melaun pottery in Oberhalbstein suggests that there was a technological transfer from East to West.

It could also be argued that the pottery finds of the Laugen-Melaun culture occur due to close 'trade' contacts. Still, finds from the canton of St. Gallen indicate that a transfer of knowledge and maybe even migrations took place. In the settlement of Flums-Gräpplang, local production of Laugen-Melaun pottery was attested.[65] This evidence illustrates some sort of technological transfer and probably the presence of people from what is now South Tyrol and the Lower Engadin who settled alongside the local population.

So far, no prehistoric mining traces have been discovered in the Alpine Rhine Valley north of the Oberhalbstein. Considering the exploitable copper deposits in the hinterland of the Rhine Valley (e.g. Mürtschenalp),[66] a connection between the significant influence of the Laugen-Melaun Culture and the extraction and distribution of copper seems conceivable. Future research and supra-regional comparisons between the mining archaeological findings from South Tyrol and eastern Switzerland will show to what extent this hypothesis is valid.

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61 Rageth 1986.
62 Roffler 2018.
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64 See section 'Traces of Bronze Age copper production in the Vinschgau'.
65 Neubauer 1995, 84–88.
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Copper Supply and Consumption: Northern Italy, Alps and Balkans

Of Hoards, Individuals and Communities in Late Bronze Age Northeastern Italy: a Diachronic Approach to Supply and Consumption of Metal

Elisabetta Borgna[1] – *Caterina Canovaro*[2]

Abstract: The contribution takes into consideration the social organisation of communities in northern Italy during the Bronze Age, starting from the perspective of bronze deposition patterns and briefly reappraising the much-debated question regarding the interpretation of metal hoards. The focus will be on some of the Late Bronze Age hoards from the northern Adriatic regions or *Caput Adriae*, where a recent archaeometallurgical project offered an addition to the archaeological research. Some major discontinuities observed in both the association of materials and in the metal composition of objects can be used to shed light on the modes and nature of the special relationships linking northern Italy to the Urnfield areas – or transalpine and western Balkan regions – from the late Recent Bronze Age onwards (BA D or Ha A1). Changes in the patterns of both metal supply and consumption are supposed to be related to substantial social transformations pointing to the emergence of political economies on a regional level. A significant contribution to the interpretation is offered by the results of the archaeometallurgical investigation, which shows that a clear discontinuity in the modes of bronze supply and circulation definitely emerged in the last centuries of the Late Bronze Age or the Italian Final Bronze Age (Ha A2–Ha B). In particular, a phenomenon of fragmentation and diversification in the metal supply and resource exploitation seems to be recognisable according to metal provenance and metallurgical composition, possibly in coincidence with the formation of political territories.

Keywords: *Caput Adriae*, Late Bronze Age, hoarding, metal supply, archaeometallurgy, Pb isotopes

In the last twenty years, the long-standing discussion on the meaning and function of hoarding has been reappraised thanks to the contribution of several scholars, mainly working in central Europe. Through a critical evaluation of a wide range of analytical categories, these scholars have convincingly explained a significant number of metal hoards as evidence of ancient rituals and even purely religious behaviour.[3]

Italian scholars have remained at the periphery of the most recent debate, possibly due to the patterns of bronze deposition in Italy appearing slightly different compared to the intense phenomenon of hoarding on a European scale. However, this could also be true because of a prevailing eclectic approach, founded on the functional and processual paradigms of the 20th century debate and not prepared to accept a general explanatory pattern, which could not adapt to the extreme variety and diversity of the phenomenon of bronze deposition at large.[4]

Starting from the current state of the art, it is possible to contend that even when the ritual nature of a bronze deposit is self-evident, a careful contextual investigation can reveal important information concerning substantial utilitarian aspects of the past. This includes the modes of metal exploitation and supply as well as its circulation and consumption, depending upon patterns of social and economic organisation of the ancient communities. From this perspective, this paper will

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3 See most recently, with references, Hansen et al. 2012; Bradley 2013; Hansen 2013; Hansen et al. 2016a; Hansen 2016b; Bradley 2017.
4 Cf. Bietti Sestieri 1973; Carancini 1997, 386; Carancini 2004; Carancini 2006; Bietti Sestieri 2010, 172; for full references, Borgna in press.

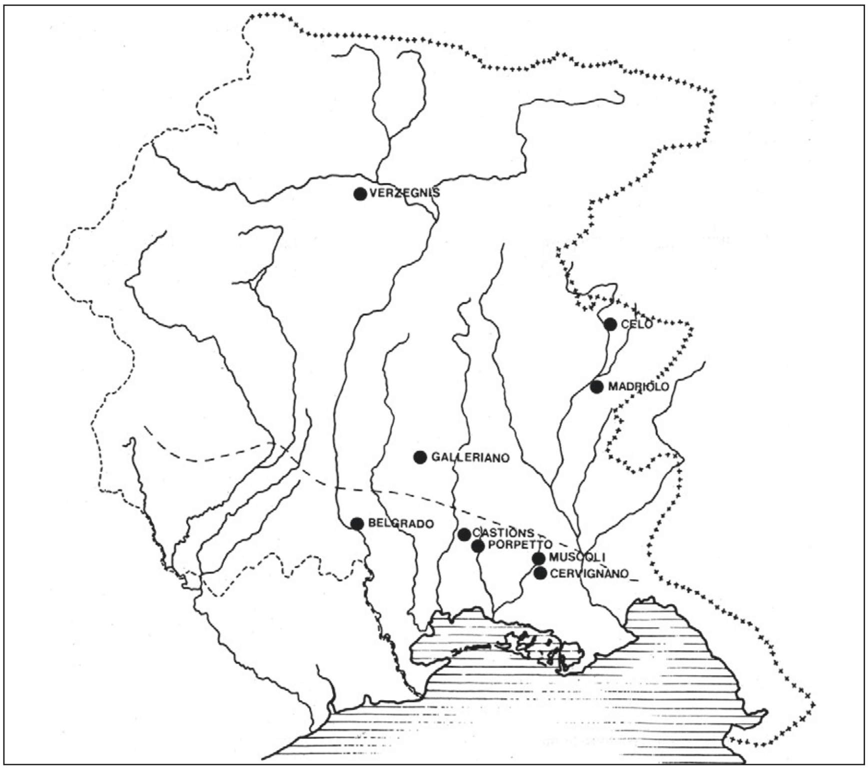

Fig. 1 Map of distribution of Late Bronze Age Bronze hoards in Friuli-Venezia Giulia (archive of the Laboratory of Prehistory and Protohistory, University of Udine)

address some of the aspects concerning metal supply and consumption in the Late Bronze Age by focusing on several hoards from northeastern Italy or *Caput Adriae* (Fig. 1). The archaeometric study of selected copper and bronze artefacts from these hoards has allowed for an investigation into the origin of the metal, by identifying exploitation areas of ores.

In this light, a short diachronic survey of bronze hoarding in northern Italy will be introduced, focusing on the meaning and social function of metal deposition. Afterwards, hoards from north-eastern Italy or *Caput Adriae* will be considered in more detail by commenting on some of the analytical results of a wider project.[5]

On the Nature of Hoards: from the Early to the Late Bronze Age[6]

In the Early Bronze Age, evidence of metal hoarding is plentiful in both northwestern and central Italy.[7] The distribution of the numerous metal hoards consisting, for the most part, of a single

5 Analysis have been carried out by the research group of the Department of Geosciences of the University of Padova under the coordination of Gilberto Artioli in the framework of a joint project with the Department of Humanities and Cultural Heritage of the University of Udine and the Soprintendenza Archeologia Belle Arti Paesaggio, Friuli Venezia Giulia; metallurgical investigations of sampled materials from the Friulian hoards constituted the core of the PhD dissertation by Caterina Canovaro (Canovaro 2016).

6 For the adopted chronology and proposed correlations I refer to Borgna et al. 2018b, tables at pp. 99–101, figs. 1–3; in particular for the subphases of the Italian Late Bronze Age (Recent Bronze Age 1, c. 1300–1200 BC; Recent Bronze Age 2, c. 1200–1150 BC; Final Bronze Age, 1150–950 BC), see Bettelli et al. 2018, 217, with reference to current chronological systems.

7 Peroni 1996, 60–61, 109–110; Carancini 1996; Carancini 1997; Carancini – Peroni 1999, 25.9; de Marinis 2006a, 220; de Marinis 2006b; Pearce 2007, 83–88; Bietti Sestieri 2010, 28, 97–99; de Marinis 2010; de Marinis 2012b; de Marinis 2016; Borgna in press.

class of materials, highly standardised flanged axes and a few bun ingots reflects a main concentration around the mining districts of mid-Thyrrenian Italy as well as along a few of the major communication routes towards the northwestern regions. Essentially, limited amounts of metal seem to have been packed and buried in isolated sites outside of the inhabited areas. In short, most hoards, which have been reasonably described as stock-in-trade, seem to have been strictly related to major economic activities of supply and distribution. Bronze axes served to fuel an economic sphere of exchange, possibly characterised by rather unrestricted access to metal sources by several groups and individuals participating in the activities of metal supply and exchange, most probably without any central control. In the course of competitive interaction, these groups moved around and progressively socialised the landscape, including the territory where the Terramare would develop in the Middle Bronze Age, substantially scattered with late Early Bronze Age hoards. The definitive burial, when not due to oblivion and/or some other occasional event, may have been dependent upon structured behaviours aiming at defining and mapping the landscape through ritual practices. The abandonment and sacrifice of some quantities of metal could have then taken place within a ceremonial framework, which was enacted during the socialisation of relevant natural places as seats of encounter and exchange. Competing groups may have used bronze deposition in order to emphasise main routes and territorial borders, thus contributing to the creation of a social landscape.[8]

In the very late Early Bronze Age, the appearance of hoards with prestige goods, mainly pertaining to the domain of personal ornaments, such as collars, and in particular to weaponry, such as the well-known hilted-daggers, prompts the inference that two separate spheres of circulation began to function. These respectively fuelled utilitarian activities, such as economic exchange and the supply of raw metal, and ceremonial exchange or ritual activities, with an impact, in particular, on long-distance communication. As Raffaele de Marinis has most recently convincingly demonstrated,[9] hoards of daggers and hoards of axes were mutually exclusive for the most part. Daggers belong reasonably to the category of goods circulating as symbolic devices in the framework of alliances and other ceremonial transactions among emergent elites at a distance. Overall, an early organisation of metallurgy based on rather unrestricted access to metal sources and a large, albeit competitive participation in supply and distribution seems to have been followed, toward the end of the Early Bronze Age, by the emergence of exclusive social components, which may have manipulated access to the metal sources and taken control of metal exchange and consumption.

The role of emergent groups also seems to be well-represented in the rare Middle Bronze Age deposits because of the exclusive collection of weapons and components of male equipment pointing to the existence of leaders and followers. This seems to be attested by the well-known deposit of Cascina Ranza near Milano, where swords, spearheads and axes, all of which find parallels in both type and function in the transalpine regions and even in eastern Europe, can be convincingly interpreted as prestigious weapons.[10] During the advanced Middle Bronze Age and an early part of the Late Bronze Age or Recent Bronze Age 1 (BA B/C 1–2 – BA D), a structured pattern of metal circulation, dependent upon control and centralisation, seems to be revealed by a kind of systematic opposition. On the one hand, an exclusive elite behaviour is shown by the evidence of highly selective ceremonies implying segregated encounters between leaders who performed their rituals and even funerary actions at emergent natural places, such as rock crevices, rivers and wet sites. On the other hand, the common occurrence of craft activities involving utilitarian metal in large nucleated settlements points to a well-functioning system of supply and distribution, which could also explain the extreme rarity of hoards.[11]

8 Cf. Carancini 1996, 50–51; Carancini 2004, 286; Borgna in press.

9 De Marinis 2016.

10 Castelfranco 1888; de Marinis 2012a, with references; de Marinis 2018; see also David et al. 2017, 568–573, figs. 5–6.

11 Borgna in press.

Metal Supply and Bronze Deposition in Northeastern Italy during the Late Bronze Age

At the beginning of the Late Bronze Age, the hoard of Cervignano[12] in the coastal plain of Friuli (Fig. 1) may well represent a stock of metal which was stored in the framework of bronze production within an industrial settlement. This settlement possibly belonged to a well-structured system made up of a chain of villages connecting the southeastern Alpine area with the western Adriatic and the Terramare.[13] The hoard, consisting primarily of a large quantity of unshaped copper and including only a few tools (such as a winged axe and a sickle, which were possible standards of bronze circulation in the circumalpine areas), is consistent with a shipment of metal suitable for both exchange and production. Recent metallurgical analyses[14] have demonstrated that the copper employed for ingots, swords, and axes from Cervignano exhibits lead isotope and chemical compositions perfectly compatible with the copper ore deposits from the Italian southeastern Alps (Valsugana VMS and South-Alpine AATV groups). This confirms the pattern of monocentric exploitation of the Southern Alps, which in the Recent Bronze Age or the period of the so-called *metallurgical koine*, served an extremely wide area, including southern Italy and possibly the Balkans.[15]

This very same pattern, which predicts a structured organisation of metal production and consumption during the Middle Bronze Age – early Recent Bronze Age, continues to be attested in the later Recent Bronze Age or early 12th century BC in the regions where well-founded long-term settlements survived, the crisis that involved most communities and whole social environments on a Mediterranean scale, c. 1200 BC. Such is the case of the Adriatic Terramare of the Valli Grandi Veronesi. It is here where the intervention of the political dimension has been used to explain a settlement system made up of large interdependent sites, possibly connected within a hierarchical pattern with a main role assigned to Fondo Paviani.[16] In this period, the flow of economic metal was still controlled by the nucleated main sites, as Fondo Paviani clearly testifies.[17] The consumption of goods (such as weapons) included their ritual deposition in structured cult sites under the control of regional elites. These sites, such as Pila del Brancon and Corte Lazise, are isolated throughout the territory but reachable through well-planned facilities such as ceremonial routes.[18]

Apart from this, a major change seems to have involved the organisation of metallurgy, starting with the later Late Bronze Age or 'Bronzo Recente' 2 or the first half of the 12th century BC. Hoards occurring south of the Alps share a number of features with the numerous Ha A1 hoards in the Alpine and transalpine regions. These hoards were mostly deposited in isolation outside of inhabited areas and along recognisable communication routes such as river valleys and consisted for the most part of large mixed compositions. They include tools, weapons and even personal objects; heavy fragmentation and a prevailing component of raw metal are also typical. Their distribution, involving northeastern Italy in particular, seems to reveal a connection with the exploitation of the southern Alpine ores.[19]

Therefore, the interpretation of most of the evidence, including the hoards of Mezzocorona in Trentino (Trento), Merlara and Lozzo in Veneto (Padova), Castions, Belgrado and Muscoli in

[12] Borgna 2001, 309–311; Borgna 2004; Borgna in press.
[13] Most recently Borgna et al. 2018c, 88–91; Borgna – Corazza 2019.
[14] Canovaro et al. 2018; Canovaro et al. 2019.
[15] Mehofer et al. 2021; Gavranović et al. 2022.
[16] Cupitò – Leonardi 2015, 221–225; Cupitò et al. 2015.
[17] Cupitò et al. 2015, 366–367.
[18] Pila del Brancon: Bietti Sestieri et al. 2013 with references. Corte Lazise: Salzani 2006; Bietti Sestieri 2010, 56–57; cf. Borgna in press. For the possible ceremonial route linking cemeteries and even cult places with bronze deposits such as Corte Lazise with main sites, see De Guio et al. 2015, in particular 331.
[19] Borgna in press with bibliography.

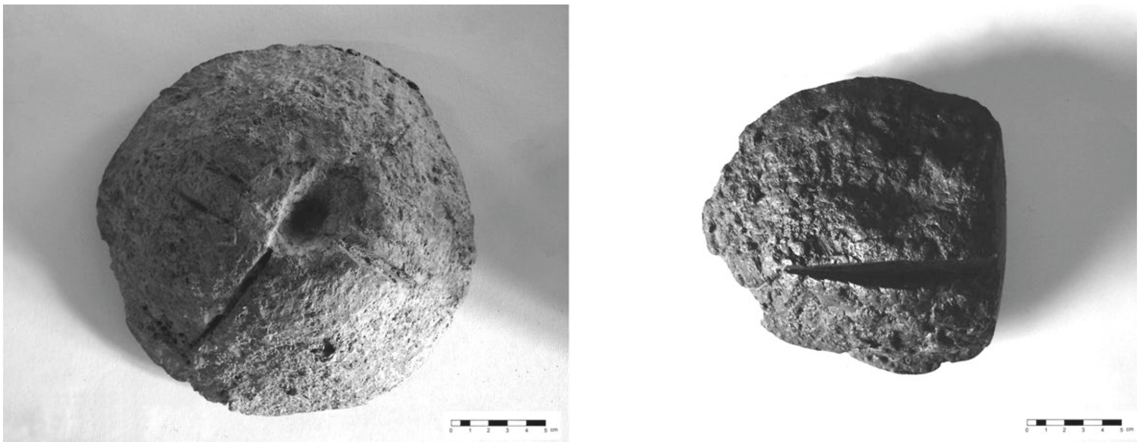

Fig. 2 Bun ingots with incision on the upper surface from the hoards of Celò and Porpetto (archive of the Laboratory of Prehistory and Protohistory, University of Udine)

Friuli (Udine) and some others is challenging.[20] European scholars would mainly agree on a religious explanation founded in particular on a most recent approach, which, by submitting to criticism and revision the opposition utilitarian vs. non-utilitarian, seems to downplay the explanatory potential of some conspicuous differences between dryland and wetland deposits. The former, most often consisting of scrap metal, were traditionally interpreted as suitable for re-cycling; the latter, related to the offering and sacrifice of irretrievable objects, were attributed to ritual behaviour.[21] Though several clues may indicate that a ritual explanation should not be ruled out for some of the dryland deposits that have traditionally been interpreted as related to the metallurgical cycle, thus confirming the ambiguity and inadequacy of the traditional analytical categories, the Italian LBA evidence nevertheless suggests that some of the traditional guidelines adopted for distinguishing utilitarian from non-utilitarian hoards are still tenable.

In particular, the process of heavy and regular fragmentation, at times clearly depending upon pre-planned strategies at the smelting site (Fig. 2) and excluding special treatments such as bending and the use of violence or fire;[22] the exclusive presence of fragments not suitable for refitting – possibly an evidence that points to the opening and re-use of the deposits over time; the absolute dominance of unshaped raw metal and the apparently unselective association of several classes of materials: these are all features that distinguish the above-mentioned hoards from a group of contemporary or Ha A1 ritual hoards deposited in special inaccessible contexts, such as rivers and caves – well-exemplified by Pila del Brancon on the Tartaro river and Mušja jama at Škocjan in Slovenian Karst, characterised by exclusive assemblages of weapons and prestige objects showing evidence of special treatment including the use of fire and other kinds of manipulation, special associations of groups of objects, and the usual occurrence of joining parts of the same object.[23]

By relying on this general opposition, the possibility that Recent Bronze Age 2 – Final Bronze Age 1 (or 12th century BC / Ha A1) mixed hoards from northeastern Italy had been primarily shipments of metal usable for both exchange and re-cycling and belonging to a mainly economic sphere of circulation, based on the mobilisation of commodities, cannot be excluded. The mixed

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[20] Mezzocorona: Campi 1891. Merlara: Callegari 1933; Leonardi 2015 with further bibliography. Lozzo: Callegari 1941. Castions, Belgrado and Muscoli: Borgna 2001; Borgna 2004; Canovaro et al. 2018. Approximately contemporary, a few hoards from northwestern Italy are comparable, including Sassello (Lo Porto 1954), Pinerolo (Doro 1975), and Soncino (Peroni 1996, 238; de Marinis 2011, 129, 130, fig. 3; de Marinis 2019); for these contexts and few others from the Verona area see also Peroni 1996; Carancini – Peroni 1999, 17 n. 101; Borgna in press.

[21] See e.g. Bradley 2013, 124–125; Dietrich 2014; Hansen 2016b; Bradley 2017.

[22] See in particular Borgna in press; cf. de Marinis 2011, 130, fig. 3.

[23] For Pila del Brancon see above, note 18. For Mušja jama: Teržan et al. 2016; cf. Borgna in press.

composition of these hoards, including parts of swords and weapons, could point to a special phenomenon of relocation of prestige objects which were previously circulating within a separate sphere, fuelling ceremonial exchange and symbolic performances. Economic and ceremonial spheres of exchange, which had previously been separate, were now overlapping under the pressure of a general phenomenon of commodification of bronze, characterising the Late Bronze Age on a Mediterranean scale.[24] Contact with new systems of values depending upon the market economies of the eastern Mediterranean societies probably played a role in the subversion of well-rooted values at a local level.[25]

Furthermore, failing a political control of modes and dynamics of bronze distribution on an interregional scale, the increasing demand for metal and the consequent industrial regime of metal exploitation in the Southern Alps[26] surely had an impact on the social organisation of work, favouring individual ventures, entrepreneurial roles and competition among groups and individuals striving to gain exclusive access to new advantageous opportunities. As a result, the well-balanced relationships between communities and their resources[27] were finally threatened. The dispersal of metal hoards in the Late Bronze Age may be explained as dependent upon a diffuse, unorganised pattern of metal circulation, which possibly played a role in the final collapse of well-founded, long-established communities such as the Terramare.

The late Recent Bronze Age hoards may, therefore, offer a glimpse into typical shipments of metal fuelling production and exchange. This cannot, however, be considered the whole story as their ultimate deposition at the beginning of the Final Bronze Age (or mid to late 12th century) could have been prompted by ritual and social constraints. The presence of prestige objects – such as bronze vessels and weapons including spearheads and socketed axes (which were relatively new entries in the Italian bronze industries) – might not only have been a marker of commodification but also a relevant indication of new social practices, adopted under the pressure of the Urnfield cultural influence affecting the Italian regions in the Final Bronze Age.[28]

The Friulian hoards of Muscoli and Castions (Fig. 1) will be considered as examples of a possible explanatory pattern able to make sense of the intense phenomenon of bronze deposition during the Recent Bronze Age/Final Bronze Age transition.

The hoard of Muscoli comes from an uncertain location on the coastal plain near Aquileia, not far from the site of the Cervignano hoard, but within an empty social environment after the abandonment of the many nucleated villages that had been involved in metallurgical production.[29] The deposit consisted of a large quantity of raw metal, mostly fragmented unshaped ingots, together with fourteen objects, including at least ten sickles, two swords and two socketed axes (Fig. 3).[30]

The fragmented swords, dating respectively to the Middle Bronze Age and the early Recent Bronze Age, could be indicative of a relocation of prestige objects to increase the volume and economic value of a stock-in-trade, well represented by the raw metal and the sickles, mostly dating to the Recent Bronze Age.[31] The two socketed axes (Fig. 4) are distinctive both typologically – pointing to the western Balkans – and for the state of preservation, as they seem to be unbroken

[24] Borgna 2023. In general, for the Mediterranean see: Sherratt 1999; Sherratt 2000; cf. Pare 2013.

[25] See also Iacono 2016.

[26] See most recently Ling et al. 2019; Melheim et al. 2018; Pearce et al. 2019, with references.

[27] Earle et al. 2015; Borgna 2023.

[28] For overall similarities between Late Bronze Age Italian 'Protovillanova' hoards and Urnfield deposits see Bietti Sestieri 1973.

[29] Borgna 2001, 311–316; Borgna 2004; Canovaro et al. 2018; Borgna in press. For the population dynamics in the area see Borgna et al. 2018b, 98–99.

[30] Though the quantity of objects forming the deposit has been carefully reconstructed through a meticulous survey in the archive of the National Museum of Aquileia (cf. Borgna 2001, 313 n. 81), we cannot exclude that the hoard included more items before entering the scientific literature (Pigorini 1904), as could be suggested by early press reports referring to the discovery: we are grateful to Annalisa Giovannini for this information, which still needs to be checked.

[31] Borgna 2001, 313 n. 81; 316, fig. 11.3–4; cf. Canovaro et al. 2018, 345; Borgna 2018.

Fig. 3 The hoard of Muscoli near Aquileia (Udine) (archive of the Laboratory of Prehistory and Protohistory, University of Udine)

and well-preserved.[32] The smaller axe (Fig. 4, right), dating well into the Final Bronze Age or second half of the 12th century BC and representing, therefore, the most recent object deposited in the hoard, might identify the authority in charge of definitely burying this stock of metal, which was possibly originally intended for supplying metal production and exchange.

The hoards of Castions di Strada, located along a main route in the mid-plain of Friuli, not far from a well-known fortified village, consisted of two groups of materials buried several hundred metres from each other and close to the spot where a much earlier sword, dating to the Middle Bronze Age, had been deposited (Fig. 5). Both contexts were closed at the beginning of the Final Bronze Age (mid-to-late 12th century BC) and included mainly fragmented materials, belonging

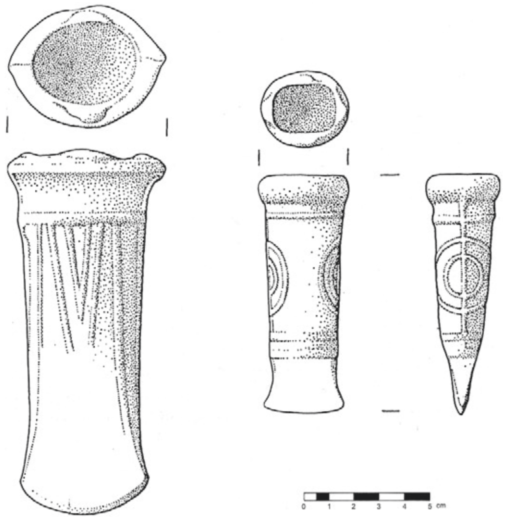

Fig. 4 Two socketed axes from the hoard of Muscoli (Udine) (Borgna 2001, 312–313, fig. 8, 1–2)

Fig. 5 The hoard B of Castions (Udine) (archive of the Laboratory of Prehistory and Protohistory, University of Udine)

32 Borgna 2001, 312–313, fig. 8.1–2; cf. Canovaro et al. 2018, 345–346; Borgna 2018.

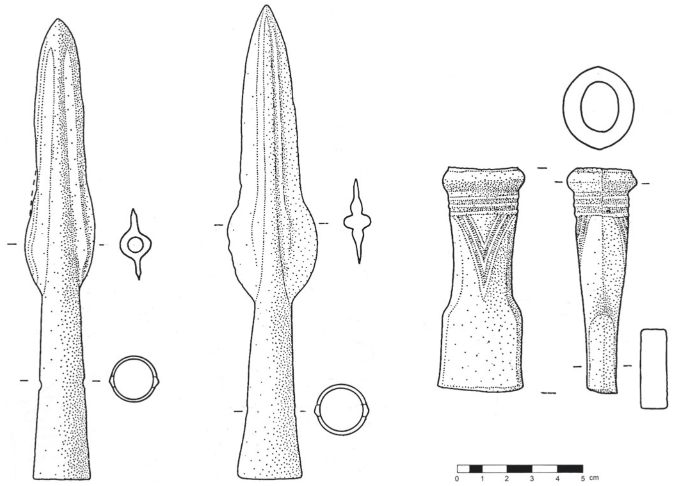

Fig. 6 Spearheads and socketed hammer from hoard B, Castions (Udine) (Borgna 2001, 323–324)

to earlier phases of metal production.[33] Recent Bronze Age axes and sickles were buried together with bun ingots, some of them with guidelines for fragmentation. A few new objects, namely weapons of recent introduction into the repertoire of Italian bronze production, such as a couple of Ha A1 spearheads and a socketed hammer from Hoard B[34] possibly indicate a new leadership asserting its control on metal circulation (Fig. 6). It may not be coincidental that also in this case the most recent items, pointing to the male warrior sphere, reflect the mobilisation – through hoarding – of a stock of utilitarian metal, possibly under ritual constraints. Though the precise nature and circumstances of the ritual performance cannot be defined, it is nevertheless possible to confirm a behavioural pattern at home in the Urnfield cultural areas, where the deposition of bronze, including weapons, ornaments and valuable objects, is well-attested.

The deposition of the northeastern Recent Bronze Age/Final Bronze Age hoards could have been prompted by the intent of launching a new organisation of metal activities, ruled by a new political economy, which would have had an impact on the patterns of centralised metal supply, exchange and consumption in the next phase. The phenomenon surely constituted a watershed in the modes of bronze circulation and probably represents the end of the phase of intense human mobility that had once had a profound impact on both the dynamics of metal supply – involving the intervention of a multiple number of new agents – and the life of the well-established central settlements of the Middle Bronze Age – Recent Bronze Age 1, weakened by the subversion of some of their core principles such as social cohesion.

New Patterns of Metal Deposition in the Final Bronze Age: an Archaeometric Perspective

The substantial change in the modes of bronze circulation and deposition in the later Late Bronze Age or Final Bronze Age 2–3 or Ha A2–Ha B1[35] is particularly perceivable in the evidence of a structured dichotomy in the typology of hoards, indicating that two separate spheres of exchange were once again functioning. On the one hand, weapons, ornaments and prestige objects entered the composition of a discrete group of hoards, which appear clearly provided with a ritual nature. At times, they can be compared with such contexts as the *Brandopferplätze* of the mountain regions.[36] On the other hand, the economic sphere is better represented by hoards of shaped ingots or standardised objects used as standards of value and showing a phenomenon of extreme commodification. These artefacts, used as distinctive tokens in the directional long-distance exchange (sickles, winged-axes, shovels and shaft-hole axes) and hoarded at times in large assemblages,

33 Borgna 2001, 296–309; Borgna 2004; Borgna in press. The multiple locations of bronzes at Castions may be compared with some European contexts defined as 'Multidepotfundstelle', see Vachta 2012.

34 Borgna 2001; Borgna 2018, 323–324.

35 Cf. Borgna 2018, 326–328; Borgna 2023.

36 Borgna 2018, 328–330 (in Friuli see possibly the deposit of Celò and Verzegnis); Borgna in press. For the relationship between *Brandopferplätze* and hoards see also Hansen 2016a, 195.

Fig. 7 Pick-ingot from the hoard of Madriolo, near Cividale (Udine) (archive of the Laboratory of Prehistory and Protohistory, University of Udine)

as is the case with pick-ingots (Fig. 7), could correspond to discrete *brands* involved in metal production and exchange and may be useful for outlining the borders of well-defined metallurgical circuits, at times coinciding with unified territories under the power of regional elites able to control the entire metallurgical cycle, from the mining sites to the craft context.[37]

Several different circuits may have intersected and overlapped at primary sites, such as Frattesina, the well-known central place located in Polesine, which functioned as a specialised industrial and trading site linking various regions of the Mediterranean and transalpine area.[38] The best parallels for the metal composition and provenance of the pick-ingots of Galleriano, a hoard retrieved near a defended settlement of central Friuli and dated to Final Bronze Age 2 or c. the 11th century BC (Fig. 8),[39] can be found indeed at Frattesina. The chemical and microstructural analyses of a couple of ingots from Galleriano revealed a low impurity bronze composition (Sn~12%), compatible with chalcopyrite as an ore charge for copper extraction. Isotopically, they overlap the Valsugana mining area.[40] A few kilometres to the southeast and closer to the coast, at Porpetto, a large industrial site where 100 kg of metal have been found, a larger number of ingots with the same shape have been analysed with substantially different results. These ingots may represent heterogeneous groups according to their metal composition, mainly exploiting *fahlerz* ore; in particular, a group rich in nickel and cobalt[41] finds parallels in the Slovenian contexts where the same ingots are attested, namely Kanalski Vrh and Veliki Otok.[42] Therefore, it would not seem coincidental that the ingots at Galleriano are associated with an arm ring of the Zerba-Pariana type (Fig. 8, bottom row, in the middle), an object widespread in mid- and northwestern Italy, with the easternmost evidence identified in Veneto.[43]

At Porpetto, on the other hand, pick ingots and shovels are associated with shaft-hole axes, a *brand* with little evidence at Frattesina. However, the *brand* is well-attested in western Slovenia and southeastern Friuli as well as in the Apennine regions and mid- and south Adriatic, a distribution possibly pointing to a maritime inter-Adriatic exchange system.[44]

Even the socketed shovels at Porpetto differ substantially from the shovels of Frattesina. While metallographic analysis seems to question their use as tools and instead support the idea of a prevailing function as ingots/standards of value, the chemical analysis proves that the objects were made by smelting *fahlerz* copper, in one case adding a high percentage (23%) of lead.[45] At

37 Borgna 2018, 326–328 with references; Borgna in press with bibliography. For *brands* see Radivojević et al. 2019.

38 Bietti Sestieri et al. 2015; Bietti Sestieri et al. 2019 with references.

39 Borgna 2001, 321–323; Borgna – Girelli 2011.

40 Canovaro 2016. For bronze-alloyed pick ingots at Frattesina see now also Giardino – Paternoster 2019, in particular 253. For provenance see also Villa – Giardino 2019.

41 For the site and the bronzes see Borgna 2001, 323–325; for the metal composition see Canovaro 2016.

42 Kanalski Vrh: Žbona-Trkman – Bavdek 1996; Trampuž-Orel – Heath 2001. Veliki Otok: Teržan 1996, 227–228, pl. 139.

43 Borgna 2001, 322, fig. 14; Borgna 2018, 327 with references.

44 From the four 'founder's hoards' of Frattesina only one fragment of a shaft-hole axe has been recognised (ripostiglio n. 2) and attributed to the Menaforno type, with distribution in central Italy: Bietti Sestieri – Giardino 2019, 190–191. For Friuli and the Adriatic: Borgna 2018, 327; Borgna et al. 2018b, 107–109; cf. Borgna – Montagnari Kokelj 1999, 146–147. For Late Urnfield/Early Iron Age Slovenia see the hoard of Dragomelj II and other finds: Turk 1997; Pavlin – Turk 2014; Turk 2018, in particular 398.

45 Canovaro 2016.

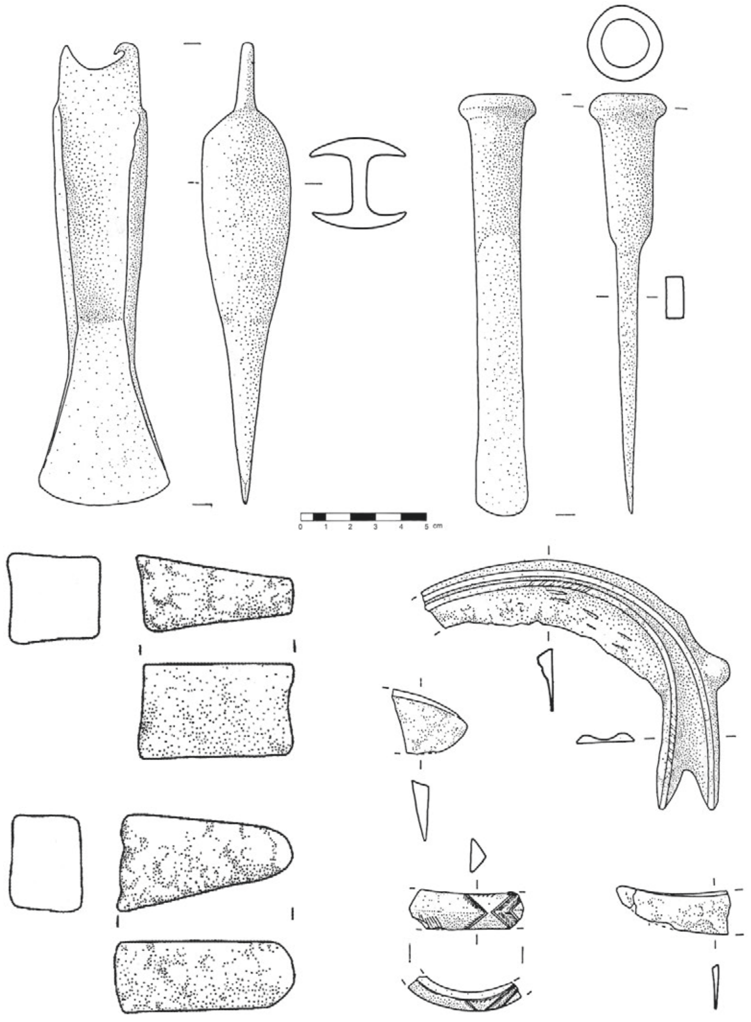

Fig. 8 The Final Bronze Age Hoard of Lestizza/Galleriano (Udine) (after Borgna 2001, 322, fig. 14; Borgna – Girelli 2011, 239)

Aquileia, a recently found pick ingot rich in lead can also be mentioned for further comparison with the Slovenian ingots (Fig. 9).[46]

It seems therefore feasible that separate, although interacting, spheres of circulation – not necessarily distinguishing goods from commodities but rather outlining well-defined metallurgical authorities on metal supply and distribution – overlapped in Friuli. These metallurgical circuits were identified both by tokens provided with limited circulation on a regional scale and by international tokens, such as possibly pick-ingots, mainly functioning in the interregional circuits, where they had identical shapes but differed in the metallurgical recipes and possibly colours.

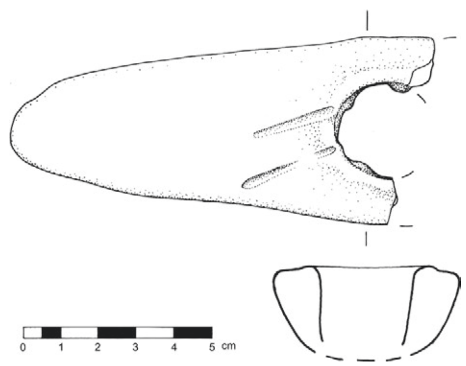

Fig. 9 A half pick-ingot, unknown provenance near Aquileia (with permission of Soprintendenza Archeologia Belle Arti Paesaggio Friuli-Venezia Giulia, drawing by G. Merlatti)

46 Borgna 2018, 321, fig. 7D; 326.

The results of the recent archaeometallurgical investigation may in some way confirm the general assumption that during the Final Bronze Age the homogeneous pattern of monocentric metal supply (largely dependent on the exploitation of the southern Alpine ores of Valsugana and Trentino-Alto-Adige) broke down and transformed into a heterogeneous pattern implying multiple sources, possibly under the pressure of social competition and political fragmentation.[47] This may be verified by comparing the data of the early Recent Bronze Age (or BA D) hoard of Cervignano, attesting to the almost exclusive exploitation of chalcopyrite deposits possibly from the southern Alpine ores – a pattern also verified at Muscoli (above) – with the later or Final Bronze Age 1–2 data from other Friulian hoards, where variability and heterogeneity in both provenance and production techniques emerge more clearly. By combining chemical data and isotope signals, it has been possible to infer that in the hoard of Castions ingots from several sources were collected, including some obtained from *fahlerz* ore with or without nickel (see below). This evidence becomes stronger in a couple of slightly later or Final Bronze Age (c. 11th century BC) assemblages, such as Celò and Verzegnis in northern Friuli, where the mixing of different types of copper – namely chalcopyrite and *fahlerz*-type ore – has been supposed to have happened on site, including a possible local contribution from the ore of Monte Avanza, northern Friuli or Carnia.[48]

Concluding Remarks

This short review suggests that beginning in the Early Bronze Age, metal hoards in mid-northern Italy contributed to the socialisation of landscapes at the peripheries of main mining regions – the Tyrrhenian districts during the Early Bronze Age and the southeastern Alps mainly during the Late Bronze Age. In addition, their distribution and concentration seem to have been strongly dependent upon the social organisation of metal supply and, ultimately, the social organisation of human communities. The widespread distribution and high concentration of hoards apparently consistent with metal shipments, which during certain chronological phases are widely attested as isolated depositions at a distance from settled areas, seem to characterise periods of low social integration, lack of communal organisation and strong individual or group competition. Competition among different agents participating in metallurgical practices, including consumption and disposal, may have fuelled ritual actions, perhaps even playing a role in the deposition of 'utilitarian' bronze or shipments of metals in coincidence with cultural discontinuities, thus explaining the permanence underground and archaeological visibility of many hoards.

Evidence of this may be found in the widespread diffusion of Early Bronze Age hoards in northwestern Italy and the Apennine area at the edge of the Po plain, preceding the formation of the large Middle Bronze Age – early Late Bronze Age nucleated settlements such as the Terramare. Afterwards, the smooth functioning of the modes and patterns of the supply of metal, controlled by and mobilised at central sites, might explain the decrease or lack of deposits outside settled areas, excluding those assemblages, mainly consisting of weapons, which depended upon exclusive cult behaviours of the emerging elite.

The interruption of regular patterns of bronze supply may consequently explain the appearance of depositional horizons consisting of multiple hoards that could be considered relevant markers of substantial changes in the political and economic control of metal production and circulation. This seems to be relevant in understanding the wide diffusion of hoards during the very Late Bronze Age, or around 1200 BC, in northeastern Italy, excluding the area belonging to the 'polity' of the Grandi Valli Veronesi, where socio-political centralisation had a longer impact

47 Cf. Borgna 2018, 328; Borgna 2023. For leaded-bronze in Final Bronze Age northern Adriatic as a sign of resources fragmentation cf. Giumlia-Mair 2003; also Giumlia-Mair 2005.

48 For Celò and Verzegnis: Borgna 2001, 317–321; Borgna 2007; Borgna 2018, 328–329; Borgna – Canovaro in press. For the archaeometallurgical data, see Canovaro 2016; Nardini et al. 2019.

on the organisation of metal supply and production and also favoured the maintenance of separate patterns of deposition, namely ritual vs. economic.

As for the number of hoards from the extreme northeastern regions or western *Caput Adriae*, archaeometallurgical research substantially contributed to a clearer definition of an explanatory framework which was already built up through the adoption of a purely archaeological perspective. This perspective predicted a diachronic pattern of change and transformation from monocentric supply and administered production firmly established as a communal resource in the central settlements during the Middle Bronze Age – Recent Bronze Age 1, c. 1500–1250/20, as exemplified by the possible workshop deposit of Cervignano, towards mobility, decentralisation and multidirectional distribution of metal starting from the industrial exploitation of the southern Alpine ores and particularly during the advanced Recent Bronze Age (BR 2/BF 1 or c. 12th century BC), as attested by the numerous hoards mostly buried in isolation outside of proper inhabited areas.

These hoards were mostly deposited at the time of cultural discontinuities, possibly involving the intervention of new agents from the transalpine/Urnfield regions, who participated in the subversion and transformation of previous patterns of metal production: the mixed metal composition of the ingots of some Final Bronze Age hoards such as Castions di Strada, Celò, Verzegnis is a significant indicator in this regard. Also, the association and composition of the bronzes in some of the hoards, such as Castions and Muscoli, could suggest the intervention of a new agency in the practices of metal circulation and consumption, pointing to a possible ritual behaviour in the final deposition of metal shipments.

The re-organisation of metallurgy according to a structured pattern implying the control of regional elites in the advanced Final Bronze Age – BF 2, 11th century BC or the age of Frattesina – likely coincided with the emergence of clearly defined metallurgical regions and even political territories exploiting different sources and depending upon authorities able to control the entire metallurgical cycle, from the mining sites to the craft contexts. Confirmation of this can be found in the different chemical and isotopic data of the materials – particularly some standards of value or tokens such as pick-ingots – from the deposits of Porpetto and Galleriano. The evidence seems to indicate the dissolution of a monocentric pattern of metal supply almost exclusively dependent upon the ores of the Italian Southern Alps.

Finally, it has been possible to identify the existence of separate spheres of exchange – an economic sphere in which metal circulated as a commodity or means of exchange and a ceremonial one serving elite consumption and accumulation through ritual strategies. These spheres may be a major indication for the integration of metallurgical activities in community life as well as for the existence of well-established emergent components. These were based either on the role – as could be the case in the Middle Bronze Age – early Recent Bronze Age contexts – or *status*, a concept that emerges overtly in the advanced Final Bronze Age.

Appendix: Archaeometric Study of the Hoard of Castions di Strada

The present unpublished data from several artefacts from Castions di Strada are reported and considered together with those that have already been published from Cervignano, Muscoli[49] and Celò[50] in order to support and reinforce the reconstruction of the flow of metal in Friuli Venezia Giulia during the Late Bronze Age.

First of all, the study focuses on ingots, which may be considered of fundamental importance, as they possessed a composition very close to the ore charge used in the smelting process. Moreover, whenever possible, the selection was extended to include weapons and tools, with the aim of more clearly outlining the commercial trade patterns and increasing knowledge about the successive steps of copperworking.

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[49] Canovaro et al. 2018; Canovaro et al. 2019.

[50] Nardini et al. 2019.

Sample	Typology	Inventory number	Description	Dimensions (cm)	Weight (g)	Chronology	Reference
CdsA-S	Flange-hilted sword, Boiu-Keszethely type	23578	Broken	L 5.9; W 3.6; H 0.6	65	MBA II–III	Borgna 2001, 299, fig. 3.3
CdSA-Ax-59	Winged-axe	2159 bis	Broken	L 13.5; W blade 4.6; H 3.6	528	MBA–RBA	Borgna 2001, 298, fig. 2.1
CdSA-AxC-4	Socketed axe	2314-2	Broken	L 8.6; W 2.8; Ø handle hole 4×2.8	126	FBA	Borgna 2001, 298, fig. 2.2
CdSB-AxA1	Winged-axe	2161	Complete	L 13.7; W blade 3.6; H 2.8	214	RBA–FBA1	Borgna 2001, 300, fig. 4.4
CdSB-AxA2	Winged-axe	2162	Broken	L 11.1; W blade 5.0; H 1.8	260	MBA–RBA	Borgna 2001, 300, fig. 4.3
CdSB-AxA9	Winged-axe	2159	Broken	L 12.8; W blade 4.9; H 3.9	550	MBA–RBA	Borgna 2001, 300, fig. 4.1
CdSB-Cp	Spearhead	23770	Broken	L 3.8;W 2.6; Ø handle hole 1.3	17	\	Borgna 2001, 299, fig. 3.2
CdSA-PnB	Bar-ingot	23759	Fragment	L 4.8; W 5.3; H 1.0	121	FBA1	Borgna 2001, 299, fig. 3.9
CdSA-P-17	Plano-convex ingot	4617a	Complete	L 19.5; W 14.5; H 4.0	2466	FBA1	
CdSA-P-19	Plano-convex ingot	4619a	2 fragments	Fr.A: L 6.5; W 4.0; H 1.3 Fr.B: L 6.5; W 4.3; H 1.3	Fr.A: 126 Fr.B: 131	FBA1	
CdSA-P-20	Plano-convex ingot	4620a	2 fragments	Fr.A: L 18.5; W 11; H 7.5 Fr.B: L 18.5; W 10.5; H 7.5	Fr.A: 3084 Fr.B: 2621	FBA1	
CdSB-P-50	Plano-convex ingot	29950	Fragment	L 9.0; W 3.8; H 2.1	268	FBA1	
CdSB-P-60	Plano-convex ingot	29960	Fragment	L 10; W 9.8; H 2.0	573	FBA1	
CdSB-P-61	Plano-convex ingot	29961	Fragment	L 12.5; W 13.2; H 2.7	1088	FBA1	
CdSB-P-81	Plano-convex ingot	29981	Fragment	L 6.4; W 7.7; H 3.8	648	FBA1	
CdSA-P-18	Truncated ingot	4618	Complete	Ø 21.2; H 7.5	8650	FBA1	
CdSA-P-22	Ingot	4622b	2 fragments	Fr.A: L 9.0; W 5.1 Fr.B: L 14.0; W 7.0	Fr.A: 893 Fr.B: 430	FBA1	
CdSB-P-71	Ingot	23771	Fragment	L 8.2; W 7.5; H 7.5	1191	FBA1	
CdSB-P-74	Ingot	23774	Fragment	L 14.5; W 6.0; H 2.8	690	FBA1	

Tab. 1 Information about the find circumstances, category of items, typology and chronology of all the analysed objects. The materials are presently preserved in the National Archaeological Museum of Cividale. L = length, W = width, H = height, Ø = hole diameter

	SEM-EDS								EPMA														Note		
Sample	Cu	Sn	Fe	S	Pb	As	Sb	Ni	S	Cl	Mn	Fe	Co	Ni	Cu	Zn	As	Ag	Sn	Sb	Pb	Bi	Sulphides	Sulphide zoning	Other inclusions
d.l. (%)									0.03	0.02	0.03	0.02	0.02	0.03	0.1	0.05	0.06	0.06	0.05	0.05	0.12	0.45			
CdSA-S*	86.2	10.3	0.9	0.8	0.8	<d.l.	<d.l.	1.0	0.01	0.00	0.01	0.24	0.04	0.23	90.27	0.01	0.13	0.05	10.06	0.00	0.04	0.02	$(Cu,Fe)_2S$	Fe+Zn; Fe	(Pb,Bi)-particles; no δ-phase; Pb in sulphides.
SD	*0.3*	*0.3*	*0.1*	*0.1*	*0.5*			*0.1*	*0.01*	*0.01*	*0.02*	*0.03*	*0.01*	*0.02*	*0.77*	*0.01*	*0.06*	*0.04*	*0.45*	*0.00*	*0.06*	*0.05*			
CdSA-Ax-59*	84.2	12.9	<d.l.	0.5	1.4	<d.l.	<d.l.	1.0	0.02	0.00	0.00	0.01	0.03	0.32	87.70	0.01	0.23	0.02	12.62	0.00	0.08	0.06	Cu_2S; $(Cu,Fe)_2S$	(Fe-Co)Ox FeOx	(Pb,Bi)-particles; δ-phase (with traces of Ni, Co, Ag and Pb); Pb in sulphides.
SD	*0.6*	*0.3*		*0.3*	*0.7*			*0.4*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*	*0.03*	*0.73*	*0.02*	*0.08*	*0.02*	*0.32*	*0.00*	*0.09*	*0.13*			
CdSA-AxC-4*	86.7	11.1	<d.l.	1.0	0.2	<d.l.	<d.l.	1.0	0.01	0.00	0.00	0.02	0.03	0.37	91.94	0.00	0.31	0.06	8.64	0.00	0.02	0.00	Cu_2S; $(Cu,Fe)_2S$	\	(Pb,Bi)-particles; δ-phase (with traces of Ni, Co and Pb); Pb in sulphides.
SD	*1.0*	*1.0*		*0.1*	*0.2*			*0.3*	*0.01*	*0.01*	*0.00*	*0.01*	*0.01*	*0.01*	*0.95*	*0.00*	*0.06*	*0.04*	*0.82*	*0.00*	*0.03*	*0.00*			
CdSB-AxA-1	86.1	13.1	<d.l.	0.4	0.4	<d.l.	<d.l.	<d.l.	0.02	0.01	0.00	0.03	0.11	0.06	86.01	0.01	0.05	0.12	14.34	0.00	0.00	0.00	Cu_2S; $(Cu,Fe)_2S$	FeOx, Fe+Zn, Fe.	(Pb,Bi)-particles; δ-phase (with traces of Ni, Co and Ag); Fe oxides; Pb, Co and Zn in sulphides.
SD	*0.3*	*0.3*		*0.1*	*0.3*				*0.01*	*0.01*	*0.00*	*0.01*	*0.02*	*0.02*	*0.36*	*0.01*	*0.06*	*0.03*	*0.24*	*0.00*	*0.00*	*0.00*			
CdSB-AxA-2	88.8	5.6	<d.l.	0.6	1.6	2.0	<d.l.	1.4	0.02	0.01	0.01	0.01	0.04	0.30	94.97	0.01	0.63	0.09	5.32	0.07	0.03	0.02	Cu_2S	(Fe-Co)Ox (Fe,Co,Zn)Ox	(Pb,Bi)-particles; no δ-phase; Pb and Ag in sulphides.
SD	*1.6*	*0.7*		*0.3*	*1.1*	*0.4*		*0.1*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*	*0.03*	*0.24*	*0.02*	*0.08*	*0.05*	*0.34*	*0.04*	*0.02*	*0.05*			
CdSB-AxA-9*	91.0	8.3	<d.l.	0.3	0.4	<d.l.	<d.l.	<d.l.	0.00	0.00	0.00	0.01	0.02	0.26	91.00	0.01	0.47	0.04	8.99	0.00	0.06	0.00	Cu_2S; $(Cu,Fe)_2S$	Fe, FeOx	(Pb,Bi)-particles; no δ-phase.
SD	*0.2*	*0.1*		*0.1*	*0.3*				*0.00*	*0.01*	*0.00*	*0.02*	*0.02*	*0.04*	*0.83*	*0.03*	*0.06*	*0.02*	*0.71*	*0.00*	*0.08*	*0.00*			
CdSB-Cp	85.0	12.1	<d.l.	1.0	0.5	<d.l.	<d.l.	1.4	0.00	0.00	0.01	0.06	0.05	0.15	88.34	0.02	0.08	0.08	11.58	0.00	0.07	0.02	$(CuFe)_2S$	Fe, Fe+Zn, FeOx	(Pb,Bi)-particles; no δ-phase.
SD	*1.0*	*0.6*		*0.2*	*0.4*			*0.2*	*0.00*	*0.01*	*0.01*	*0.01*	*0.02*	*0.04*	*0.59*	*0.02*	*0.04*	*0.04*	*0.34*	*0.00*	*0.09*	*0.05*			
CdSA-PnB*	91.0	<d.l.	1.0	1.4	tr	3.6	2.1	1.0	0.01	0.00	0.00	0.44	0.11	0.32	95.87	0.01	2.58	0.03	0.09	1.56	0.03	0.01	Cu_2S; $(Cu,Fe)_2S$	\	As-rich segregations; Ag, Sn, Ni and Co in sulphides.
SD	*0.4*		*0.2*	*0.3*		*1.7*	*0.2*	*0.2*	*0.02*	*0.01*	*0.01*	*0.11*	*0.02*	*0.06*	*1.23*	*0.02*	*0.46*	*0.02*	*0.04*	*0.45*	*0.07*	*0.03*			
CdSA-P-17	92.3	<d.l.	1.0	1.5	1.3	2.2	1.0	<d.l.	0.02	0.01	0.01	0.33	0.03	0.07	98.98	0.00	1.13	0.02	0.00	0.05	0.02	0.00	$(Cu,Fe)_2S$	Fe, FeOx	Pb particles; As-rich segregations; Co and As in sulphides.
SD	*1.1*		*0.2*	*0.5*	*0.6*	*0.5*	*0.6*		*0.02*	*0.00*	*0.01*	*0.09*	*0.01*	*0.01*	*0.11*	*0.01*	*0.17*	*0.02*	*0.01*	*0.04*	*0.04*	*0.00*			
CdSA-P-18	96.2	<d.l.	0.7	1.8	1.3	<d.l.	<d.l.	<d.l.	0.02	0.01	0.01	0.17	0.18	0.13	99.77	0.00	0.14	0.04	0.03	0.03	0.00	0.00	$(Cu,Fe)_2S$	\	(Pb,Bi)-particles; Pb, Ag and Co in sulphides.
SD	*0.5*		*0.2*	*0.7*	*0.4*				*0.02*	*0.00*	*0.01*	*0.09*	*0.01*	*0.01*	*0.11*	*0.01*	*0.17*	*0.02*	*0.01*	*0.04*	*0.04*	*0.00*			
CdSA-P-19	94.5	<d.l.	2.3	1.6	1.6	<d.l.	<d.l.	<d.l.	0.01	0.01	0.01	1.94	0.04	0.03	98.75	0.05	0.04	0.06	0.06	0.02	0.00	0.00	$(Cu,Fe)_2S$	Fe	(Pb,Bi)-particles, (Pb,Ag)-particles; Pb, Ag and Zn in sulphides.
SD	*1.0*		*0.1*	*0.7*	*0.5*				*0.01*	*0.02*	*0.01*	*0.27*	*0.02*	*0.01*	*0.52*	*0.03*	*0.08*	*0.05*	*0.05*	*0.03*	*0.00*	*0.00*			
CdSA-P-20	89.5	<d.l.	0.7	3.8	1.6	1.2	1.6	1.5	0.00	0.01	0.00	0.17	0.01	0.87	99.21	0.01	0.48	0.01	0.02	0.43	0.02	0.00	Cu_2S; $(Cu,Fe)_2S$	Fe	Sb-rich segregations.
SD	*0.6*		*0.1*	*0.5*	*0.3*	*0.3*	*0.4*	*0.1*	*0.00*	*0.01*	*0.00*	*0.01*	*0.01*	*0.05*	*0.73*	*0.01*	*0.17*	*0.01*	*0.01*	*0.16*	*0.03*	*0.00*			

	SEM-EDS								EPMA														Note		
Sample	Cu	Sn	Fe	S	Pb	As	Sb	Ni	S	Cl	Mn	Fe	Co	Ni	Cu	Zn	As	Ag	Sn	Sb	Pb	Bi	Sulphides	Sulphide zoning	Other inclusions
d.l. (%)									0.03	0.02	0.03	0.02	0.02	0.03	0.1	0.05	0.06	0.06	0.05	0.05	0.12	0.45			
CdSA-P-22*	92.3	<d.l.	<d.l.	<d.l.	<d.l.	4.4	3.3	<d.l.	0.01	0.01	0.01	0.01	0.01	0.16	95.68	0.00	3.00	0.02	0.01	0.70	0.01	0.00	Cu_2S	\	(Pb,As,Sb)-particles; (As,Sb)-rich segregations; mineral remains.
SD	*1.3*					*0.4*	*1.0*		*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*	*0.81*	*0.00*	*0.59*	*0.02*	*0.02*	*0.26*	*0.03*	*0.00*			
CdSB-P-50	96.5	<d.l.	1.3	2.2	tr	<d.l.		<d.l.	0.02	0.01	0.01	0.76	0.33	0.19	98.85	0.02	0.29	0.04	0.03	0.00	0.05	0.00	$(Cu,Fe)_2S$	\	(Pb,As)-particles; As-rich segregations; Co, As and Pb in sulphides.
SD	*0.5*		*0.2*	*0.3*					*0.01*	*0.01*	*0.01*	*0.09*	*0.05*	*0.05*	*0.47*	*0.03*	*0.11*	*0.04*	*0.04*	*0.00*	*0.07*	*0.00*			
CdSB-P-60	82.5	<d.l.	9.5	2.3	<d.l.	3.2	1.3	1.1	0.02	0.01	0.00	2.61	0.03	0.10	97.18	0.01	1.05	0.02	0.01	0.18	0.05	0.00	$(Cu,Fe)_2S$	Fe	(Pb,As,Sb)-particles; As-rich segregations; Fe-rich phases (89%Fe); As and Ni-Co in sulphides.
SD	*6.6*		*5.6*	*0.5*		*0.2*	*0.6*	*0.2*	*0.01*	*0.01*	*0.00*	*0.45*	*0.02*	*0.02*	*0.48*	*0.02*	*0.69*	*0.02*	*0.02*	*0.14*	*0.07*	*0.00*			
CdSB-P-61	93.8	<d.l.		1.9	<d.l.	1.9	1.5	1.8	0.01	0.01	0.00	0.00	0.00	0.42	98.92	0.01	0.68	0.01	0.02	0.34	0.02	0.00	Cu_2S	(Fe, Co, Ni, Zn) Ox	Ag-particles; Sb-rich segregations.
SD	*1.3*			*0.6*		*0.5*	*0.4*	*0.2*	*0.02*	*0.01*	*0.00*	*0.00*	*0.01*	*0.08*	*0.19*	*0.02*	*0.15*	*0.03*	*0.02*	*0.12*	*0.05*	*0.01*			
CdSB-P-71	96.9	<d.l.	0.7	2.4	<d.l.	<d.l.	<d.l.	<d.l.	0.01	0.00	0.01	0.42	0.37	0.05	99.43	0.01	0.11	0.02	0.03	0.01	0.02	0.02	$(Cu,Fe)_2S$	Fe-Co	(Pb,Ag)-particles; As in sulphides.
SD	*1.8*		*0.5*	*1.6*					*0.01*	*0.00*	*0.01*	*0.08*	*0.07*	*0.02*	*0.27*	*0.01*	*0.04*	*0.03*	*0.03*	*0.02*	*0.05*	*0.04*			
CdSB-P-74	91.7	<d.l.	1.0	1.5	tr	3.4	2.4	<d.l.	0.01	0.01	0.01	0.71	0.14	0.17	96.76	0.00	2.03	0.03	0.03	0.49	0.01	0.03	Cu_2S; $(Cu,Fe)_2S$	\	(Pb,As,Sb)-particles; Sb-rich segregations; Fe-Co phases.
SD	*0.3*		*0.2*	*0.6*		*0.7*	*0.6*		*0.01*	*0.01*	*0.01*	*0.02*	*0.02*	*0.02*	*0.28*	*0.00*	*0.22*	*0.03*	*0.02*	*0.06*	*0.01*	*0.08*			
CdSB-P-81	96.5	<d.l.	<d.l.	1.5	2.5	<d.l.	<d.l.	<d.l.	0.02	0.01	0.00	0.14	0.02	0.02	99.95	0.09	0.03	0.06	0.01	0.03	0.00	0.00	$(Cu,Fe)_2S$	\	(Pb,Bi)-particles; Pb and Zn in sulphides.
SD	*0.5*			*0.2*	*0.7*				*0.02*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.19*	*0.07*	*0.03*	*0.07*	*0.01*	*0.02*	*0.01*	*0.00*			
Cel-Pal*	92.5	5.7	<d.l.	0.4	0.6	<d.l.	<d.l.	0.6	0.01	0.01	0.01	0.07	0.08	0.27	94.27	0.01	0.48	0.03	5.62	0.00	0.01	0.01	$(Cu,Fe)_2S$	Fe	Pb-particles; δ-phase with Ni (1%).
SD	*0.4*	*0.3*		*0.0*	*0.1*			*0.1*	*0.01*	*0.01*	*0.01*	*0.02*	*0.01*	*0.03*	*1.55*	*0.01*	*0.07*	*0.02*	*1.30*	*0.01*	*0.02*	*0.02*			
Cel-AxC1*	91.3	6.9	<d.l.	0.2	0.6	<d.l.	<d.l.	0.9	0.01	0.01	0.01	0.01	0.02	0.38	93.33	0.00	0.67	0.05	6.35	0.04	0.03	0.03	Cu_2S	FeOx	Pb-particles; δ-phase with Ni (3%).
SD	*0.8*	*0.5*		*0.1*	*0.3*			*0.4*	*0.00*	*0.01*	*0.01*	*0.01*	*0.02*	*0.03*	*1.05*	*0.00*	*0.18*	*0.05*	*0.97*	*0.07*	*0.05*	*0.06*			
Cel-AxC8*	91.0	8.0	<d.l.	0.2	0.4	<d.l.	<d.l.	0.3	0.01	0.01	0.01	0.01	0.04	0.33	91.93	0.01	0.41	0.06	7.39	0.00	0.03	0.00	Cu_2S	Fe	Pb-particles; (Pb,Bi)-particles; δ-phase with Ni (3%).
SD	*0.2*	*0.7*		*0.1*	*0.4*			*0.1*	*0.01*	*0.01*	*0.02*	*0.01*	*0.01*	*0.04*	*0.88*	*0.02*	*0.10*	*0.03*	*0.58*	*0.01*	*0.05*	*0.00*			
Cel-AxA2	92.4	6.7	<d.l.	0.3	0.7	<d.l.	<d.l.	<d.l.	0.02	0.01	0.02	0.01	0.04	0.39	92.18	0.01	0.37	0.04	7.15	0.00	0.05	0.04	Cu_2S	FeOx	(Pb,Bi)-particles; no δ-phase.
SD	*0.2*	*0.2*		*0.1*	*0.1*				*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	*0.02*	*0.64*	*0.03*	*0.07*	*0.03*	*0.30*	*0.00*	*0.05*	*0.09*			
Cel-AxA3	90.9	8.1	<d.l.	0.2	0.8	<d.l.	<d.l.	<d.l.	0.00	0.00	0.01	0.07	0.04	0.33	89.74	0.01	0.49	0.05	9.25	0.00	0.05	0.00	$(Cu,Fe)_2S$	Fe	(Pb,Bi)-particles; no δ-phase.
SD	*0.2*	*0.2*		*0.2*	*0.0*				*0.00*	*0.00*	*0.00*	*0.02*	*0.02*	*0.02*	*0.54*	*0.02*	*0.06*	*0.03*	*0.08*	*0.00*	*0.06*	*0.00*			
Cel-AxA8	91.0	7.7	<d.l.	0.4	0.4	<d.l.	<d.l.	0.5	0.01	0.01	0.01	0.06	0.05	0.51	90.00	0.01	0.72	0.07	8.62	0.00	0.05	0.02	$(Cu,Fe)_2S$	Fe; FeOx	(Pb,Bi)-particles; no δ-phase.
SD	*0.1*	*0.2*		*0.0*	*0.1*			*0.1*	*0.00*	*0.01*	*0.01*	*0.03*	*0.00*	*0.03*	*0.51*	*0.02*	*0.09*	*0.04*	*0.25*	*0.01*	*0.06*	*0.04*			

Tab. 2 SEM-EDS and EPMA chemical analyses (wt%) of the α-phase of all the analysed objects and ingots from Castions di Strada. Data are calculated as a mean of 5÷10 points analysis. Data are reported as obtained by the analyses. d.l. = detection limit; SD = standard deviation of the measures; tr = traces; * = arithmetic mean between Cu-rich and Cu-poor phases

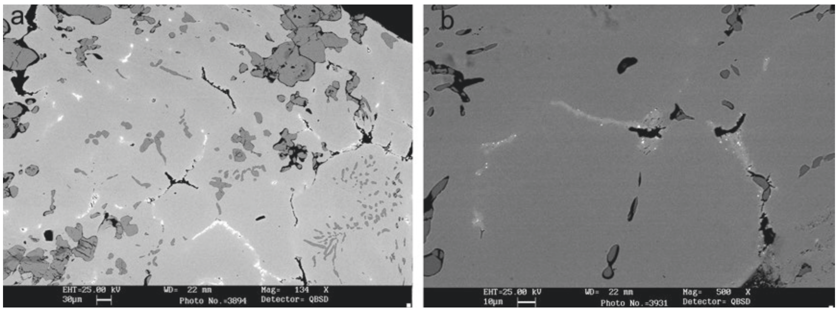

Fig. 10 SEM-BSE image of ingots. a. Plano-convex ingot CdSA-P-20, exhibiting a coarse dendritic structure; b. Microstructure of plano-convex ingot CdSA-P-17 showing As- and Sb-rich segregations (pale grey) into interdendritic spaces and copper-iron sulphides are dispersed in the α-phase (C. Canovaro)

The multi-analytical approach applied[51] focuses on the study of chemical composition and the observation of any residual phases due to an incomplete refinement of the raw material in order to shed light on the employed Cu-ore charge. As this information is often insufficient to clearly identify the exploitation area of the metal, such investigation methods were coupled with lead isotopes analysis (LIA). Therefore, the set of mineralogical, metallurgical, chemical and isotopic analyses, through a comparison with existing Pb-isotope databases, published data and the Alpine Archaeocopper Project database (AAcP)[52] allowed for the identification of the provenance of the metal.

In the hoard from Castions di Strada, the selected finds for the analyses are listed in Table 1. The results obtained by the elemental analyses (Tab. 2) clearly show the presence of two compositional groups. The first is composed of three ingots, chemically and microstructurally similar to those of Muscoli and Cervignano that exhibit a mean Fe content varying from 0.7% to 2.3%. Nevertheless, in all of these samples, no traces of Zn were detected except in CdSB-P-81. Conversely, the second group of ingots is characterised by varying amounts of As (1–3.5%), Sb (1–3.3%), Ni (1–1.8%) and traces of Co. These samples are characterised by a coarse dendritic structure (Fig. 10), indicating relatively low cooling rates after the casting process. In all of the analysed ingots, significant amounts of copper and copper-iron sulphides are dispersed in the α-phase (Fig. 10.a, in dark grey), suggesting the use of sulphide ores for producing the metal. Moreover, considering the chemical composition, the extractive charge of the first group of samples may be associated with chalcopyrite/sphalerite and small contents of galena (as for the Cervignano and Muscoli ingots), while the charge from the second group can be identified as a *fahlerz*-ore type because of its distinctive chemical pattern.[53]

Consistently, LIA suggests a diversification in terms of raw materials and exploited resources (Tab. 3); indeed, Figure 11 shows that six out of the seven analysed ingots fall in a region of the diagrams out from the eastern Southern Alps field (dotted circle), suggesting a derivation from distant sources. In particular, three ingots exhibiting a *fahlerz* composition (CdSA-P-17, CdSB-P-74 and CdSB-P-60, marked in the plot as a Fhlz ingot) appear clustered together, whereas a fourth ingot (CdSA-PnB, another Fhlz ingot), is slightly removed. All of the *fahlerz* ingots are isotopically fully consistent with the ores from the Austrian Tyrol, and, therefore, they may derive from the same ore charge and perhaps even from the same ore source or mine. Conversely, two samples (CdSA-P-18 and CdSB-P-50, yellow circles) are characterised by a comparatively pure copper with only small traces of As, Sb, Ni and Co, and, therefore, it is not possible to make a certain attribution. Bulgaria, Austria and central Europe are all equally probable source areas.

Finally, the last ingot (CdSB-P81), obtained from the smelting of chalcopyrite, shows a lead isotope composition that could match with both the Valsugana VMS and Carinthia (Austria)

51 Canovaro et al. 2019.
52 AAcP: <http://geo.geoscienze.unipd.it/aacp/welcome.html> (last accessed 27 March 2024).
53 Craddock 1995.

Sample	Type	206/204	±2SE	207/204	±2SE	208/204	±2SE
CdS A-P-17	Plano-convex	18.837	0.004	15.688	0.004	39.120	0.009
CdS A-P-18	Truncated ingot	18.894	0.004	15.698	0.003	39.213	0.008
CdS B-P-50	Plano-convex	18.703	0.003	15.686	0.003	38.739	0.007
CdS B-P-74	Ingot	18.845	0.002	15.686	0.002	39.142	0.006
CdS B-P-81	Plano-convex	17.922	0.002	15.637	0.002	38.143	0.005
CdSA-PnB	Bar-ingot	18.704	0.003	15.689	0.003	38.963	0.007
CdSB-P60	Plano-convex ingot	18.821	0.002	15.692	0.002	39.116	0.008
CdS A-S	Flange-hilted sword, Boiu-Keszethely type	18.135	0.002	15.658	0.002	38.357	0.006
CdS B-AxA-1	Winged-axe	18.189	0.002	15.669	0.002	38.424	0.007
CdS B-AxA-2	Winged-axe	18.464	0.002	15.681	0.002	38.690	0.007
CdS B-AxA-9	Winged-axe	18.372	0.002	15.673	0.002	38.562	0.007
CdS A-Ax-59	Winged-axe	18.342	0.002	15.665	0.002	38.463	0.006
CdS A-AxC-4	Socketed axe	18.334	0.002	15.670	0.002	38.505	0.008
CdS B-Cp	Spearhead	18.192	0.003	15.663	0.003	38.436	0.008

Tab. 3 Samples analysed and Pb isotope values divided by typology. 2SE is analytical uncertainties calculated as twice the individual in-run precision on the samples

regions and, because of the fairly similar lead isotope ratios of these two fields, it is currently impossible to clearly distinguish its provenance. On this basis, two hypotheses are equally plausible: it is possible that *fahlerz*- and chalcopyrite ores could have been mined in Austria from the Tyrol and Carinthia regions, respectively. However, it is also possible that the Valsugana continued to be exploited in FBA1 for the supply of chalcopyrite. In either case, the presence of copper ingots of different origins found at the same site provides evidence for the movement of the metal from the Alps toward central Europe and the Balkans. Interestingly, different types of ores were smelted. These observations are in line with events in central Europe during the Late Bronze Age. As stated by Joachim Lutz and Ernst Pernicka,[54] a resumption of *fahlerz* employment has been recorded in this period, possibly due to the rising demand for copper that could not be covered by the chalcopyrite mines alone.

As for the weapons, chemical analyses revealed that all of the objects belonging to the hoards from Castions di Strada are bronzes characterised by a Sn content with an average rate of 10.5% (Tab. 2), ensuring a good workability of the alloy. Regarding the trace elements, Ni is always present (~1%), while As varies from 0.2% to 2.0% (Tab. 2). Lead isotope signals of the investigated objects seem to be more uniform than those of the ingots. The sword, the spearhead and one of the axes (CdSA-AxA1) mostly lie between the two major fields of the eastern southalpine region, close to the South-Alpine AATV mines. The lowering in $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios is especially evident for the sword and can be explained by a contribution of copper from the Calceranica and Vetriolo mines. The results of the Euclidean test performed on the other axes revealed a sure attribution to the South-Alpine AATV mines for one sample (CdSB-AxA9), while two other samples (CdSB-AxA2 and CdSB-C4) revealed an ambiguous situation, which did not allow for a safe geographical attribution. However, their chemical composition and context argue in favour of the exploitation of the Eastern Alps, even if it is not possible at the moment to provide a clearer discrimination. Additionally, another doubt arose from CdSA-Ax59, as this axe exhibits a low $^{207}Pb/^{204}Pb$ ratio and falls in an area equally distant from some Slovakian deposits and the Trentino Alto Adige mines.

54 Lutz – Pernicka 2013.

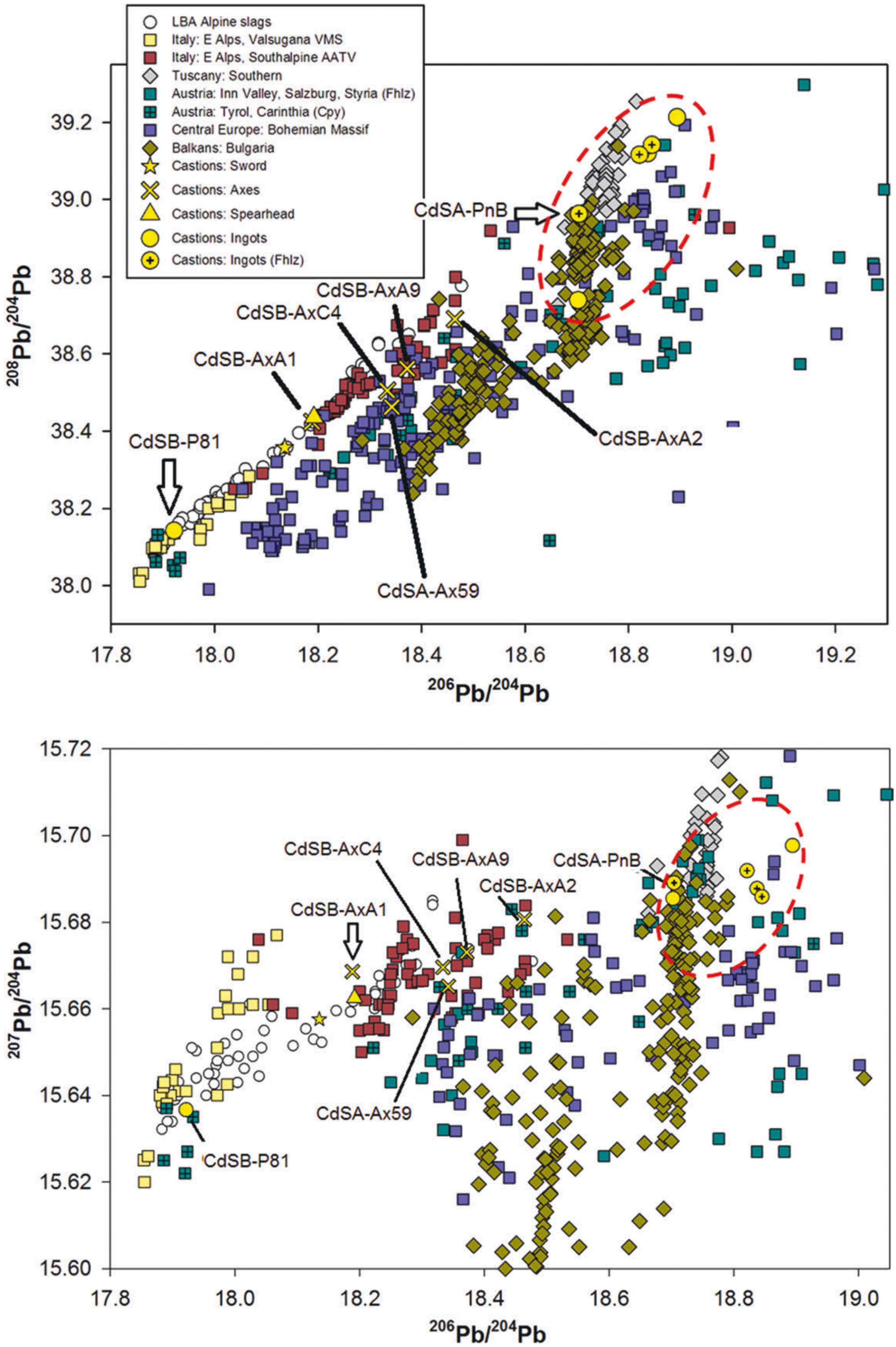

Fig. 11 Lead isotope ratios diagrams of the ingots and the artefacts from the hoard of Castions di Strada compared with the possible ore sources. The analytical uncertainty is equivalent or smaller than the size of the symbols. Data: Lattanzi et al. 1992; Stos-Gale et al. 1998; Niederschlag et al. 2003; Höppner et al. 2005; Artioli et al. 2008; Nimis et al. 2012; Addis 2013; Artioli et al. 2016; Chiarantini et al. 2018; Artioli et al. 2020 (chart: C. Canovaro)

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Ingots from Italy, Metals from Mitterberg, Copper from Cyprus: Studies on Bronze Age Metal Procurement in the Western and Central Balkans

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Abstract: This article discusses the nature of copper supply in the western and central Balkans. A systematical evaluation of 49 plano-convex and rod ingots, all dated to Ha A1, forms the basis for further conclusions. In particular, we focus on the raw metal pieces found in five hoards and a settlement in Bosnia-Herzegovina (Cvrtkovci, Kućišta, Novigrad, Paležnica, Podzvizd and Topolovaca Bregovi) and 13 hoards found in Serbia (Futog, Hetin, Klenje, Kličevac-Pomrlovo, Kličevac-Rastovača, Krčedin, Laznica, Privina Glava, Popinci, Rudnik, Trlić, S. Karlovci, Vitojevac). The archaeometallurgical analyses allow us to conclude that their copper can be traced back to either the mining fields in Trentino and the Vinschgau region (Italy) or to the Mitterberg (Hochkönig, Austria) area. Additionally, we discuss Cyprus as a further (subordinated) origin of the metals and a Mycenaean sword from Tetovo (MKD). The plano-convex ingots themselves contain raw copper, which is only in rare cases alloyed with lead or tin (a marker for recycling). Meanwhile, the rod ingots are more often alloyed with these agents. The presence of copper from different mining regions within the same hoard gives insight into the distribution mechanisms of this object type. It shows that ingots from both major mining areas regularly circulated in the region under study. Furthermore, ingot fragments with similar geochemical patterns can be found in different depots. This allows us to conclude that their copper has the same production area (using ore from the same mine). One might hypothesise that they travelled along the river routes (Danube, Sava, Drava), arriving together at the Balkans and were then distributed. Finally, it is absolutely worth noting that we find the same analytical results in plano-convex ingots and finished objects found in Croatia and Slovenia. This provides evidence that these regions also participated in the same exchange systems, which started in the Alpine regions.

Keywords: Bronze Age, copper trade, Trentino, Mitterberg, Cyprus, lead isotope analyses, mixing, recycling, Mycenaean sword

Introduction

The exchange of goods, especially metals, has been a focus of archaeological research for a long time, as these have played a crucial role in characterising long-range connections. The various forms of evidence (raw material, semi- and finished products) have allowed for different interpretations about the nature and intensity of such contacts.

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During the last decades, the source regions of the metals, the copper ore deposits and metallurgical remains in the Alps (e.g., in North Tyrol, Salzburg or Styria) underwent intensive archaeometric research. Copper produced in the Eastern Alpine mining areas has been found in the famous sky disk from Nebra and in countless ingots, semi-finished and artefacts, demonstrating that it was the main copper supplier in Europe.[8] Additionally, the use of eastern Alpine copper from these eastern Alpine mining regions in the Balkans was first discussed in relation to a dagger from Gnojnice in southern Bosnia-Herzegovina[9] and is evident for the later periods of the Bronze Age in this region.[10] The adjoining southern Alpine region, especially South Tyrol, Trentino and the Veneto, has also been more extensively investigated during the last ten years.[11] Recent research by Reinhard Jung and Mathias Mehofer has already shown that the Trentino area in northern Italy played a crucial role in the copper supply of the Apennine Peninsula,[12] with raw metal and finished objects originating from these mining regions finding their way to central and southern Italy. Finished artefacts and copper ingots were excavated in Coppa Nevigata, Punta di Zambrone, and Rocca Vecchia,[13] providing evidence that metal smiths in southern Italy had access to the north Italian exchange networks via the Adriatic Sea.[14] Publications by Johan Ling, Heide Nørgaard and others showed that Trentino metal also reached the regions north of the Alpine ridge to Denmark and beyond.[15] Furthermore, we demonstrated that this copper was also traded to the central and western Balkan region from approximately BA B1 onwards and was dominantly used in the following centuries.[16] It must be pointed out that objects made of southern Alpine copper are also present in the eastern Mediterranean world; however, in this region, it is highly interesting that only finished artefacts (belonging to the 'urnfield bronzes') are made of copper from northern Italy. The most prominent example is a Naue-II-sword, which forms part of the so-called Tsountas hoard I in Mycenae, which dates to the 13th century BC. As its copper is of north Italian provenance and its typological form was unknown in Greece during that time, Jung and Mehofer concluded that this artefact came as a finished piece to the Peloponnese.[17] In contrast, all objects from the hoard, which can be assigned to local Mediterranean metal types, are made of Cypriot metal. Oxhide ingots, as the most prominent form of Cypriot raw copper, are known from all over the eastern Mediterranean world – from Sardinia to the Near East as well as from Romania to the North African regions.[18] These observations show that various exchange networks were active during the Bronze Age, overlapped in the central and western Balkans, and transported copper in every area of the study region. The common trading forms of these exchange networks – the plano-convex and the rod ingots – will be in the focus of this study.

8 Stöllner 2011; Pernicka et al. 2016; Stöllner 2019.

9 Mehofer et al. 2021, fig. 14 no. 362. Second possible source would be the Bulgarian region. A further object with such a provenance from the western Balkans is listed in Schmitt-Strecker – Begemann 2005, 54, tab. 2, no. 1025.

10 Trampuž Orel 1996; Trampuž Orel – Trampuž 2009; Gavranović et al. 2022, 16, 17, fig. 5.

11 Artioli et al. 2016.

12 Jung et al. 2011; Jung – Mehofer 2013; Artioli et al. 2016; Mehofer et al. 2020.

13 Jung et al. 2021; Jung et al. in press.

14 Jung et al. 2011.

15 Melheim et al. 2018; Ling et al. 2019; Kmosek et al. 2020; Nørgaard et al. 2021; Nørgaard et al. 2023.

16 Schmitt-Strecker – Begemann 2005, 54 tab. 2; Mehofer et al. 2021; Gavranović et al. 2022. This can also by hypothesised for some objects from the western Balkans, dated to BA B2–C1. These are the finds no. 779, 782, 785, 786, 790, 795, 796, 799, 1022, 1023, 1032, 1048 published by Schmitt-Strecker – Begemann 2005, 54, tab. 2.

17 Jung – Mehofer 2013.

18 Primas – Pernicka 1998; Gale – Stos-Gale 2005; Molloy 2018, 146, figs. 2A and 2B, 148–149; Athanassov et al. 2020.

Questions and Objectives

For the Middle and Late Bronze Age, copper ingots are a common form in the archaeological record – e.g. in hoards[19] – and mark the exchange of raw metal between copper mining areas and the final users and/or consumers. As it is widely accepted that they can be directly linked to the production area (the vicinity of the smelting sites) where they were melted,[20] they serve as good vehicles for exploring trading and exchange connections. Within this examination, we will investigate the influx of such raw material (plano-convex and rod ingots) to the central and western Balkans to understand the use and distribution of copper. Furthermore, we will investigate whether and to what extent the geochemical signature was changed during the processing of the copper, with particular emphasis on the possible evidence of mixing and recycling.

Materials

In total, our dataset comprises 560 analyses of objects from the western and central Balkans, including Croatia, Bosnia-Herzegovina, Serbia, Kosovo and North Macedonia, and covers the time of BA A – Ha C1. In some cases, it was necessary to take several samples from single objects, as they are made from different construction elements. The sampling strategy encompassed context,

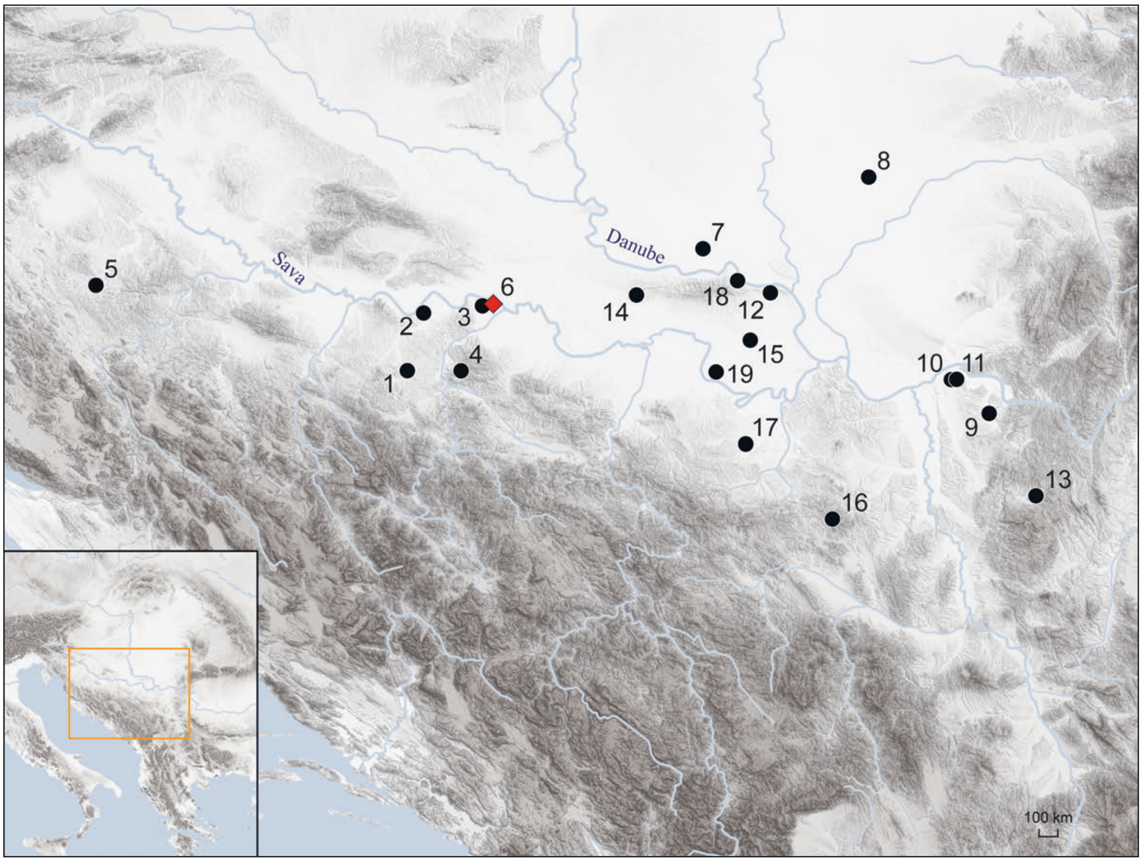

Fig. 1 Map of the sites included in the presented analyses. 1: Cvrtkovci; 2: Kućišta; 3: Novigrad; 4: Paležnica; 5: Podzvizd; 6: Topolovaca Bregovi; 7: Futog; 8: Hetin; 9: Klenje; 10: Kličevac-Rastovača; 11: Kličevac-Pomrlovo; 12: Krčedin; 13: Laznica; 14: Privina Glava; 15: Popinci; 16: Rudnik; 17: Trlić; 18: S. Karlovci; 19: Vitojevac, black dot: hoard find, red diamond: settlement (design: I. Petschko, OeAI-OeAW, basemap data: NASA JPL, Natural Earth)

[19] See the contribution of M. Gavranovic et al. in this volume.

[20] Modl 2019.

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Object	Site	Country	Analyses
DobM 39*	–	MA-152364	plano-convex ingot, frag.	Topolovaca Bregovi	BIH	ED-XRF, LIA
DobM 49	1792	MA-152365	plano-convex ingot, frag.	Kućišta	BIH	ED-XRF, LIA
DobM 61	1867	MA-186702	ring- or ingotfrag., frag.	Kućišta	BIH	ED-XRF, LIA
DobM 69	4426	MA-152366	plano-convex ingot, frag.	Paležnica	BIH	ED-XRF, LIA
DobM 70	4428	MA-152367	plano-convex ingot, frag.	Paležnica	BIH	ED-XRF, LIA
DobM 72	4885	MA-152368	plano-convex ingot, frag.	Cvrtkovci	BIH	ED-XRF
DobM 86	1216	MA-152369	plano-convex ingot, frag.	Paležnica	BIH	ED-XRF
SJLM 39*	32793	MA-195997	plano-convex ingot	Novigrad	BIH	ED-XRF, LIA
SJLM 48*	32791	MA-186719	plano-convex ingot	Novigrad	BIH	ED-XRF, LIA
SJLM 49	32792	MA-196002	plano-convex ingot	Novigrad	BIH	ED-XRF, LIA
SJLM 71*	550	MA-196005	ingot, frag.	Podzvizd	BIH	ED-XRF, LIA
SJLM 74	552	MA-196006	ingot, frag.	Podzvizd	BIH	ED-XRF, LIA
SJLM 77	–	MA-196007	ingot, frag.	Podzvizd I a	BIH	ED-XRF, LIA
BelM 440	2136v	MA-196310	plano-convex ingot	Privina Glava	SRB	ED-XRF, LIA
BelM 441	2136g	MA-196311	plano-convex ingot	Privina Glava	SRB	ED-XRF, LIA
BelM 447	3275b	MA-196317	ingot	Rudnik	SRB	ED-XRF, LIA
BelM 449*	3275	MA-196318	plano-convex ingot	Rudnik	SRB	ED-XRF, LIA
BelM 465	1464a	MA-196322	rod ingot	Trlić	SRB	ED-XRF, LIA
BelM 467*	14464d	MA-196323	rod ingot	Trlić	SRB	ED-XRF, LIA
BelM 471	14465d	MA-196324	ingot	Trlić	SRB	ED-XRF, LIA
BelM 474*	14465f_1	MA-196325	plano-convex ingot, frag., lower layer	Trlić	SRB	ED-XRF, LIA
BelM 475*	14465f_2	MA-196326	plano-convex ingot, frag., upper layer	Trlić	SRB	ED-XRF, LIA
BelM 504	26030_a	MA-196342	ingot	Kličevac-Pomrlovo	SRB	ED-XRF, LIA
BelM 505	26030_b	MA-196343	rod ingot	Kličevac-Pomrlovo	SRB	ED-XRF, LIA
BelM 530	26224	MA-196364	rod ingot	Laznica	SRB	ED-XRF, LIA
BelM 532	26330	MA-196365	plano-convex ingot	Laznica	SRB	ED-XRF
BelM 534	26332	MA-196366	plano-convex ingot	Laznica	SRB	ED-XRF
BelM 535	26331	MA-196367	plano-convex ingot	Laznica	SRB	ED-XRF, LIA
BelM 536	26512	MA-196368	plano-convex ingot	Vitojevac	SRB	ED-XRF, LIA
BelM 538	26514	MA-196451	plano-convex ingot	Vitojevac	SRB	ED-XRF, LIA
PozM 35*	2222	MA-186761	rod ingot	Kličevac-Rastovača	SRB	ED-XRF, LIA
PozM 36	2224	MA-196058	rod ingot	Kličevac-Rastovača	SRB	ED-XRF, LIA
PozM 39	2144	MA-186762	ingot-semi-finished product?	Kličevac-Rastovača	SRB	ED-XRF, LIA
PozM 56	1007b	MA-196070	ingot fragment	Klenje	SRB	ED-XRF, LIA
PozM 58	1008b	MA-186768	ingot fragment	Klenje	SRB	ED-XRF, LIA
PozM 69*	–	MA-186770	plano-convex ingot, frag.	Klenje	SRB	ED-XRF, LIA

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Object	Site	Country	Analyses
VoNSM 157	3296	MA-196146	plano-convex ingot, frag.	Krčedin	SRB	ED-XRF, LIA
VoNSM 187	3419	MA-196167	plano-convex ingot	Futog	SRB	ED-XRF, LIA
VoNSM 189	3421	MA-196168	plano-convex ingot	Futog	SRB	ED-XRF, LIA
VoNSM 190	3422	MA-196169	rod ingot	Futog	SRB	ED-XRF, LIA
VoNSM 204	400A	MA-196179	plano-convex ingot, frag., upper layer	Popinci	SRB	ED-XRF, LIA
VoNSM 205	400A	MA-196180	plano-convex ingot, frag., lower layer	Popinci	SRB	ED-XRF, LIA
VoNSM 208	400D	MA-196181	plano-convex ingot	Popinci	SRB	ED-XRF, LIA
VoNSM 215	3287	MA-196186	plano-convex ingot	Hetin	SRB	ED-XRF, LIA
VoNSM 217	3291a	MA-196188	plano-convex ingot, frag.	Hetin	SRB	ED-XRF, LIA
VoNSM 218	3291b	MA-196189	plano-convex ingot, frag., rectangular inclusion	Hetin	SRB	ED-XRF, LIA
VoNSM 221*	3294	MA-196190	plano-convex ingot	Hetin	SRB	ED-XRF, LIA
VoNSM 223	199?	MA-196191	Barren	S. Karlovci	SRB	ED-XRF
SkoM 228 (blade) SkoM 229 (rivet)	4460a	MA-186791	Mycenean sword	Tetovo	MKD	ED-XRF, LIA

* Data first published in Gavranović et al. 2022, 8, tab. 1.

Tab. 1 List of analysed finds. DobM = Museum Doboj, B-H; SJLM = National Museum of Bosnia and Herzegovina, Sarajevo, B-H; BelM = National Museum Belgrade, SRB; PozM = National Museum in Požarevac, SRB; VoNSM = Museum of Vojvodina, Novi Sad, SRB

dating, form, function, and local or interregional distribution of the specific type. In particular, we will focus on the results of the plano-convex ingots (pc-ingots) and the rod ingots, as they represent the raw material circulating in the region under study. Very often, they are found in hoards.[21] All ingots analysed so far in our study date to Ha A1,[22] 13 derive from hoards and a settlement excavated in Bosnia-Herzegovina (Cvrtkovci, Kućista, Novigrad, Paležnica, Podzvizd and Topolovaca Bregovi)[23] and 35 from hoards found in Serbia (Futog, Hetin, Klenje, Kličevac-Pomrlovo, Kličevac-Rastovača, Krčedin, Laznica, Privina Glava, Popinci, Rudnik, Trlić, S. Karlovci, Vitojevac)[24] (Tab. 1, Fig. 1).

Generally speaking, raw copper is present as plano-convex ingots (complete and fragmented),[25] rod ingots, and pieces with arbitrary forms. Ingots with a specific shape, like pick ingots, are distributed only in the Alpine region and immediate neighbouring areas (e.g., Slovenia or northern Croatia), but they do not occur in the (southern) Balkans.[26] Oxhide ingots, another typical

21 Hansen 1994.
22 Gavranović et al. 2022.
23 König 2004, 206, 216; Belić 2010, 227; Pavlin – Jašarević 2016.
24 Garašanin 1954, 31; Jacanović 1986; Borić 1997, 65; Jacanović 2000, 39; Koledin 2001, 37.
25 Nessel 2017. See also the contribution of B. Nessel and C. Uhnér in this volume.
26 Tarbay 2019, 294, fig. 10A.

Bronze Age ingot form, are known from a few examples in the Balkans, which were recently identified as Cypriot imports.[27]

Ingots are, as commonly assumed, closely linked to the copper smelting sites where their metal was smelted. Analyses of visible production traces by Daniel Modl suggest that ingots can – but must not – be produced within a single casting step, with rare examples displaying several layers.[28] In our dataset, only two of the 39 pc-ingots show such layering, one from the Popinci hoard (VIAS lab. no. VoNSM 204 and VoNSM 205) and one from the Trlić hoard (VIAS lab. no. BelM 474 and BelM 475),[29] both of which have an upper and a lower layer.

Modl also points out that scrap metal can be added to the casted copper charge, which could change the geochemical fingerprint of the ingot metal to a certain extent. If raw copper was melted together with finished objects containing copper from the same smelting sites or region, it is improbable that the trace element pattern would be completely altered.[30] In cases where scrap metal containing copper from a different mining region is added, the degree of alteration depends on the mass ratio of raw copper to scrap metal and the concentration of trace and alloying elements (especially lead) in the admixtured bronze. In any case, we would expect an elevated tin concentration (coming from the added bronze scrap) and/or an elevated lead concentration as found in the pc-ingot (VIAS lab. no. DobM 39) from the Topolovaca Bregovi settlement.[31] Macroscopically visible signs of possible remelting are only describable for one of our examined pc-ingots, a piece found in Hetin hoard (VIAS lab. no. VoNSM 217).[32] It has a rectangular-shaped inclusion, which might have been added scrap metal (VIAS lab. no. VoNSM 218).

Methods

The metal samples were taken with a polished 1 mm stainless steel drill bit. Before use, each drill was cleaned with highly concentrated ethyl alcohol (97%) to remove possible remains from the production process (e.g. polishing emulsion). As a first step, the patina was removed with a drill, and afterwards, a new bit was used to drill a 1–2 mm deep hole. Finally, the resulting drill shavings were collected. If corroded material was still present in the sample, it was removed under a microscope.

All samples were examined at the Curt-Engelhorn-Zentrum Archäometrie (CEZA) in Mannheim. For the measurements of the trace element concentrations, an energy dispersive X-ray fluorescence (EDXRF) spectrometer (ARL Quant X, Thermo Scientific) was used to analyse the elements silver (Ag), arsenic (As), bismuth (Bi), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), tin (Sn), antimony (Sb), tellurium (Te) and zinc (Zn). The following reference materials of Bundesanstalt für Materialforschung (BAM) and -prüfung (BAM-367, BAM-368, ERM-EB374, ERM-EB375, BAM-376) were used for calibration accompanied by various in-house standards. Each sample was measured in two exposures of 600 seconds with two standard materials (BAM-211 and BAM-376) included in each run. The measurements were normalised to 100%. The detection limits lie at approximately 0.005% for Ag, Sb, Sn, Pb, Bi, and 0.05% for Fe, and around 0.01% for Co, Ni, and As. Se and Te were measured but were below 0.005% in all samples. Zn was below the detection limit of 0.1% in all samples due to spectral interference with copper. Sulphur was not measured.[33]

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27 Molloy 2018, 146, 2a and b; Athanassov et al. 2020.
28 Modl 2019, 376, fig. 2.
29 Garašanin 1954, 31.
30 Berger et al. 2022; Gavranović et al. 2022, 18.
31 As e.g. demonstrated by the results of a plano-convex ingot from Topolovaca Bregovi (VIAS lab. no. DobM 39).
32 Koledin 2001, 37.
33 Nørgaard et al. 2021.

The lead isotope ratios ($^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{204}Pb$) were measured using a high-resolution multi-collector mass spectrometer (Thermo Scientific Neptune Plus) with inductively coupled plasma as ion source (HR-MC-ICP-MS). The $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ ratios were calculated from the aforementioned measured ratios. The drill shavings were rinsed with dilute HNO_3 to remove any surface contamination, then dissolved in half-concentrated HNO_3 in an ultrasonic bath (70˚C) for several hours. Insoluble residues were removed by decantation; afterwards, the solution was diluted with deionised water. Ion exchange columns were prepared with PRE-filter and Sr-resin and were preconditioned with 500 µl 3N HNO_3 before the solution was added. In four steps, the matrix was first eluted using HNO_3, and then the Pb was eluted using HCl. The mass fractionation of lead is corrected by the addition of thallium (Tl), for which a ratio of $^{205}Tl/^{203}Tl = 2.3871$ and an exponential fractionation behaviour are assumed. The interference of ^{204}Pb and ^{204}Hg was corrected by measuring ^{202}Hg with a ratio of $^{204}Hg/^{202}Hg = 0.2293$. The in-run precision of the measurement was typically 0.02 to 0.05% (2σ), depending on the isotopic ratio. The reference sample NIST SRM 981 was measured after every eight samples to check for instrumental drift and to guarantee high-level precision and accuracy. The methods are described in detail by Joachim Lutz and Ernst Pernicka[34] and Niederschlag et al.[35] All measurements are given in mass%.

The elements Ni, As, Sb, Ni and Bi were combined to double logarithmic diagrams, and the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ lead isotope ratios were used to generate bivariate comparative lead isotope plots for the discussion of the data. The tin and lead concentrations served as parameters for describing the alloying practices. First, the archaeological information (context, chronology, typology, spatial distribution) was combined with the chemical and isotopic data of the artefacts in order to define groupings and dispersion. Afterwards, the possible provenance of the copper-based objects was examined by comparing their geochemical information with those of known ore deposits in the regions under study. The final theory-based archaeometallurgical and archaeological interpretation focused on the discussion of the proposed provenance of copper and its implications concerning alloying, recycling, metal circulation and exchange in a supra-regional perspective.[36]

Three selected samples were examined by Neutron activation analysis (NAA) at the Institute for Chemistry, Johannes Gutenberg University Mainz, with the TRIGA (Mark II) reactor to determine the trace element values (especially gold and silver) with high accuracy.

Discussion

Trace Element Analyses

Trace element and lead isotope analyses make it possible to draw wide-ranging conclusions about the metal exchange in the western and central Balkans (Tabs. 2–3). In previous works, we have already pointed out that most of our analysed finished objects are made of eastern and southern Alpine copper.[37] In the following, we will focus on the raw material necessary to produce these artefacts. By comparing the results from the analysis of the plano-convex ingots and the rod ingots, it is possible to describe the provenance of the imported raw metal and explore the alloying habits of the Bronze Age metal workers.

As a first step, the analytical results were intensively studied to get an overview of the geochemical characteristics of the metals that circulated in the regions under study. Generally speaking, all plano-convex ingots contain raw copper; the elevated iron (Fe) concentrations are

34 Lutz – Pernicka 1996.
35 Niederschlag et al. 2003.
36 Nørgaard et al. 2021; Berger et al. 2022.
37 Mehofer et al. 2021; Gavranović et al. 2022, 18.

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Cu		Fe		Co		Ni		Zn		As		Se		Ag		Sn		Sb		Pb		Bi	∑Ni, As, Ag, Sb, Bi
DobM 39	–	MA-152364	97		1.36		0.03		0.03	<	0.1		0.37	<	0.01		0.185		1.01		0.008		0.09		0.10	0.68
DobM 49	1792	MA-152365	100	<	0.05		0.08		0.09	<	0.1		0.05	<	0.01		0.029	<	0.005	<	0.005		0.02	<	0.01	0.18
DobM 69	4426	MA-152366	99		0.05		0.06		0.05	<	0.1		0.53	<	0.01		0.014		0.009		0.014		0.03	<	0.01	0.62
DobM 70	4428	MA-152367	97		1.50		0.56		0.14	<	0.1		0.71	<	0.01		0.055		0.138		0.007		0.06	<	0.01	0.92
DobM 72	4885	MA-152368	94		1.07		0.14		0.11	<	0.1		4.3	<	0.01		0.012		0.010		0.138		0.03	<	0.01	4.59
DobM 86	1216	MA-152369	95		2.23		0.04		0.88	<	0.1		0.85	<	0.01		0.004		0.006		0.75		0.010	<	0.01	2.50
DobM 61	1867	MA-186702	92	<	0.05		0.02		0.41	<	0.1		0.240	<	0.005		0.033		7.0		0.194		0.148		0.006	0.89
SJLM 39	32793	MA-195997	92		2.25		0.16		0.28	<	0.1		3.6	<	0.005		0.027		0.012		1.97		0.076		0.005	5.86
SJLM 48	32791	MA-186719	96		1.62		0.02		0.92	<	0.1		1.03	<	0.005		0.006		0.008		0.82		0.005	<	0.005	2.78
SJLM 49	32792	MA-196002	97		0.93		0.01		0.67	<	0.1		0.51	<	0.005		0.013		0.006		0.83	<	0.005	<	0.005	2.03
SJLM 71	550	MA-196005	99		0.62		0.03		0.02	<	0.1		0.007	<	0.005		0.025		0.010		0.010		0.030	<	0.005	0.07
SJLM 74	552	MA-196006	99		0.21		0.37		0.13	<	0.1		0.233	<	0.005		0.031		0.010	<	0.002		0.008	<	0.005	0.40
SJLM 77	–	MA-196007	99		0.39		0.10		0.11	<	0.1		0.135	<	0.005		0.045		0.007		0.019		0.054		0.186	0.50
BelM 440	2136v	MA-196310	72	<	0.05	<	0.01		0.34	<	0.1		0.60	<	0.02		0.022		0.098		0.71		26.0	<	0.05	1.72
BelM 441	2136g	MA-196311	97		0.68		0.11		0.26	<	0.1		2.11	<	0.005		0.009		0.004		0.181		0.021	<	0.005	2.57
BelM 447	3275b	MA-196317	100		0.12		0.02		0.01	<	0.1	<	0.005	<	0.005		0.038		0.011		0.029		0.051		0.006	0.09
BelM 449	3275	MA-196318	97		1.87		0.03		1.05	<	0.1		0.43	<	0.005		0.002		0.015		0.085	<	0.005	<	0.005	1.57
BelM 465	1464a	MA-196322	95		0.61		0.07		0.29	<	0.1		0.95	<	0.01		0.023		1.22		0.42		1.32	<	0.01	1.69
BelM 471	14465d	MA-196324	84		15.1		0.05		0.67	<	0.1		0.237	<	0.005		0.004		0.018		0.091	<	0.005	<	0.005	1.01
BelM 474	14465f-1	MA-196325	100	<	0.05	<	0.01		0.02	<	0.1		0.007	<	0.005		0.008		0.003		0.003	<	0.005	<	0.005	0.04
BelM 475	14465f-2	MA-196326	100	<	0.05	<	0.01		0.01	<	0.1		0.008	<	0.005		0.006		0.003		0.003	<	0.005	<	0.005	0.04
BelM 504	26030a	MA-196342	98		0.21		0.16		0.08	<	0.1		0.84	<	0.005		0.048		0.062		0.113		0.020		0.259	1.34
BelM 505	26030b	MA-196343	96	<	0.05		0.02		0.11	<	0.1		0.38	<	0.005		0.021		3.6		0.090		0.28	<	0.005	0.60
BelM 530	26224	MA-196364	91		0.31		0.12		0.32	<	0.1		0.68	<	0.005		0.034		7.0		0.226		0.33		0.009	1.27
BelM 532	26330	MA-196365	95		1.03		0.04		0.07		0.7		0.12	<	0.01		0.160		0.092		0.123		2.27	<	0.05	0.52
BelM 534	26332	MA-196366	95		1.20		0.34		0.58	<	0.1		0.57	<	0.01		0.153		0.030		0.089		1.79		0.20	1.60

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Cu		Fe		Co		Ni		Zn		As		Se		Ag		Sn		Sb		Pb		Bi	∑Ni, As, Ag, Sb, Bi
BelM 535	26331	MA-196367	100	<	0.05		0.00		0.01	<	0.1	<	0.005	<	0.005		0.056		0.018		0.057		0.16	<	0.005	0.13
BelM 536	26512	MA-196368	100		0.14		0.01	<	0.01	<	0.1	<	0.005	<	0.005		0.028		0.002		0.009		0.023	<	0.005	0.06
BelM 538	26514	MA-196451	91		2.93		0.27		0.16	<	0.1		5.5	<	0.005		0.023		0.015		0.244		0.11	<	0.005	5.90
BelM 467	14464d	MA-196323	97		0.46		0.03		0.65	<	0.1		0.69	<	0.005		0.015		0.247		0.56		0.012	<	0.005	1.91
PozM 39	2144	MA-186762	100	<	0.05	<	0.01	<	0.01	<	0.1	<	0.005	<	0.005		0.007		0.003		0.003		0.006	<	0.005	0.03
PozM 56	1007b	MA-196070	100		0.4085	<	0.01		0.0125	<	0.1	<	0.005	<	0.005		0.012		0.013	<	0.002	<	0.005	<	0.005	0.04
PozM 58	1008b	MA-186768	78		21.2	<	0.01		0.06		0.4		0.005	<	0.005		0.181		0.193		0.010	<	0.005	<	0.005	0.26
PozM 69	–	MA-186770	95		2.93		0.11		0.09	<	0.1		1.13	<	0.005		0.019		0.011		0.54		0.037	<	0.005	1.78
PozM 36	2224	MA-196058	99		0.14		0.20		0.25	<	0.1		0.31	<	0.005		0.020		0.018		0.181		0.012	<	0.005	0.76
PozM 35	2222	MA-186761	96		0.16		0.03		0.28	<	0.1		0.133	<	0.005		0.048		3.6		0.076		0.041		0.021	0.56
VoNSM 157	3296	MA-196146	100	<	0.05		0.02		0.04	<	0.1		0.041		0.011		0.025	<	0.002	<	0.002		0.007	<	0.005	0.11
VoNSM 187	3419	MA-196167	99	<	0.05		0.02		0.62	<	0.1		0.065	<	0.005		0.014		0.007		0.002	<	0.005	<	0.005	0.71
VoNSM 189	3421	MA-196168	99	<	0.05	<	0.01		0.32	<	0.1		0.44	<	0.005		0.008		0.004		0.57	<	0.005	<	0.005	1.35
VoNSM 190	3422	MA-196169	95		3.6		0.05		0.10	<	0.1		0.50	<	0.005		0.003		0.40		0.181		0.007	<	0.005	0.78
VoNSM 204	400A	MA-196179	97		0.77		0.02		0.80	<	0.1		0.52	<	0.005		0.006		0.005		0.45		0.008	<	0.005	1.78
VoNSM 205	400A	MA-196180	98		0.74		0.02		0.83	<	0.1		0.45	<	0.005		0.004		0.005		0.37		0.007	<	0.005	1.66
VoNSM 208	400D	MA-196181	99		0.13		0.10		0.11	<	0.1		0.142	<	0.005		0.027		0.011	<	0.002		0.009	<	0.005	0.29
VoNSM 215	3287	MA-196186	97		0.15	<	0.01		0.90	<	0.1		0.96	<	0.005		0.004		0.005		0.71	<	0.005	<	0.005	2.58
VoNSM 217	3291a	MA-196188	93		2.02		0.21		0.22	<	0.1		3.3	<	0.005		0.038		0.013		1.23		0.23	<	0.005	4.74
VoNSM 218	3291b	MA-196189	93		1.93		0.21		0.22	<	0.1		3.3	<	0.005		0.039		0.013		1.31		0.25	<	0.005	4.84
VoNSM 221	3294	MA-196190	99	<	0.05	<	0.01		0.49	<	0.1		0.50	<	0.005		0.004		0.006		0.36	<	0.005	<	0.005	1.36
VoNSM 223	199?	MA-196191	83		0.11		0.01		0.03	<	0.1		4.3	<	0.005		0.99	<	0.005		11.5		0.033		0.074	16.94
SkoM 228	4460a	MA-186791	91		0.07		0.01		0.01	<	0.1		0.103		0.008	<	0.002		9.0	<	0.002		0.005	<	0.005	–
SkoM 229	4460a	MA-186792	94		0.13		0.01		0.01	<	0.1		0.088		0.009	<	0.002		5.4	<	0.002		0.014	<	0.005	–

Tab. 2 Chemical composition of the analysed objects as determined with energy-dispersive XRF. All values are given in mass percent. Se and Mn was below the detection limit of 0.01%, Te below 0.005% in all samples. ‘–’ = no inventory number/information. Due to the rounding of decimal places, the total sum is higher than 100%, and specific values, such as that of Cu, are also increased.

a marker that these pieces are still closely related to the primary production (Tab. 2).[38] The majority of the ingots can be defined as chalcopyrite-dominated copper. A few contain significantly elevated Sb and As concentrations, indicating that they are likely smelted from fahlore or ores with accessory fahlore minerals.

The tin amounts in the plano-convex ingots are meagre, with the average concentration being around 0.047 mass% and the mean at 0.01 mass% or even below the detection limit of the analytical device. When elevated tin amounts (ca. >1%) are found in an ingot, this hints at the addition of scrap metal during the production process, as detected in the analyses of the pc-ingot VIAS lab. no. DobM 39 from the Topolovaca Bregovi settlement.[39] Other ingots with slightly elevated concentrations are VIAS lab. no. PozM 58 from the Klenje hoard,[40] VIAS lab. no. DobM 70 from the Paležnica hoard[41] and VIAS lab. no. BelM 538 from the Vitojevci hoard (Tab. 2).[42] Their tin values are at 0.193%, 0.138% and 0.244% (Tab. 3), which is ten times higher than the mean values of the remaining ingots (Tab. 2).[43] These values may be caused by the addition of scrap (bronze) metal. However, we must be cautious as such values may not be conclusive enough to demonstrate the mixing of scrap metal with raw copper. Lead, another important alloying agent, appears seldom in our dataset. Only a few pieces have raised concentrations above 1%: pc-ingots VIAS lab. no. BelM 532, BelM 534, BelM 440, and the rod ingot VIAS lab. no. BelM 465, whose data suggest the deliberate addition of lead.

The pc-ingots VIAS lab. no. BelM 449 and SJLM 48 have the highest Ni concentrations, with 1.05% and 0.92%, with the latter also having elevated As (1.03%) and Sb (0.82%) concentrations. Among the ingots, VIAS lab. no. DobM 72 and VoNSM 223 stand out, as their arsenic concentrations reach 4.3%, with VoNSM 223 (S. Karlovci hoard) also containing 11.5% Sb and 0.99% Ag (the highest value of all ingots), demonstrating that it is a fahlore-based metal. The following highest antimony concentrations are found in the pc-ingot from the Hetin hoard (VIAS lab. no. VoNSM 217 and VoNSM 218), with 1.23% and 1.31% Pb respectively. Together with its arsenic concentration of 3.3%, this ingot can also be seen as a fahlore-influenced metal (cf. the mineralisations described for the Hochkönig-Mitterberg).

A small group of ingots is interesting due to their decreased trace element concentrations, which are atypical within our dataset. The ingot VIAS lab. no. PozM 39 from the Kličevac-Rastovača hoard[44] is a metal with very low element concentrations (but not untypical for Cypriot metal),[45] followed by the VIAS lab. no. BelM 474 and BelM 475, which were found in the Trlić hoard and VIAS lab. no. PozM 56, which forms part of the Klenje hoard. Additionally, we can list the VIAS lab. no. BelM 536 (Vitojevac), SJLM 71 (Podzvizd), BelM 447 (Rudnik), and VoNSM 157 (Krčedin). This different element pattern is also reflected in the lead isotope results, and the provenance assignment is difficult. Still, we suggest some of them can be related to the Valsugana VMS ore region in the Trentino and the Vinschgau mining region (Austroalpine AA (Alto Adige)).

In addition to provenance, the analyses of rod ingots give further insights into metal processing. Raw copper must be purified, and non-metallic inclusions must be removed by slagging to produce good-quality artefacts. Therefore, the raw metal, in the form of complete or sectioned ingots,

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38 Mehofer et al. 2021. During the smelt, the craftsman tried to oxidise the iron (coming from the ore, e.g. $CuFeS_2$) and slag it, a target which is only partially achievable with prehistoric methods. Therefore, one can find iron sulfides or copper-iron-sulfides up to 10% and more in the metal. By remelting an ingot several times, it is purified and the iron content decreases.

39 Belić 2010, 227; Gavranović et al. 2022, 18.

40 Jacanović 1986.

41 Belić 2010, 227.

42 The finds are stored in the National Museum Belgrad and in the process of publishing.

43 Interestingly, these pieces cannot be assigned to the Trentino or the Hochkönig-Mitterberg mining areas. The Vinschgau region seems to be the best candidate for their provenance.

44 Jacanović 2000, 39. See fig. 5 in the contribution of Gavranović et al. in this volume.

45 Hauptmann et al. 2002, 20, tab. 1.

is remelted and cast into a new form – in our case, the rod ingots. As semi-finished objects, they can be easily portioned or worked, e.g., forging a wire, etc. Within our samples, part of the ingots are unalloyed raw copper, like VIAS lab. no. PozM 36 (Kličevac-Rastovača), BelM 467 (Trlić), and VoNSM 190 (Futog),[46] while others contain tin (1.22–7.0%), as for VIAS lab. no. PozM 35 (Kličevac-Rastovača), BelM 465 (Trlić), BelM 505 (Kličevac-Pomrlovo), and BelM 530 (Laznica) and DobM 61 (Kućišta).[47]

Lead Isotope Analyses

As a next step, the lead isotope ratios of the ingots were evaluated (Tab. 3). One can recognise that some of the ingot samples are entirely consistent with the isotope values of copper ore deposits in northern Italy – the Trentino (Fig. 2), which covers the Valsugana VMS and part of the South-Alpine AATV region (Alto Adige, Trentino, Veneto).[48] Meanwhile, others can be assigned to the mining regions of the Eastern Alps, most probably the ore deposits in the Hochkönig-Mitterberg region (Tab. 1).[49] The trace element analyses corroborate this observation (Figs. 3–4). It is evident that ingots (green diamonds) assigned to the ores of Hochkönig-Mitterberg, Kitzbühel-Kelchalm, and the Viehhofen region (Eastern Alps), are characterised by higher nickel (Ni), antimony (Sb) and arsenic (As) values, and lower silver (Ag) and lead (Pb) amounts (Tab. 2). This corresponds well with the mineralisation of the latter ore deposits, which also have low lead concentrations.[50]

The second group (red diamonds, Fig. 3) consists of samples whose metal comes from the Alpine region of northern Italy. To test this provenance assignment, further plano-convex and pick ingots found in Frattesina[51] in the Po Valley, which have an attested provenance from the Trentino mines, were also plotted in the diagrams. Their trace element concentrations display the same pattern as our samples, supporting the assumption of a common origin. In Figure 3, a third group (black diamonds) is formed by plano-convex ingots with no clear provenance assignment. The $^{206}Pb/^{204}Pb$ isotope ratios of these pieces vary between 18.533 and 18.75, a range suggestive of the copper ore deposits in the Southern and Eastern Alps and the Vinschgau (South Tyrol), Slovakia, Serbia, and Bulgaria (Fig. 2), leading to an overlap of the different ore fields in the lead isotope diagrams. We will discuss the provenance of these ingots in detail in the following section.

A comparison of the data with ores and slags from LBA smelting sites[52] in the Vinschgau region in South Tyrol provides an additional opportunity to refine the provenance of the copper ingots with $^{206}Pb/^{204}Pb$ isotope ratios outlined above. In the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram (Fig. 2), the Vinschgau ores and slags separate well from those of the Eastern Alps (Hochkönig-Mitterberg, Kitzbühel-Kelchalm, Viehhofen), and those of the Trentino region. Their range variation is consistent with isotope values of fahlores found in the Inn Valley[53]. However, none of the ingots (VIAS lab. no. DobM 49, DobM 70, SJLM 74 and PozM 56) potentially associated with the Inn Valley deposits consist of fahlore-based copper (Tab. 2). Therefore, these ore deposits can be excluded as copper suppliers, making the Vinschgau region more probable. This provenance assignment is especially clear from the analysis of the pc-ingot sample VIAS lab. no. DobM 49 from the Kućišta hoard and ingot sample VIAS lab. no. SJLM 74 coming from the Podzvizd hoard. Both samples have isotope ratios that correlate with smelting slags from the sites Prad-SP1 and Stilfs-SP2 in the Vinschgau. Although the values do not directly correlate with ore data from

46 Borić 1997, 65.
47 König 2004, 206.
48 Artioli et al. 2016, 31, 32, tab. 2.
49 Mehofer et al. 2021.
50 Pernicka et al. 2016, 23, 29.
51 Mehofer et al. 2020; Gavranović et al. 2022, 19, fig. 6.
52 Koch Waldner et al. 2020, 5.
53 Höppner et al. 2005, 305, tab. 3.

VIAS lab. no.	Inv./ mus no.	CEZA lab. no.	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	Suggested ore region
DobM 39	–	MA-152364	2.1077	0.85760	18.260	38.486	15.660	Southern Alps
DobM 49	1792	MA-152365	2.0709	0.83967	18.678	38.680	15.683	Southern Alps (Vinschgau)
DobM 61	1867	MA-186702	2.1006	0.85483	18.327	38.497	15.666	Southern Alps
DobM 69	4426	MA-152366	2.0783	0.84343	18.486	38.42	15.592	Cyprus
DobM 70	4428	MA-152367	2.0750	0.84080	18.648	38.693	15.679	Southern Alps
SJLM 39	32793	MA-195997	2.0765	0.83134	18.867	39.177	15.685	Eastern Alps
SJLM 48	32791	MA-186719	2.0578	0.82036	19.138	39.383	15.7	Eastern Alps
SJLM 49	32792	MA-196002	2.0430	0.80784	19.464	39.766	15.724	Eastern Alps
SJLM 71	550	MA-196005	2.1207	0.86723	18.038	38.253	15.643	Southern Alps
SJLM 74	552	MA-196006	2.0704	0.83895	18.698	38.714	15.687	Southern Alps (Vinschgau)
SJLM 77	–	MA-196007	2.0911	0.84479	18.558	38.806	15.678	Multiple sources
BelM 440	2136v	MA-196310	2.0909	0.84616	18.506	38.695	15.659	No information, alloyed with lead
BelM 441	2136g	MA-196311	2.0737	0.82920	18.918	39.232	15.687	Eastern Alps
BelM 447	3275b	MA-196317	2.1272	0.87271	17.911	38.100	15.631	Southern Alps
BelM 449	3275	MA-196318	1.9713	0.77815	20.253	39.925	15.760	Eastern Alps
BelM 465	14464a	MA-196322	2.0911	0.84661	18.498	38.681	15.661	No information, alloyed with lead
BelM 467	144464d	MA-196323	2.0841	0.84075	18.644	38.857	15.675	Eastern Alps
BelM 471	14465d	MA-196324	1.9757	0.77590	20.320	40.147	15.766	Eastern Alps
BelM 474	14465f-1	MA-196325	2.0897	0.84416	18.579	38.825	15.684	Multiple sources/mixing
BelM 475	14465f-2	MA-196326	2.0893	0.84504	18.546	38.746	15.672	Multiple sources/mixing
BelM 504	26030a	MA-196342	2.0831	0.83966	18.669	38.890	15.676	Multiple sources
BelM 505	26030b	MA-196343	2.0659	0.83448	18.796	38.832	15.685	Multiple sources/mixing
BelM 530	26224	MA-196364	2.0976	0.85336	18.357	38.506	15.665	Southern Alps
BelM 532	26330	MA-196365	2.1182	0.86593	18.064	38.263	15.642	Southern Alps
BelM 534	26332	MA-196366	2.1041	0.85483	18.325	38.558	15.665	Southern Alps
BelM 535	26331	MA-196367	2.1270	0.87255	17.920	38.115	15.636	Southern Alps
PozM 35	2222	MA-186761	2.1029	0.85591	18.303	38.489	15.666	Southern Alps
PozM 39	2144	MA-186762	2.0786	0.84366	18.485	38.422	15.595	Cyprus
PozM 56	1007b	MA-196070	2.0384	0.82267	19.084	38.901	15.700	Multiple sources
PozM 58	1008b	MA-186768	2.0852	0.84723	18.472	38.516	15.65	Multiple sources
PozM 69	–	MA-186770	2.0751	0.82973	18.907	39.233	15.687	Eastern Alps
VoNSM 157	3296	MA-196146	2.0772	0.84232	18.615	38.667	15.680	Multiple sources (probably Vinschgau)
VoNSM 187	3419	MA-196167	2.0868	0.84443	18.555	38.720	15.668	Multiple sources
VoNSM 189	3421	MA-196168	2.0455	0.80832	19.452	39.789	15.723	Eastern Alps
VoNSM 190	3422	MA-196169	2.0815	0.84322	18.576	38.666	15.664	Multiple sources/mixing
VoNSM 204	400A	MA-196179	2.0636	0.82830	18.940	39.085	15.688	Eastern Alps
VoNSM 205	400A	MA-196180	2.0783	0.83858	18.691	38.845	15.674	Eastern Alps
VoNSM 208	400D	MA-196181	2.0790	0.84490	18.551	38.567	15.674	Southern Alps
VoNSM 215	3287	MA-196186	2.0332	0.80004	19.663	39.979	15.731	Eastern Alps
VoNSM 217	3291a	MA-196188	2.0745	0.82956	18.909	39.225	15.686	Eastern Alps
VoNSM 218	3291b	MA-196189	2.0745	0.82956	18.909	39.226	15.686	Eastern Alps
VoNSM 221	3294	MA-196190	2.0412	0.81121	19.373	39.543	15.716	Eastern Alps
SkoM 228	4460	MA-186791	2.0627	0.83545	18.694	38.559	15.618	Cyprus

Tab. 3 Lead isotope ratios in the samples discussed within this article. The precision of measurement is less than ± 0.01% for ratios with ^{206}Pb in the denominator and up to ± 0.03% for $^{206}Pb/^{204}Pb$. '–' = no inventory number. 'Eastern Alps' covers the ore deposits from the Hochkönig-Mitterberg, the Viehhofen and the Kitzbühel-Kelchalm mining areas, 'Southern Alps' include the mining sites in the Trentino, the Vinschgau, Carnia and Veneto.

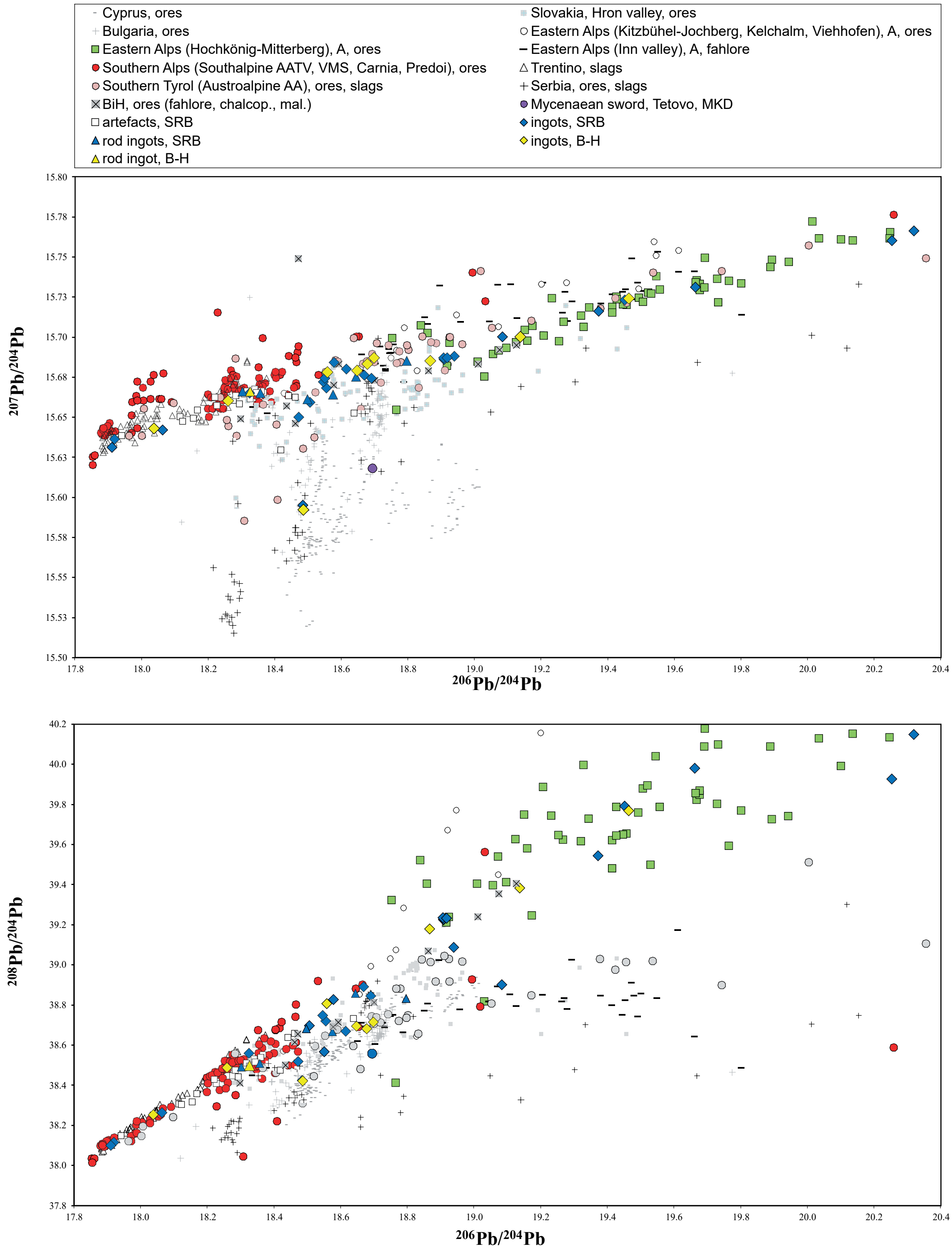

Fig. 2 The lead isotope diagrams show a comparison of the ingots' LI signatures with those of ores and slags found in the Alpine region, the Balkans and the Mediterranean. It becomes obvious that most of the ingots are consistent with ore deposits in the Southern and Eastern Alps. Data: Greece: OXALID database; Pernicka et al. 1993, 26, tab. 8; Pernicka et al. 1997, 168, tab. A5; Schreiner 2007, 245; Addis 2013, tab. 7.4; Artioli et al. 2016, 32, tab. 2; Pernicka et al. 2016, 54, tab. 5, 55, tab. 6; Mehofer et al. 2020, 192, tab. 2; Koch Waldner et al. 2020, 18, tab. 4; Gavranović et al. 2022, tab. 2 (chart: M. Mehofer, University of Vienna)

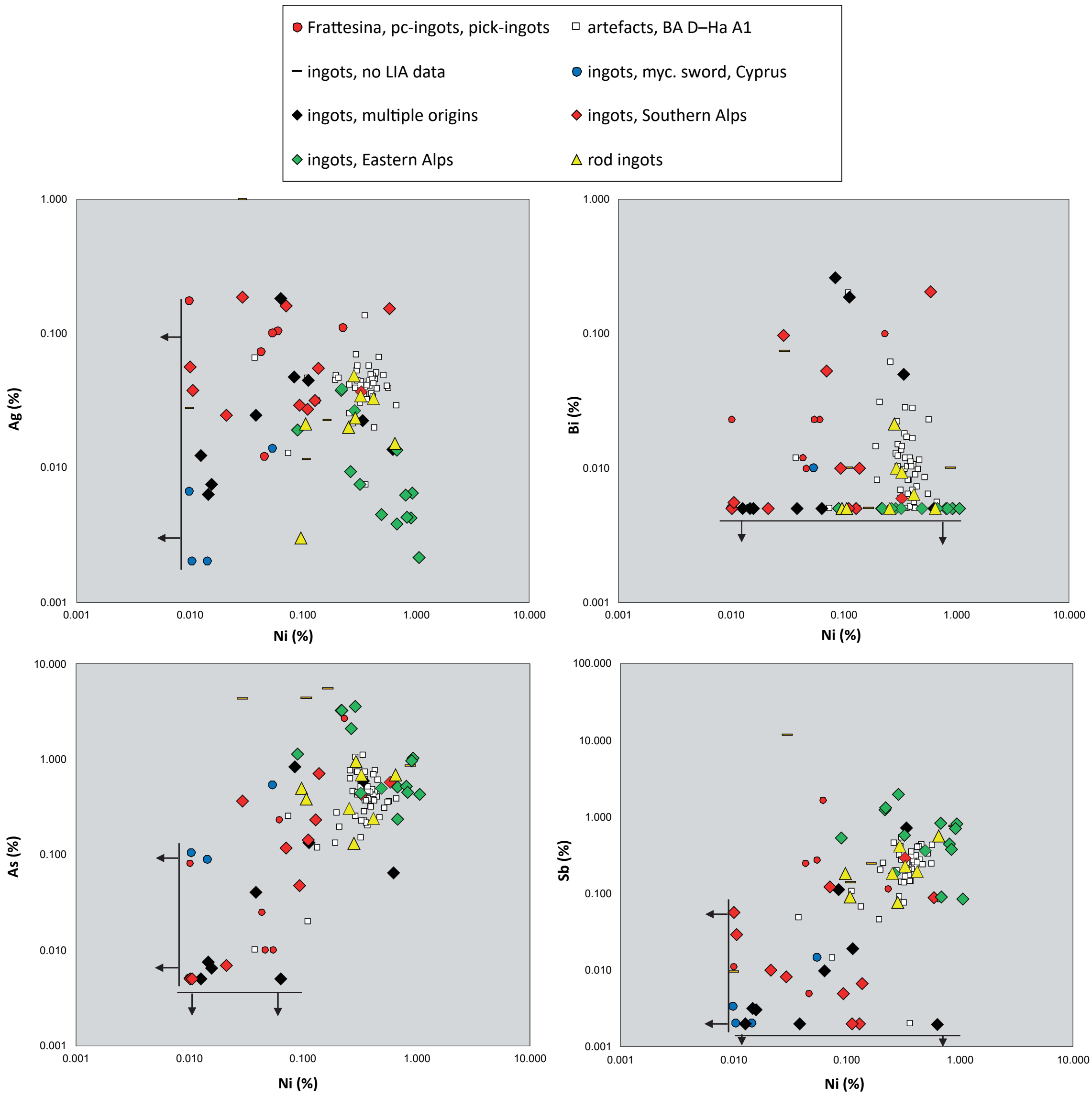

Fig 3 The double logarithmic diagrams show the analytical results of the ingots, compared with those of objects found in northern Italy (red circles). One can recognise that the ingots with eastern and southern Alpine provenance are well separated from each other. The rod ingots form an intermediary group. The black arrows mark the detection limit of the analytical device. Data: Mehofer et al. 2020, 191, tab. 1; Gavranović et al. 2022, tab. 1 (chart: M. Mehofer, University of Vienna)

Vinschgau, the trace element concentrations of both the ingots (Fig. 3) and the slags indicate the use of a chalcopyrite-ore-basis, and chalcopyrite dominated ore deposits are known from that region.[54] While it is important to be cautious with such interpretations as the amount of analytical data from the region is still low, our current results results do not rule out the possibilty that the mining region was a further copper supplier for the central and western Balkans.

[54] Koch Waldner et al. 2020, 9, tab. 1.

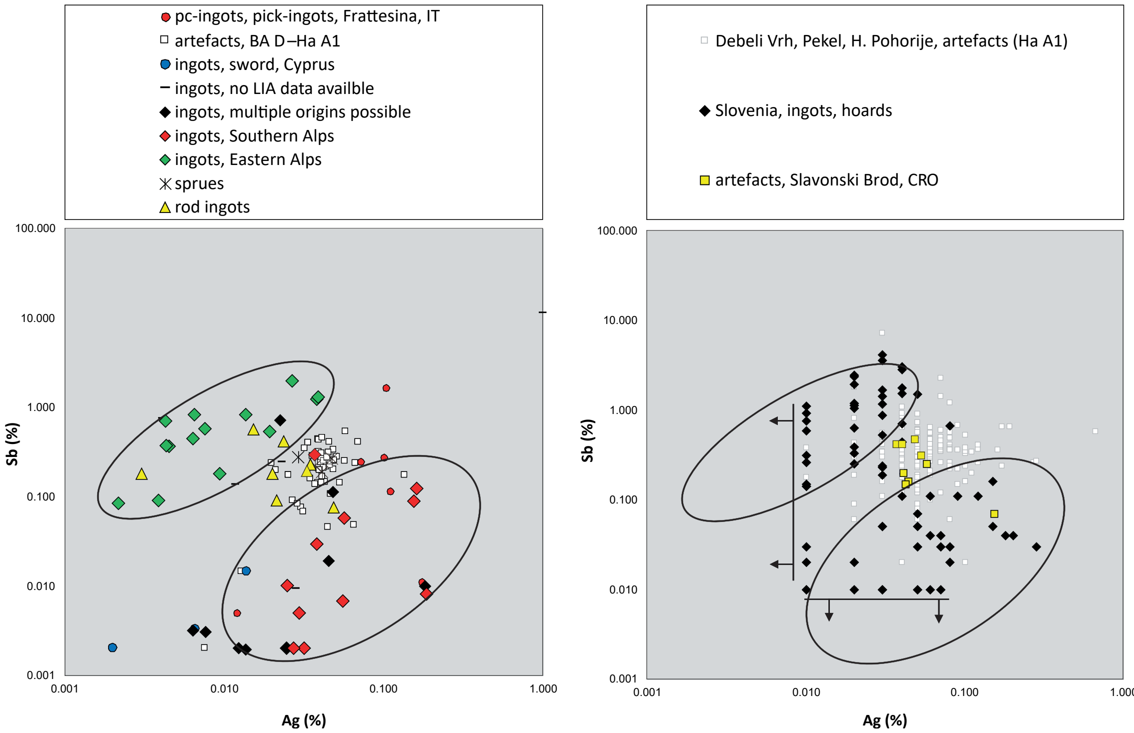

Fig. 4 Comparison of the antimony-silver values of northern Italian, Balkan and Slovenian artefacts. The left picture displays the antimony-silver concentrations found in ingots from northern Italy and the western and central Balkans. The right presents the same combination with the Croatian and Slovenian artefacts. The ellipses circumscribe the trace element variation of the ingots with eastern and southern Alpine origins. The black arrows mark the detection limit of the analytical device. All values are given in weight%, data: Trampuž Orel 1996, 213, app. A; Klemenc et al. 1999, 143, tab. 1; Mehofer et al. 2020, 191, tab. 1; Gavranović et al. 2021, tab. 1; Perez Gonzalez – Schwab 2023, 247, tab. 2 (chart: M. Mehofer, University of Vienna)

In the lead isotope diagrams (Fig. 2), two additional samples of ingots stand out (VIAS lab. no. PozM 39 and DobM 69). They are situated in an isotopic range compatible with ores from Cyprus[55] and ores and slags from Bulgaria and Serbia (Fig. 2). Still, additional analyses using neutron activation analyses (NAA) have confirmed a Cypriot origin (see below Fig. 6).

The ore deposits in Bosnia-Herzegovina, Serbia (e.g., the Bor region), and Bulgaria could be potential candidates for supplying copper during the Late Bronze Age, but to date, published evidence for LBA mining in these areas is missing[56] due to later Medieval and more modern mining activities which have erased them. The ores from the Slovakian ore mountains can be widely excluded as their isotope values are predominantly different to those of the Balkan artefacts analysed in this study. The $^{207}Pb/^{204}Pb$ ratios of these ores are slightly lower than most of the ingots examined here, and also, there is no direct match between an ingot and an ore data point in the diagrams. Anyhow, we should be open to the possibility that metal pieces from the Slovakian ore mountains or Romania entered the Balkan metal trading networks.[57]

55 Gavranović et al. 2022, 16. See contribution of Gavranović et al. in this volume.

56 For example, even though we have analytical evidence for BA copper production in Bor, eastern Serbia, traces of mining dated to this period are still missing.

57 Stöllner 2021, 13. Thomas Stöllner describes that the results of a currently running archaeometallurgical PhD, hosted at the DBM Bochum, hints at LBA smelting of copper in the Hron valley.

	Eastern Alps (n=14)		Southern Alps (Trentino, Vinschgau) (n=10)		Cyprus (n=2)		Salzburger Gusskuchen-Projekt		
element	mean	median	mean	median	mean	median	min	max	median
Fe	2.22	1.27	0.63	0.42	0.05	0.05	–	–	–
Co	0.07	0.03	0.16	0.06	0.03	0.03	0.01	0.46	0.04
Ni	0.55	0.58	0.12	0.08	0.03	0.03	0.05	9.5	0.4
As	1.32	0.74	0.22	0.13	0.27	0.27	0.012	3.1	0.32
Ag	0.013	0.007	0.076	0.046	0.010	0.010	0.002	0.02	0.007
Sb	0.679	0.555	0.033	0.009	0.009	0.009	0.005	0.41	0.028
Pb	0.048*	0.006	0.449**	0.057	0.019	0.019	–	–	–
Bi	0.005	0.005	0.040	0.008	0.008	0.008	0.01	0.01	0.01
∑Ni, As, Ag, Sb, Bi	2.565	1.906	0.488	0.342	0.325	0.325			

* In this calculation the lead values of VoNSM 217 and 218 are included as it cannot be decided whether the lead was deliberately added or not. If they are excluded the value goes down to 0.015% Pb.

** In this calculation the lead values of BelM 532 and 534 are incorporated. If they are excluded the value goes down to 0.052% Pb.

Tab. 4 The mean and median values of the chalcopyrite based copper ingots are presented in this list. Only ingots with unambiguous provenance were chosen for this calculation. Rod ingots were, as potential results of mixing, not included.

Hochkönig-Mitterberg vs. Trentino-Vinschgau Ores

To test this division made by lead isotope ratios, the ingots with different provenance underwent closer examination (Tab. 4).[58]

When looking at the data, it becomes obvious that the eastern Alpine ingots have higher trace element concentrations than the metals coming from the Southern Alps, especially when looking at their mean and median element values (Tab. 4). The Hochkönig-Mitterberg ores are defined as chalcopyrite ores, but the mineralisation in the southern sector contains pyrite, chalcopyrite and erythrite (an oxidised cobalt arsenate) with accessory minerals including gersdorffite (NiAsS), millerite (NiS), arsenopyrite (FeAsS) and fahlore, mainly of the tetrahedrite ($Cu_{12}Sb_4S_{13}$) type. Copper, coming from the Hochkönig-Mitterberg, can have (depending on where it was mined) a high correlation of arsenic and nickel and a low silver concentration, as the fahlore at the Hochkönig-Mitterberg seems to contain silver only in the range of 0.1% (found in a sample with 10% antimony). Chemically, the ores from Hochkönig-Mitterberg, Kitzbühel-Kelchalm, and Viehhofen are closely comparable, only distinguishable from each other via the elevated bismuth and selenium concentration associated with the Kitzbühel-Kelchalm ores. When these ores are smelted, they result in a nickel, arsenic, and antimony-rich as well as silver and lead-poor metal similar to the ingots analysed by Lutz in the Salzburger Gusskuchenprojekt.[59]

In Figure 5, one can recognise that the western and central Balkans and the eastern Alpine ingots (found in Salzburg) vary within the same minimal and maximal range (only the Balkan Sb values are slightly higher), confirming a common eastern Alpine provenance.[60]

58 Ingot VIAS lab. no. VoNSM 223 with 11.5% Sb is not incorporated, as it is fahlore based metal and no lead isotope analyses are available.

59 Lutz et al. 2019, 369, tab. 1.

60 It should be noted that some outliers from our study reach higher values of As (max. 3.6%), Sb (max. 1.97%) and Ag (max. 0.039%) but are still consistent with an eastern Alpine origin.

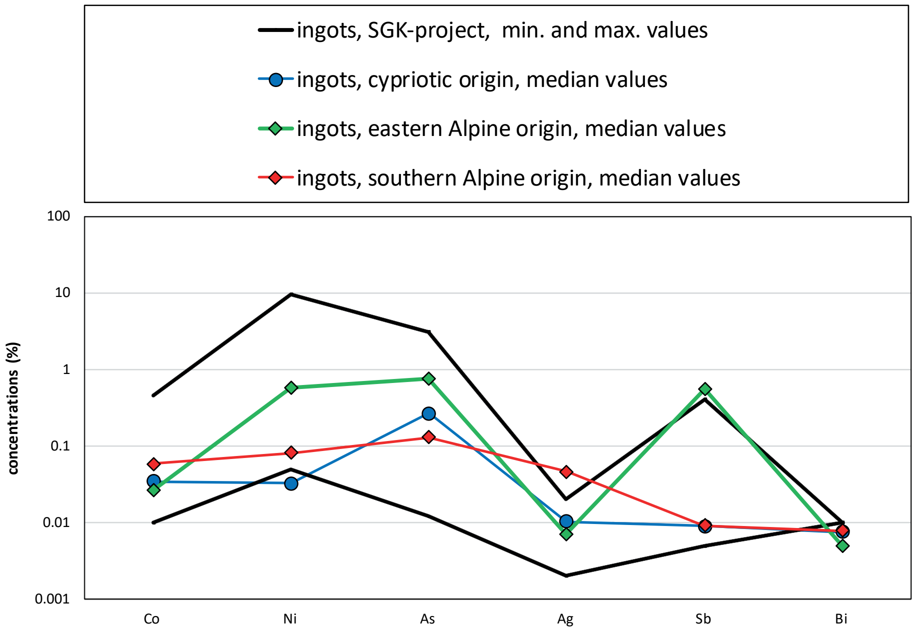

Fig. 5 Comparison of the median trace element concentrations of the ingots analysed in this project with the minimal and maximal values of those found in Salzburg (black lines). The ingots with eastern Alpine provenance (green diamonds) coincide well with them. Meanwhile, the ingots with southern Alpine or Cypriot origin (red diamond) differ. 'SGK' = Salzburger Gusskuchenprojekt. Data: Lutz et al. 2019, 369, tab. 1 (chart: M. Mehofer, University of Vienna)

From a mineralogical point of view, the ore deposits in the Trentino and South Tyrol (including Vinschgau) provide a heterogeneous picture.[61] The deposits contain chalcopyrite-pyrite, tetrahedrite-tennantite and polymetallic CuZnPb sulphides ore deposits, which Gilberto Artioli[62] summarises as the South-Alpine AATV (Alto Adige, Trentino and Veneto), Austroalpine AA (Alto Adige) and Valsugana VMS fields (Volcanogenic Massive Sulphides). The latter comprises deposits along the Valsugana thrust with copper-bearing ores, typically including small amounts of chalcopyrite in pyrite-dominant mineralisation, with accessory minerals of galena, arsenopyrite and sphalerite. The South-Alpine AATV deposits are geologically younger and genetically related to magmatism, being primarily formed of polymetallic sulphidic ores (Pb, Zn, Cu with minor concentrations of Ag, Sb, Co, Bi, As). The mineralisation generally consists of chalcopyrite – sphalerite - galena - pyrite types, accompanied by less common mineral assemblages of tetrahedrite ± galena, chalcopyrite-bearing magnetite and pyrrhotite, bornite-chalcopyrite-chalcocite, and chalcopyrite-pyrite-bismuthinite. Ores with a more distinctive tetrahedrite-rich composition are found in the Carnic Alps, but these are not of interest for discussion within this study, as no find can be related to them. The ore deposits in the Vinschgau region belong to the Austroalpine units of South Tyrol (Austroalpine AA) and comprise malachite, pyrite, chalcopyrite, stibnite, tennantite, bismuthinite, Bindheimite, Boulangerite.[63] Due to the low number of comparative ore, slag, and metal data from the Vinschgau region, it was not possible to separate it well from the Trentino. Therefore, their results were treated as one group. The ore compositions of the Vinschgau ores result when smelted in a metal with a more variable composition. It is characterised by a lower Ni, As and Sb value and contains more Ag and Pb, which makes it more easily distinguished from the eastern Alpine copper. The two ingots associated with the Vinschgau (VIAS

[61] For a detailed discussion, see Artioli et al. 2016.
[62] Artioli et al. 2016, 31.
[63] Koch Waldner et al. 2020, 9, tab. 1.

lab. no. DobM 49 and SJLM 74) do not show any element pattern, which would separate them from the Trentino metals.

The different ore genesis reconstructed from the copper found in the ingots with assumed eastern and southern Alpine provenance, which directly influence the trace elements concentration, can also be expressed more conclusively numerically (Tab. 4). When adding up the Ni, As, Ag, Sb, and Bi values, the southern Alpine ingots deviate between 0.07–0.92% (with an outlier at 1.6%),[64] while the eastern Alpine ingots vary between 1.01–5.86%. These numbers are good additional parameters to discuss the provenance of a single object. They will also help to track down further finished objects with former eastern Alpine ore provenance, which was erased due to the mixing with southern Alpine copper. For example, a socketed axe (VIAS lab. no. PozM 55) and an arm ring (VIAS lab. no. PozM 79) from the Klenje hoard have comparable (eastern Alpine) trace element patterns, even though their lead isotopes point to the Southern Alps as the origin of the copper.[65] A discussion of whether these trace element characteristics apply to all our finished objects would go too far, as we have to run further tests if this assumption holds true.[66]

Regional Distribution of Raw Metals

In the following, we will discuss the ingots found in various hoards and a settlement in Bosnia-Herzegovina and Serbia to get further insights into the metal distribution (Tab. 1). The examined ingots come from various hoards with mixed components containing socketed axes, spearheads, sword fragments or personal implements.[67] Even though it is not the topic of this article to discuss the character and interpretation of hoards, the results provide insights into which raw material was available during the time of collection and deposition.

Starting with sample VIAS lab. no. DobM 61 from the Kućišta hoard[68] (either a tin alloyed ring or ingot fragment) one can describe that it coincides with the Trentino deposits (South-Alpine AATV), while the pc-ingot (VIAS lab. no. DobM 49) from the same hoard, has chemical and isotopic data that fits well with ores and slags connected to the Vinschgau (Austroalpine AA, as outlined in the previous section, Figs. 2–3). This association is also found for the sample VIAS lab. no. DobM 39 from the settlement Topolovaca Bregovi,[69] which contains 1.01% Sn (hinting at the addition of scrap metal) but is entirely consistent with the Trentino ore deposits (Fig. 7). Obviously, the added tin did not substantially change the isotope pattern. In comparison, the low

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Cu %	Fe %	As	Sb	Co	Ni	Ag	Au	Zn	Sn	Se	Te	(Hg)
DobM 69	4426	MA-152366	97	< 0.1	4800	140	440	< 500	125	19	100	< 860	71	< 100	< 2
PozM 39	2144	MA-186762	100	< 0.03	44	28	2	< 200	63	2	23	< 100	11	< 100	5
SkoM 228	4460	MA-186791	89	< 0.06	1050	29	91	< 200	15	4	< 100	101000	83	< 100	< 2

Tab. 5 Results of the neutron activation analyses. All values are given in ppm, except for Cu and Fe.

64 Based on this high sum the ingot (VIAS lab. no. BelM 534, Laznica hoard) would be suspicious to come from the Eastern Alps, buts its lead isotopes are well situated in the field of the Trentino ores. Restrictively, one has to mention, that it has 1.79% lead, meaning this association can also be caused by the addition of southern Alpine lead.

65 See fig. 5 in the contribution of Gavranović et al. in this volume.

66 Furthermore, the ED-XRF data would allow to interpret two subgroups within the eastern Alpine ingots, but, before we can describe this, more analyses of ingots are necessary.

67 Gavranović et al. 2022. See contribution of Gavranović et al. in this volume.

68 König 2004, 206.

69 Belić 2010, 227.

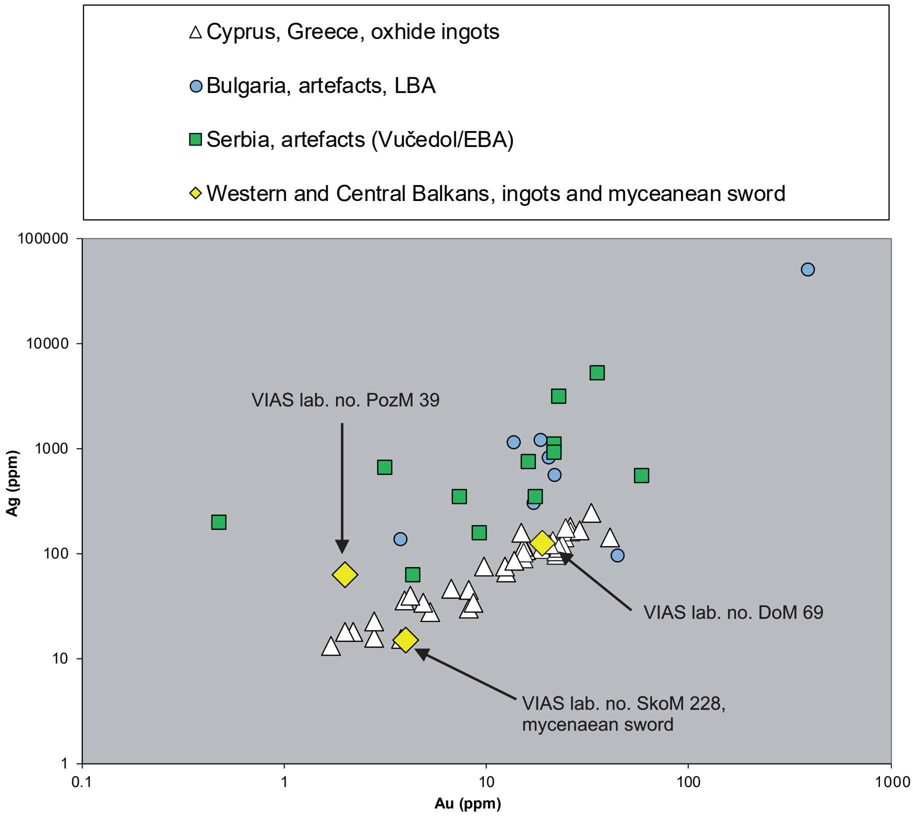

Fig. 6 Ag/Au diagram for artefacts with assumed Cypriot copper provenance, compared to data from oxhide ingots found in Greece, in Cyprus and in objects from Bulgaria and Serbia. Data: Pernicka et al. 1997, tab. A4, A5; Pernicka et al. 1993, 10, tab. 3 (chart: M. Mehofer, University of Vienna)

lead concentration of 0.09% excludes the possibility that this alloying agent was additionally added to alter the casting properties of the object. In the hoard of Cvrtkovci,[70] only one ingot (VIAS lab. no. DobM 72) underwent ED-XRF analyses. The trace element concentrations would again favour a north Italian provenance of the copper, but unfortunately, we do not have lead isotope data to verify this interpretation.

Now, turning to three ingots from the Paležnica hoard, VIAS lab. no. DobM 70, DobM 86, and PozM 69.[71] The chemical data for the first is connected to the north Italian mining regions, with isotopic data comparable to slags and ores from the Vinschgau region (Fig. 2). Unfortunately, we do not have lead isotope data for the second ingot (VIAS lab. no. DobM 86), but his trace element concentrations would again generally support the provenance of copper from northern Italy. The results of a third ingot (VIAS lab. no. DobM 69) suggest a Cypriot origin with isotope ratios that are interestingly closely comparable to an ingot from Kličevac-Rastovača (VIAS lab. no. PozM 39). This ingot was also interpreted as likely coming from Cyprus in the first publication. However, it should be noted that in the range of the ingots, data ores of some Bulgarian and Serbian ores and slags are situated that do have similar isotope ratios to Cyprus.

Neutron activation analyses (NAA) can further help to identify the origin of copper as this method enables the determination of gold and silver concentrations with high accuracy (Tab. 5).[72] In the diagram (Fig. 6), the latter element values of oxhide ingots found in Cyprus are combined with those of LBA objects from the western and central Balkans, Bulgaria, Eneolithic and EBA

[70] Blečić Kavur et al. 2019.
[71] Pavlin – Jašarević 2016.
[72] Begemann et al. 2001, 56, fig. 7a.

finds from Serbia[73] as well as from Mycenaean rapier from Tetovo (VIAS lab. no. SkoM 228), which was already suspicious to originate from the Mediterranean (Fig. 2).[74] In the range covered by the element ratios of the oxhide ingots, one finds the data points coming from the Mycenaean rapier as well as from the ingot (VIAS lab. no. DobM 69) from the Paležnica hoard. This observation provides evidence that the metal from these two pieces comes from the copper mines on Cyprus. The mentioned ingot from Kličevac-Rastovača (VIAS lab. no. PozM 39) does not show such a clear association (see discussion below).

The analysis of the three pc-ingots from the Novigrad hoard (VIAS lab. no. SJLM 39, SJLM 48 and SJLM 49)[75] confirms that their metal is entirely consistent with the Hochkönig-Mitterberg mining areas; elevated Ni and low Ag and Pb concentrations (Figs. 3–4) are present. The ingot fragments from the Podzvizd hoard[76] are connected to the southern Alpine ore deposits in the Trentino and the Vinschgau regions – especially the ingot VIAS lab. no. SJLM 71, which is entirely consistent with the Trentino ores (Valsugana VMS). The isotope ratios of the remaining two ingots from this hoard would allow several interpretations, but at least for the VIAS lab. no. SJLM 74, a direct overlap with BA copper smelting slags from the Vinschgau is possible. This is supported by the trace element analyses, which have, generally speaking, concentrations comparable to those from the southern Alpine region (Fig. 3). The third ingot from Podzvizd (VIAS lab. no. SJLM 77) has isotope ratios situated in the overlapping area of the various ore deposits and can therefore not be assigned to a single source. However, his trace element concentration correlates with those of ingots from the southern Alpine area, making it highly probable that its copper also comes from this region (Fig. 3).

Serbia

The Serbian hoards from Futog, Klenje, Kličevac-Rastovača, Kličevac-Pomrlovo, Privina Glava, Popinci, Rudnik, and Trlić follow the same general provenance pattern; some can be traced back either to the Eastern Alps or the Southern Alps (Trentino, Vinschgau region) or have an unknown provenance (Figs. 2–3).

A good example of the mixed provenance within a hoard is represented by the two pieces from the Futog hoard,[77] whereby sample VIAS lab. no. VoNSM 189 – has lead isotope ratios that are undoubtedly related to the Hochkönig-Mitterberg region, whilst the isotope ratios from VoNSM 187 do not correspond to any of the major mining regions in the Alps. Instead, this sample's isotope ratios are orientated along a potential mixing line between the southern and the eastern Alpine ore deposits, suggesting the use and mixing of metal from both sources. In general, the trace element pattern would hint at a southern Alpine origin, but the raised nickel concentration (0.62%) fits better to the Hochkönig-Mitterberg region. As such, its provenance remains unclear. Turning next to the rod ingot VIAS lab. no. VoNSM 190, which also forms part of the Futog hoard, it is neither alloyed with tin nor has an elevated lead content. The isotope values of this piece vary in the same range as ingot sample VoNSM 187 discussed above, and again, as such, determination of provenance is difficult. In particular, the Ni/Ag ratio of the VIAS lab. no. VoNSM 190 is quite different from those of the eastern and southern Alpine ingots, so one cannot decide on a definitive source area. The inconclusive data from this piece could be partly explained by the fact that it is a rod ingot. This ingot type is the result of a further processing step that includes purification,

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[73] Pernicka et al. 1993, 10, tab. 3, 22, tab. 6, 32, tab. 9; Pernicka et al. 1997, 162, tab. A4, 168, A5; Stos-Gale et al. 1997, 110, tab. 6.

[74] Gavranović et al. 2021, 142. In the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram its isotope ratios are not fully consistent with the ore data from Cyprus.

[75] König 2004, 216.

[76] König 2004, 216.

[77] Borić 1997, 65.

remelting, or mixing of the raw metal, which naturally would have a significant impact on identifying the provenance of the copper metal.

The three pc-ingots from the Hetin hoard (VIAS lab. no. VoNSM 215, VoNSM 217, VoNSM 218, and VoNSM 221)[78] all exclusively contain copper from the Hochkönig-Mitterberg mining region, and their elevated trace element concentrations separate them well from the southern Alpine pieces. Significantly, during the examination of one of these pc-ingots (VIAS lab. no. VoNSM 217), we observed a rectangular feature which could have been added scrap metal. In order to test the potential influence of adding scrap metal, we drill-sampled this feature (VIAS lab. no. VoNSM 218). The trace element concentrations, especially those of Ni (0.22%) and As (3.3%), were identical in both samples, strongly suggesting that either the feature/object was completely dissolved or was never deliberately added as scrap metal. In this respect, it is interesting that this Hetin ingot is the only one with eastern Alpine provenance with a slightly elevated lead value (0.23% and 0.25%). Its tin concentrations remain at 0.013% in both cases. In comparison, the mean tin concentration of all the others varies around 0.005–0.006%, which is lower.

The analyses of the Popinci ingots demonstrate that raw metal with different origins is present within the same hoard.[79] One of the pc-ingots displays layering; therefore, both the upper and the lower layers were sampled (VIAS lab. no. VoNSM 204 and VoNSM 205) to get a deeper insight into the production steps of this object type. As presented in Figure 3, the elemental data shows that both layers have concentrations corresponding with those of eastern Alpine provenance; meanwhile, in the lead isotope diagram, only the upper layer (VIAS lab. no. VoNSM 204) is entirely consistent with mining fields of the Hochkönig-Mitterberg region. The nearly identical trace element concentrations of both layers, as well as the fact that their isotope ratios (especially VIAS lab. no. VoNSM 205)[80] are still within the range of the Hochkönig-Mitterberg mining fields, make this assignment highly probable. When this ingot fragment is melted for casting an object, the isotope ratios would be oriented along a mixing line between the two data points of the single layer but still be positioned in the Hochkönig-Mitterberg mining area. The second analysed ingot (VIAS lab. no. VoNSM 208) from this hoard displays a southern Alpine trace element pattern, but the evaluation of the isotope ratios does not allow such a clear association. They are again situated in a range where Vinschgau ores and ores from the Slovakian ore mountains vary. Due to the good comparability of the trace element concentrations, a Vinschgau /southern Alpine origin is, at the current stage of research, preferred.

A complex picture was also found in the data of the plano-convex ingot fragment from Krčedin (sample VIAS lab. no. VoNSM 157).[81] The trace element concentrations fit those of ingots with southern Alpine provenance, but the lead isotope analyses place it in a section where many ore deposits are present. In the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram, it has the best correlation with ores from the Vinschgau region, making this the best option for its provenance.

Two plano-convex ingots from the Privina Glava hoard were also analysed.[82] The element concentrations for VIAS lab. no. BelM 440 suggests an eastern Alpine provenance, but the lead isotope ratios do not support it. This is the result of alloying copper with lead (26%),[83] which, in effect, erases all isotopic information coming from copper ore. Interestingly, this plano-convex ingot and a rod ingot from Trlić (VIAS lab. no. BelM 465, 1.32% Pb) have closely comparable lead isotope ratios, which provides evidence that both contain lead from the same source (Tab. 2). It was added in the course of the production of the pc- and the rod ingot (wherever that happened).

78 Koledin 2001, 37.
79 Unpublished, the finds are stored in the Museum of Vojvodina, Novi Sad, Serbia.
80 For this sample Serbian ore deposits would also be a potential copper source, but the closely comparable trace element concentrations of both layers make this unlikely.
81 Harding 1995, 34; Vasić 2003.
82 Garašanin 1975, 68.
83 Trampuž Orel 1996. The high lead concentration (26%) of ingot VIAS lab. no. BelM 440 is, from an analytical point of view, best comparable with the later dated ingots from Slovenia, which also contain such high lead values.

A direct connection (e.g., the rod ingot was produced with metal from the pc-ingot) can be denied, as the trace elements do not coincide. This is especially true for the Fe, the As and of course, the lead content. Concerning their provenance, it is not possible to assign them to a specific mining region. The second analysed ingot (VIAS lab. no. BelM 441) from Privina Glava is again related to the Eastern Alps by its geochemical pattern.

Two ingots were analysed from the Rudnik hoard,[84] VIAS lab. no. BelM 447, whose composition indicates an origin from copper ores in the Valsugana thrust (VMS) in the Trentino and VIAS lab. no. BelM 449, which comes from the eastern Alpine mining area.

The results from the four analysed pieces (two plano-convex as well as two rod ingots) from the Trlić hoard enlarge this picture. The metal in the ingot sample VIAS lab. no. BelM 471 derives, based on its trace element values and isotope ratios, again from the Hochkönig-Mitterberg region. The second analysed plano-convex ingot can be divided into an upper and a lower layer (samples VIAS lab. no. BelM 474 and BelM 475), which were both examined. The ED-XRF and lead isotope results allow us to conclude that both layers are made of the same copper. The low trace element concentrations are comparable to those of the ingots with southern Alpine – Trentino provenance; however, plotting the isotope ratios in the diagrams again places them with ore data of multiple origins. As the $^{208}Pb/^{204}Pb$ isotope ratios of the Vinschgau ores are lower than those of the ingot layers and are therefore to be excluded, leaving the Southern Alps or mixing of metal with different provenance is the most likely explanation. The evaluation of the results of the rod ingots found in the Trlić hoard samples (VIAS lab. no. BelM 465 and BelM 467) reveals further interpretative problems, possibly related to the processes used during production. Both ingots are alloyed with tin, whilst VIAS lab. no. BelM 465 also contains lead, notably with similar isotope ratios to VIAS lab. no. BelM 440, discussed above. Their elevated nickel concentrations would correlate them to the ingots with eastern Alpine copper, while their lead isotope ratios are between the Trentino and the eastern Alpine ores. Such patterning strongly indicates the mixing of copper from both main mining areas, making it impossible to narrow the results down to one source.

Turning now to the ingots from the Kličevac-Pomrlovo hoard (VIAS lab. no. BelM 504 and 505),[85] it is apparent that they fall within a range similar to ores and slags from Kitzbühel – Kelchalm (Eastern Alps), the Vinschgau, and Serbia. The analytical data for ingot sample VIAS lab. no. BelM 504 would allow several interpretations (Figs. 3–4). On the one hand, its low nickel value (0.08%) and higher bismuth content (0.259%) separate it from our typical eastern Alpine ingot trace element pattern (Figs. 3–4).[86] On the other hand, the Bi concentration connects it to the Kitzbühel – Kelchalm, Eastern Alps, but the isotope values do not support such a provenance. The Vinschgau ores could also be a source, as copper mineralisation with elevated Bi concentrations is known for this mining region.[87] Due to these uncertainties, its provenance cannot be clarified. The second piece from this hoard – a rod ingot (sample VIAS lab. no. BelM 505) – has a tin concentration of 3.6%, which indicates alloying. Charting the trace element concentrations places the sample between the ingots with eastern and southern Alpine origins (Fig. 2), with the same situation noted for the lead isotope ratios. The lower $^{208}Pb/^{204}Pb$ isotope ratios separate it from the eastern Alpine ores and place it in a range where the Vinschgau ores and slags are situated, but a direct overlap cannot be observed. Such patterning indicates that this ingot is the product of mixing copper from different mining regions.

Three analysed pieces from the Laznica hoard have trace element concentrations and lead isotope ratios, which coincide with Trentino copper (South-Alpine AATV and Valsugana VMS region).[88] Samples VIAS lab. no. BelM 532, BelM 534 and BelM 535 contain 2.27%, 1.79% and

84 Garašanin 1954, 31.
85 Jacanović – Radojčić 2001, 67.
86 Pernicka et al. 2016, 29.
87 Koch Waldner et al. 2020, 17 tab. 3.
88 Jacanović – Radojčić 2014, 35.

0.16% lead, respectively, which is far higher than the median value of the ingots typically coming from the southern Alpine mining region. It is generally lower at 0.057%, including these pieces and 0.030% without the three pieces. One can assume that either lead (with southern Alpine provenance) was added during the production or that lead mined in northern Italy was mixed with the copper. Metals with elevated lead concentrations are not completely unknown in the archaeo-metallurgical record of northern Italy. For comparison, the data of an ingot and a socketed shovel, both found in hoard 2, Frattesina, were considered. They contain lead (1.9% and 1.62%), but their isotope ratios are consistent with the Trentino slags and ores.[89] This means that the alloying could have already taken place in the centres of production in the Trentino region, and then the ingots were traded to the Balkans. Another possibility is that Cu-Pb ores were smelted. The tin bronze containing rod ingot sample VIAS lab. no. BelM 530 from Laznica hoard shows a comparable picture. It also has a slightly elevated lead content (0.33%), but its lead isotope ratios are again entirely consistent with the Trentino ores.

We do not have lead isotope analyses at hand for two pc-ingots from the Vitojevci hoard,[90] but their trace element concentrations would (hypothetically) allow assigning VIAS lab. no. BelM 536 to the Southern Alps, while the second (VIAS lab. no. BelM 538) would be associated with the Eastern Alps. The latter is, to be mentioned, the ingot with the highest As concentration (5.5%) in our dataset.

Our next Serbian hoard from Klenje contains three raw metal finds of particular interest.[91] Two stuffed into the socket of a socketed axe (VIAS lab. no. PozM 56 in the axe no. PozM 55 and VIAS lab. no. PozM 58 in no. PozM 57) and the third being a plano-convex ingot fragment (VIAS lab. no. PozM 69).[92] The ingot VIAS lab. no. PozM 56 stands out due to its very low trace element concentrations, with arsenic, antimony, lead and bismuth lying below the detection limit of the analytical device. Nickel (0.01%) and silver (0.012%) are also very low compared to all of the other ingots analysed in our study. Concerning this, it should be noted that the in-compatibility of the low trace element concentrations jeopardises the possibility of providing a final assignment to the major provenance groups. In the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram, the data point is situated close to the Inn Valley fahlores, but this can be excluded as its metal is not fahlore-dominated. In general, the data provides the closest match with ores and slags from the Vinschgau region, but this must remain uncertain. The data for the ingot VIAS lab. no. PozM 58 presents a similar complex picture with trace element concentration aligned with the raw metal pieces from the Trentino. At the same time, the lead isotope ratios are situated in a range where Trentino ores, Vinschgau ores, and fahlores from Bosnia-Herzegovina are present. At least the latter can be excluded, as the ingot's chemical composition is not associated with fahlores. The third ingot of this hoard (VIAS lab. no. PozM 69) is undoubtedly related to the Eastern Alps and the Hochkönig-Mitterberg region.

The analysed sample set from the Kličevac-Rastovača hoard comprises two rod ingots (VIAS lab. no. PozM 35 and PozM 36) and an axe-shaped ingot (VIAS lab. no. PozM 39).[93] The first rod ingot, which contains 3.5% tin, corresponds to the Trentino mining regions, a provenance also suggested by its trace element concentrations, although they are situated on the edge of the possible trace element variations of the Trentino ingots. The element concentrations of the second (unalloyed) rod ingot place it again in an area between the typical range of the southern and eastern Alpine ingots, which could result from mixing. However, we cannot explore this possibility further as no lead isotope values are available. The third analysed piece (VIAS lab. no. PozM 39)

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89 Socketed shovel (Inv. No. IG 272469) and plano-convex ingot (IG 272521). Mehofer et al. 2020, 190 fig. 10, 191, tab. 1, 192, tab. 2.

90 Unpublished, the finds are stored in the National Museum of Serbia in Belgrad, Serbia.

91 Jacanović 1986.

92 See the contribution Gavranović et al. in this volume.

93 Jacanović 2000, 39; Gavranović et al. 2022, 13, 29, tab. S1, 29, tab. S2. See the contribution of Gavranović et al. in this volume.

is related to the ore deposits of Cyprus, but in that section of the isotope diagrams, we also find data of some Serbian ores and Bulgarian ores and slags. In the Ag/Au diagram, one can recognise that its ratio does not entirely coincide with those of oxhide ingots from Cyprus. Still, all of the other trace element concentrations are comparable to those of oxhide ingots with Cypriot provenance (Fig. 6, Tab. 5).[94] We, therefore, can still assume an eastern Mediterranean ore deposit as a source of its copper.

The final piece to discuss is an ingot from the S. Karlovci hoard (VIAS lab. no. VoNSM 223). Its trace element concentrations point to fahlore as a source, but lead isotope analyses must be carried out to give further information on its provenance.

Plano-convex Ingots – Rod Ingots – Finished Objects

Many of our analysed hoards contain ingots from both major mining areas in the Alps. In principle, each hoard, or more specifically, each ingot, reflects the copper (with a specific geochemical pattern) available in the region during the time of deposition. Connected to this, it is very interesting that certain ingots have close analytical connections to each other. This is recognisable when comparing the ingot data from the Serbian hoards of Hetin (VIAS lab. no. VoNSM 217 and VoNSM 218), Klenje (VIAS lab. no. PozM 69), and the Privina Glava hoard (VIAS lab. no. BelM 441), which all have almost identical lead isotope ratios, and whose geochemical composition suggests they all came from one mining area – in that specific case the Buchberg lode at the Hochkönig-Mitterberg. It is possible that their metal was produced during smelting events. Such close relations can also be assumed for the ingot VIAS lab. no. SJLM 49 (Novigrad) with VoNSM 189 (Futog), coming from the Buchberg or Brandner lode (Hochkönig-Mitterberg). The ingots VIAS lab. no. BelM 475 (Trlić hoard) with VoNSM 187 (Futog), BelM 447 (Rudnik) and BelM 535 (Laznica), as well as BelM 532 (Laznica) and SJLM 71 (Podzvizd), are also connected by their closely related isotope ratios, which means it is probable they are made of copper from the same smelting area.[95] Even though some deviations in the element concentrations are observed, presumably caused by the use of different ore portions and/or smelting conditions, they show a consistent picture.[96]

When these ingots with different provenance are melted together, or metal remains from a previous melt are still present in the crucible, the geochemical pattern of both components is mixed, producing a metal with an average metal composition. As such, they (would) form an intermediary group. When combining the ingot data with those of the artefacts, dated to BA D–Ha A1, it becomes obvious that, especially in the Sb/Ag diagram (Fig. 4), finished objects like those from, e.g., the Klenje or Kličevac-Rastovača[97] are placed between the clusters or vary in the field of the eastern Alpine plano-convex ingots. The same is describable for the rod ingots, which are semi-finished products used to cast the finished artefacts (yellow triangles, Fig. 4). During the melting and casting event, the element concentrations get homogenised, and the pattern can but must not shift[98] towards the cloud-like centre of such a cluster – in our case, to the eastern Alpine ingot cluster (Figs. 3–4). This is caused by the elevated trace element concentrations (especially Ni, As and Sb) in raw metals from the latter region, which are higher than in the southern Alpine

94 Athanassov et al. 2020; 326, tab. 5.

95 The isotope values of PozM 39 and DobM 69 are closely related, but their trace element concentrations, especially the As values, are deviating. Therefore, a close connection is not describable. It only can be stated that both come from Cyprus.

96 One cannot expect that copper from different smelting events is chemically identical, as the composition of the ore, the beneficiation process as well as possible other intentional or unintentional additions (slag sand, gangue, etc.) influence the geochemical composition of the smelting products.

97 See fig. 5 in the contribution of Gavranović et al. in this volume.

98 This essentially depends on the mass ratio and the lead concentrations of the different used metals.

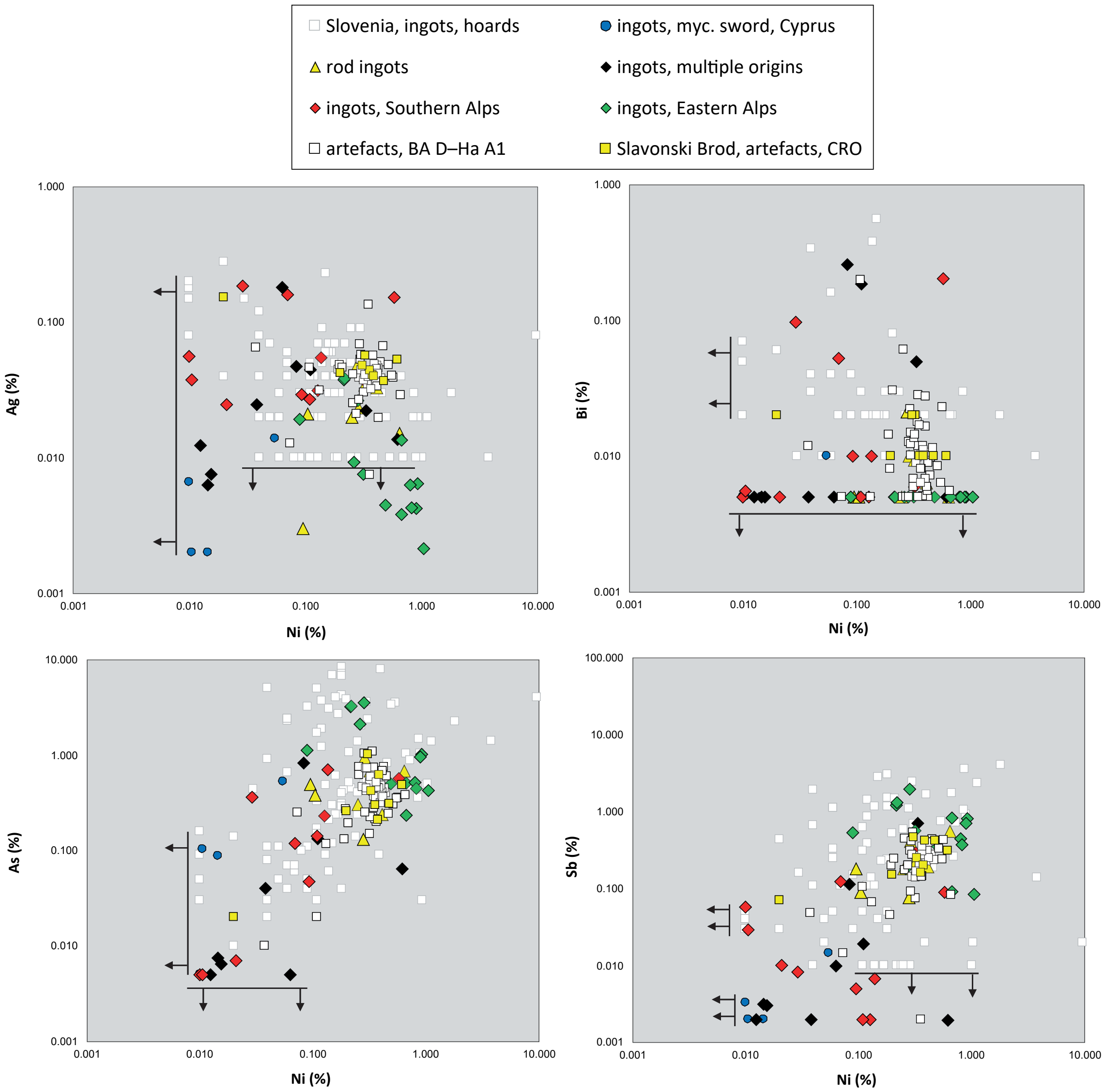

Fig. 7 Concentrations of silver, bismuth, nickel, arsenic and antimony in plano-convex copper ingots, rod ingots, as well as bronze weapons and implements from Bosnia-Herzegovina, Serbia, Slovenia and Croatia. The black arrows mark the detection limit of the analytical device. Data: Klemenc et al. 1999, 143, tab. 1; Mehofer et al. 2020, 191, tab. 1; Gavranović et al. 2021, tab. 1; Perez Gonzalez – Schwab 2023, 247, tab. 2 (chart: M. Mehofer, University of Vienna)

ingots. In the lead isotope diagrams, one can interestingly observe the opposite effect. The low lead concentration in the eastern Alpine ingots leads to the fact that their isotope ratios are erased[99] when mixed with southern Alpine ingots, whose average lead concentrations are higher (Tabs. 2, 4). Consequently, the finished objects are mostly assigned to the Southern Alps, whilst none can be assigned to the Eastern Alps.[100] It should be noted that a comparison using our complete dataset does not result in such a stringent picture. A part of the finished objects, dated to BA D–Ha A1, has trace element concentrations higher than those in the ingots. This means that, due to the small number of analysed pieces, either the entire possible range of variation in the trace element concentrations is not known or that a first influx of fahlore or diluted fahlore (with higher trace

[99] Nørgaard et al. 2023, 137. A similar observation for eastern Alpine copper was made for finds found in Denmark and South Sweden.
[100] Gavranović et al. 2022.

element concentrations) is visible already during the Ha A1 period. Of course, there are also finished objects with southern Alpine trace elements and lead isotope patterns.

Finally, let's have a view to the north. Within a recent publication, analyses of finished objects from the Slavonski Brod hoard (dated to Ha A1) were published.[101] Their trace elements have the same pattern as presented here (Fig. 7). While we acknowledge that lead isotope analyses are missing, they are highly likely made of the same copper from the Southern and/or Eastern Alps. Analyses of contemporary pc-ingots from Slovenia also support this observation.[102] In the Sb/Ag diagram, the pc-ingots from Črmošnjice, Udje, Debeli vrh, Jurka vas, Silovec, Pekel and Hočko Pohorje (in total 95 pieces) group with our pc-ingots with either southern or eastern Alpine provenance (Fig. 4), hinting to the same metal exchange networks and metallurgical practices observable in the regions to the south: ingots with southern Alpine and eastern Alpine provenance were also melted together in the Slovenia and Croatian metal workshops,[103] producing artefacts with trace element pattern comparable to the finished objects analysed in this study. In the double logarithmic diagrams, the latter bronzes seem to form a group not untypical for mixing/recycling processes. However, our further research on Late Bronze Age axes from Serbia demonstrates that at least two trace element groups can be detected within these BA D – Ha A1 dated objects.[104] This demonstrates that such large datasets must always be discussed in detail by their typological, chorological or chronological information.

One can assume that mixing and recycling was a common metallurgical practice during the Late Bronze Age. There is no doubt that metal waste, scrap metal, casting remains or broken objects were remelted. Peter Bray attempts to approach the subject from a theoretical as well as an analytical point of view, looking for systematic chemical changes within the trace elements in the copper.[105] The complexity of recycling – and the difficulty of understanding and detecting it – is also shown by the fact that he mentions many different terms to describe the reuse/remelting of metal. From an analytical point of view, recycling can be recognised when certain elements are depleted during remelting (if oxidising conditions are present). A decreasing gradient (e.g., of arsenic) should thus be recognisable.[106] The discovery of such a gradient is only possible under two conditions: firstly, that only metal from the adjacent region is remelted, and secondly, that no fresh copper – e.g., in the form of ingots – is available at a greater distance from the mine. This would lead to the reintroduction of fresh metal with increased trace element concentrations far away from the deposits. Consequently, the attenuated gradient would no longer be practically measurable. This corresponds to the situation in the study area during the Late Bronze Age when ingots were present in many hoards, and fresh copper was permanently reintroduced into the exchange systems.[107] Generally speaking, many parameters must be taken into consideration when evaluating for recycling: ore deposits that are not fully analytically characterised, raw metal and ingots of different provenance and composition, mixing of copper already in their production areas (e.g. hypothesised for the ingots BelM 532, 534 and 535 with their increase lead concentrations, see above), remelting of waste metal, influx of metal from other metal exchange networks and many more.[108] To conclude, the identification of mixing and recycling in the analytical record remains challenging and demands a broad variety of methods.

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101 Perez Gonzalez – Schwab 2023, 247, tab. 2.
102 Trampuž Orel 1996; Klemenc et al. 1999.
103 Gavranović et al. 2022, 16–20.
104 Mehofer forthcoming.
105 Bray 2022, 92.
106 Bray 2022, 93.
107 Our dataset of analysed ingots, rod ingots, semi-finished and finished objects shows decreasing tin concentrations, in some cases elevated lead concentrations and partly homogeneous trace element patterns over time and the used of 'diluted' fahlore copper (mixture of fahlore and chalcopyrite based copper) from Ha A2 onwards discussed. Gavranović et al. 2022, 26, tab. 2.
108 Berger et al. 2022; Berger et al. 2023.

Conclusion

Based on the data presented, we have examined the nature of copper supply and use in the western and central Balkans in more detail. Within the trading systems, copper from Trentino, Vinschgau, the Eastern Alps (Mitterberg, Kitzbühel-Kelchalm, Viehhofen), and Cyprus were circulated.[109] We can describe the regular use of low-impurity chalcopyrite-like copper,[110] a result that fits well with the appearance of this phenomenon across Europe at this time.[111] In the hoards from both Bosnia-Herzegovina and Serbia, one finds (fragmented) plano-convex ingots and rod ingots, the latter representing a further processing step (remelting, purification, alloying) of the metal (Tab. 1). The analytical results indicate that copper from different regions was mixed, with the chemical composition of the finished artefacts deviating from those of the ingots. This phenomenon is best explained by the melting together of ingots (as seen in the diagrams Fig. 4) or the mixing of ingots with scrap metal. The low lead concentrations in the eastern Alpine and Cypriot raw metals are superseded when mixed with southern Alpine copper, which has higher average lead concentrations (Figs. 2, 4). Therefore, metal from these two sources is no longer traceable in the analytical record.[112] In our dataset, we find such ingots with very low lead concentrations but also a few with elevated lead values above 1%.[113] If these are mixed, artefacts with raised lead concentrations are produced, and they are detectable in our data. Although this explanation might be the most probable one, it must be treated with caution, as questions still have to be clarified.

At the current state of research, our data shows that many of these hoards dominantly contain metal from the Eastern and the Southern Alps, whilst local ore deposits seem to be unexplored. When looking at the provenance data of the ingots already analysed, it appears that in the Bosnian territory, ingots from Trentino are most prominent, while eastern Alpine copper is dominant in Serbia. The analysing strategy may also influence this picture with 13 samples from Bosnia and 35 from Serbia. However, it should also be noted that our work is ongoing with planned analysis of additional ingots, which might change the picture in the future. Furthermore, we were able to assign the copper of two ingots from the study region and a Mycenaean rapier from Tetovo (MKD) to the ore deposits of Cyprus.

As a significant result, we can point out that there are close analytical relations between specific ingots, which demonstrates that ingots or ingot pieces that arrived (together) in the Balkans were then distributed to different areas. The copper was smelted at certain places, e.g., in the wider region or the Buchberg or the Brandner lode at the Hochkönig-Mitterberg and then traded to the south. Presumably, batches of metal from the same smelting site travelled along the main exchange routes and reached the regions under study, where it was distributed to different places and eventually hoarded. For example, we can name ingots found in the hoards from Hetin, Klenje and Privina Glava, all located in Serbia. There are also analytical connections between ingots found at a wider distance; one ingot fragment from the Novigrad hoard (Bosnia-Herzegovina) and one from the Futog hoard are closely comparable by their lead isotope ratios. Such analytical relationships demonstrate that the Serbian and Bosnian regions were connected to the same exchange networks that possibly used the Danube, the Drava and the Sava Rivers as main communications and trading routes. A similar situation can be described for the adjacent Croatian and Slovenian territories. The comparison has shown that the published chemical data of Late Bronze Age ingots

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109 Gavranović – Mehofer 2016; Mehofer et al. 2021; Gavranović et al. 2021; Gavranović et al. 2022.

110 Gavranović et al 2022, 22, 24, fig. 8. High impurity fahlore-type copper and diluted fahlore copper are not (with one exception) present in the dataset discussed in this study. These metal types occur rather from Ha A2 onwards on the western and central Balkans.

111 Pernicka et al. 2016, 39, fig. 20.

112 The Mycenaean rapier from Tetovo was made in the Mediterranean and therefore only contains Cypriot copper.

113 This is ingot VIAS lab. no. BelM 440, BelM 532 and BelM 534. Further ones do have slightly elevated lead concentrations over the average values like VoNSM 217 and VoNSM 218 or BelM 535.

and artefacts is entirely compatible with the trace element concentration of contemporary ingots and finished artefacts in our study area.

Although we still have open questions on aspects of our analyses, the data evaluation allows for further remarkable conclusions. Based on this systematic analytical survey, the description of the metal supply and use in the western and central Balkans can now be set on a solid basis. From a broader perspective, one can state that the Eastern Alps with the Hochkönig-Mitterberg region was the dominant copper supplier during the Middle Bronze Age in Europe,[114] with its copper being found in many copper and bronze artefacts. Of course, other mining areas like those in the Tyrolian region, the Great Orme mine (GB), and the Slovakian ore mountains also fed copper into the exchange networks. At the beginning of the 12th century BC, the Mitterberg copper production decreased and continued on a much lower level, with reduced production capacities also resulting in a reduced number of ingots being exported. This, in turn, naturally reduces the number of available ingots with such a geochemical signature in the analytical record and might be a further explanation as to why no finished object with Hochkönig-Mitterberg signature was found in our study region. Sometime earlier, a new node was established in the copper supply networks. Now, the southern Alpine region (especially the Trentino)[115] has become an essential supplier of metal in the European networks. It started the large-scale production of copper, and its metal is detectable in many European bronzes– from Denmark to the Balkans, southern Italy, and even the eastern Mediterranean since that time.[116]

With the help of this analysis, it is now possible to close the analytical gap between the western and central Balkans and the Adriatic region. The comparison of the results makes it more than reasonable that in Slovenia and Croatia, metal from the Trentino and the Hochkönig-Mitterberg circulated, defining the whole region as a consumer of Alpine metal. Our analyses additionally mark the Vinschgau region as a further supplier of copper in these networks, but, to date, we do not know the full extent of its production volume.[117] Finally, we can state that during the Late Bronze Age, metal from the southern Alpine mining regions in Trentino was dominant in all Italian and Balkan metals, providing evidence for its important position within the exchange systems south of the Alpine ridge. Whether and to what extent this copper was locally remelted/recycled or whether stable exchange networks guaranteed the permanent influx of fresh copper will be the focus of our future research.

Acknowledgements: This research was conducted within the FWF project 'New insight in Bronze Age metal producing societies in western and central Balkans' (P 23095), PI: M. Gavranović and was financially supported by the Austrian Science Fund and the Vienna Institute for Archaeological Science (VIAS), University of Vienna. We want to thank Irene Petschko from the Austrian Archaeological Institute (OeAI) for creating and editing the maps. We owe gratitude to Clare Burke, Meghan Crnjak and Sheba Mehofer-Schilk for the proofreading of the text.
Writing of sections: Mathias Mehofer: Introduction, Questions and Objectives, Materials, Methods, Discussion, Conclusion.
Authors Contributions: Mathias Mehofer: Conceptualisation, data curation, formal analyses, investigation, methodology, supervision, writing – original draft, writing – review and editing – final text; Mario Gavranović: project administration, resources, writing – review and editing – final text

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Copper From Far Away: Chemical and Lead Isotope Analyses of Metal Objects from Late Bronze Age Hoards Klenje and Kličevac-Rastovača, Northeastern Serbia

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Abstract: In this paper, we discuss the results of the chemical and lead isotope analyses on metal objects from the Late Bronze Age hoards Klenje and Kličevac-Rastovača, both located in northeastern Serbia. The results of trace element analysis are available for 31 finds from Klenje, and 15 finds from Kličevac-Rastovača, showing a range of different alloys in terms of added tin or lead and the presence of various impurities (arsenic, antimony, nickel, and silver). In order to narrow down the possible source of copper used for the production, lead isotope analyses were additionally conducted on 12 samples from Klenje and four samples from Kličevac-Rastovača. Most of the finds confirmed the general trend for the Late Bronze Age in the western and central Balkans, with a prevalence of copper having an isotopic signature that corresponds to the Trentino mining region in northern Italy.[4] However, we also attested the copper from other distant regions such as Eastern Alps (Hochkönig-Mitterberg) and Cyprus. Based on the typo-chronological evaluation of deposited objects, both hoards can be associated with the stage Ha A1 or the second horizon/stage of Late Bronze Age hoards, according to the regional chronologies for southeast Europe.[5] This period (13th and early 12th century BC) is marked by the peak of deposition activity in a vast area between central Europe, the Adriatic Sea and the Carpathian Mountains with well-recognisable regional hoarding patterns and wide distribution of specific metal types.[6] Indicative of Klenje and Kličevac-Rastovača and other hoards in northeastern Serbia around Požarevac is their position on the southeastern fringe of the overall distribution in Europe and their proximity to the abundant copper ore deposits in eastern Serbia.

Keywords: Late Bronze Age, hoards, northeastern Serbia, copper alloys, copper provenance

Archaeological Information

The area of northeastern Serbia, also known as the Braničevo district, between the Danube, Velika Morava, Mlava and Pek Rivers is characterised by a number of metal hoards from the Bronze and Iron Ages.[7] A particularly striking hoard density during the Ha A1 period makes this area comparable with other micro-regional clusters in southeastern Europe.[8] A similar concentration occurs in the Vršac Mountains in the Banat region,[9] in the area around Slavonski Brod in Croatia[10] or in

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3 National Museum Požarevac, Serbia.
4 Mehofer et al. 2021; Gavranović et al. 2022.
5 Holste 1951; von Brunn 1968; Garašanin 1975; Vinski-Gasparini 1973; Petrescu-Dîmbovița 1978; Vasić 1982; Mozsolics 1985; Jacanović 1986; Hansen 1994; Teržan 1995; Jacanović 2000; König 2004.
6 Soroceanu 1995; Hänsel 1997; Váczi 2013; Dietrich 2014; Szabó 2019.
7 Jacanović 1992; Jacanović 1997; Stojić – Jacanović 2008.
8 Jacanović 1992.
9 Jovanović 2010.
10 Vinski-Gasparini 1973; Miklik-Lozuk 2009; Miklik-Lozuk – Ložnjak Dizdar 2011.

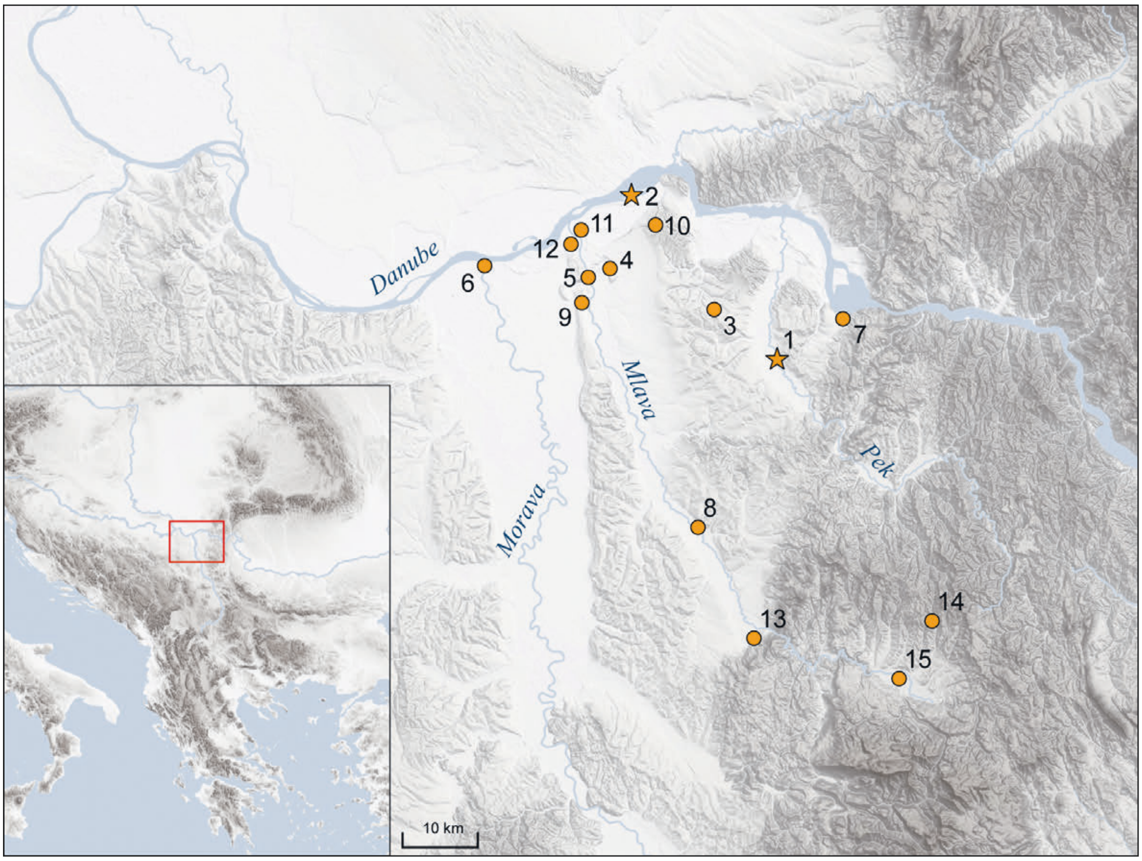

Fig. 1 Map of the Ha A1 hoards in northeastern Serbia 1. Klenje; 2. Kličevac-Rastovača; 3. Pečanica; 4. Bradarac-Drmno; 5. Bradarac-Rukumija; 6. Dubravica; 7. Golubac-Groblje; 8. Pregudovo; 9. Klenovnik-Cirikovac; 10. Kličevac-Pomrlovo; 11. Novi Kostolac; 12. Stari Kostolac; 13. Šetonje; 14. Laznica; 15. Suvi Do-Žagubica. All after Stojić – Jacanović 2008 (map: I. M. Petschko, OeAI-OeAW)

the middle course of the Bosna River in Bosnia-Herzegowina,[11] to name just a few. In contrast, there are also territories with a very limited number of contemporary hoards, such as Bačka/Bácska in Vojvodina and southern Hungary[12] or northwestern Bosnia along the Save River.[13] Even if these differences are admittedly partially artificial and caused by the uneven state of research and varying intensity of agricultural or building activities that led to the discovery of the hoards, the existence of distinct geographical regions with a significantly higher number of metal hoards seems to be hardly disputable.

The mere fact that hoards appear more frequently in a particular region says nothing about the intensity of local metal production, especially if other evidence is missing. It is however reasonable to assume that the amount of circulated metal in such regions, regardless of its production place, was relatively high. Thus, the number of uncovered Ha A1 hoards in northeastern Serbia speaks for an increased deposition activity but does not necessarily imply an engagement of local populations in metal production. However, due to the distribution along the Mlava and Pek Rivers that connect nearby large copper ore deposits of eastern Serbia with the Danube River, most of the studies regarded the hoards from northeastern Serbia in a context of collective votive offerings and related to ores, metals and mining.

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11 König 2004; Blečić-Kavur – Jašarević 2014; Blečić-Kavur et al. 2019.

12 Garašanin 1975, 105; Mozsolics 1985, 518; Hansen 1994, Beilage 1.

13 König 2004, 15.

In terms of composition, the hoards from northeastern Serbia and finds from Banat and the area around the Iron Gates follow a specific regional pattern described as ‘Region 15’ in S. Hansen’s fundamental study on metal hoarding during the periods BA D and Ha A1.[14] According to this, typical of this region is a higher number of socketed axes and bracelets in mixed hoards, as well as the appearance of smaller hoards containing only bracelets or socketed axes.[15] With regard to the structure, S. Hansen pointed at a similar composition in adjacent territories of Transylvania to the northeast (‘Region 11’) and Slavonia/Syrmia to the west (‘Region 14’) with a difference that in ‘Region 15’ sickles are less represented. Given the publication of new hoards after the study of S. Hansen, this assessment would require certain adjustments, especially due to the relatively high proportion of sickles in Kličevac-Rastovača (20 sickles vs 6 socketed axes), Kličevac-Pomrlovo (46 sickles vs 19 socketed axes)[16] and Šetonje (24 sickles vs 12 socketed axes).[17]

The Klenje hoard was discovered in 1982 on the bank of a small creek that flows to the Pek River.[18] The 129 metal objects were deposited in a pottery vessel without indication of a settlement or any other prehistoric activity in the surrounding area. Indicative of the Klenje hoard is a high number of undamaged objects (98 pieces) and the absence of weaponry, apart from the one arrowhead of a local type.[19] Decisive for the chronological determination are socketed axes with bell-shaped decorations and vertical ribs (Appendix, VIAS lab. no. PozM 55, PozM 57, PozM 60), considered a regional metal type of the late Ha A1.[20] The majority of other objects, including knobbed and tanged sickles,[21] decorated and ribbed bracelets,[22] pins with maze-shaped and with spindle heads,[23] saws,[24] and a decorated belt made of the bronze sheet,[25] are all well-known metal types with most analogies coming from the Ha A1 hoards in the wider region of southeast Europe. What should be pointed out among the finds from Klenje are the axes with other metals stuffed in the socket (Appendix, VIAS lab. no. PozM 55–60). An arrangement of the objects in the axe socket for the purpose of the final deposition is a phenomenon already observed in the Carpathian Basin during Ha A1, which in later stages (Ha B) also occurs in west Europe.[26] In the case of Klenje, two axes were stuffed with smaller ingot fragments, while the socket of the third axe was blocked with a bend saw and a fragment of a ribbed bracelet. Such compositions with metals in the socket are described as ‘miniature hoards’.[27] Our aim was to examine a possible technological connection between the finished object (socketed axes) and ingots stuffed in the socket. Apart from Klenje, the combination of a socketed axe and a stuffed ingot piece is thus far evidenced only in the Dolina hoard in the middle course of the Sava River in Croatia.[28] To summarise, the Klenje hoard has several distinct features as compared to the majority of the hoards in the region. The absence of weaponry, the fact that most objects do not belong to the category of scrap metal as a common component of Ha A1 hoards,[29] and the occurrence of socketed axes

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14 Hansen 1994, 356.
15 Hansen 1994, 348.
16 Jacanović – Radojčić 2001.
17 Jacanović – Radojčić 2003.
18 Jacanović 1986. All finds from the Klenje hoard are stored at the National Museum in Požarevac.
19 Vasić 2015, 75.
20 Dergačev 2010, 98 (‘Typ Banat’); Gavranović – Kapuran 2014, 4; Dietrich 2021.
21 Vasić 1994, nos. 16, 45–46, 101, 193, 261–262.
22 Jacanović 1986, 170.
23 Vasić 2003, nos. 514, 589.
24 Jacanović 1986, 169.
25 Hansen 1994, 238, fig. 151; Tarbay 2014, 200, fig. 19.
26 Hansen 2000; Dietrich 2014; Dietrich – Mörtz 2019, 281; Dietrich 2021, 801. These studies considered the finds from Klenje, however, with a false location of the site referring to the village Klenje in Mačva (northwestern Serbia). The hoard Klenje was found some 150 km further to the east between Golubac and Požarevac in the same-named village (see Fig. 1), ca. 5 km south of the Danube River. See also Rezi – Gogâltan 2019, 193, fig. 3.
27 Dietrich 2014, 471.
28 Schauer 1974, 99, fig. 3, 5.
29 Vasić 1982; Hansen 1994; Dietrich 2014; Hansen 2016.

with blocked sockets are all pointing at either somewhat different backgrounds of hoarding and/or perhaps at certain chronological delays. Since there are no finds that would suggest a convincing dating in Ha B1, we would argue that the Klenje hoard was probably deposited in the later stages of Ha A or in time of the late 12th century BC.

The Kličevac-Rastovača hoard came to light in 1993 in the course of building activities on the left bank of the Danube in the close vicinity of the mouth of the Mlava River.[30] Until recently, this area was a large river island (20 km long and 3 km wide) called 'Ostrovo'. As in the case of Klenje, no archaeological sites from the Bronze and Iron Ages have been identified in the surrounding area. The 110 metal objects were placed in a large vessel with a black polished surface and a 'false cord' decoration.[31] In the urn cemeteries of the Belegiš group, such as Karaburma,[32] Kaluđerske Livade[33] or Belegiš,[34] all located on the river banks of the Danube, similar vessels (urns) are indicative of the transition between the Belegiš I ('false cord') and the Belegiš II (black polished surface) phase, which roughly corresponds to BA D–Ha A1. The composition of the Kličevac-Rastovača hoard with fragments of swords, spearheads, daggers, sickles, socketed axes, knives, razors, bracelets, pins, decorated discs, bronze vessels and ingots fits perfectly to the structure of the hoards in the region of neighbouring Syrmia and Slavonia or 'Region 14', according to the classification of S. Hansen.[35] As in a number of contemporary hoards in southeastern Europe, the metals from Kličevac-Rastovača show specific and deliberate breaking patterns of swords, socketed axes, sickles or spearheads.[36] The typological assessment of the finds points to a clear association with the spectrum of metal finds from Ha A1 in the southern part of the Carpathian Basin. These include a flange hilted sword of Reutligen Type, Variant Staro Topolje (Appendix, VIAS lab. no. PozM 32),[37] pins of Velemszentvid type with round head (Appendix, VIAS lab. no. PozM 49), pins with a biconical head (Appendix, VIAS lab. no. PozM 48), *Petschaftkopfnadel* (Appendix, VIAS lab. no. PozM 37), socketed axes with three V-ribs (Appendix, VIAS lab. no. PozM 38),[38] tanged sickels of Uioara types 1, 2 and 8 (Appendix, VIAS lab. no. PozM 40, PozM 42, PozM 44),[39] and spearheads with a profiled middle part (Appendix, VIAS lab. no. PozM 46).[40] What makes Kličevac-Rastovača interesting with regard to production and technological background is the presence of not only fragments of plano-convex ingots but also so-called rod ingots (Appendix, VIAS lab. No. PozM 35, PozM 36), a semi-finished object (Appendix, VIAS lab. no. PozM 39) and amorphous metals described as casting waste.[41]

Analyses and Objectives

The sampling of objects from Klenje and Kličevac-Rastovača in the National Museum Požarevac and subsequent analyses were conducted in the frame of the research project 'New insight in Bronze Age metal producing societies in western and central Balkans' (2019–2023) supported by the Austrian Science Fund[42] and the VIAS – Vienna Institute for Archaeological Science, University of Vienna. The main aim of the project is to increase our knowledge about the Bronze Age

30 Jacanović 2000. All finds are stored at the National Museum in Požarevac.
31 Jacanović 2000, 35.
32 Todorović 1977.
33 Petrović 2006.
34 Vranić 2002.
35 Hansen 1994, 357, fig. 208.
36 Rezi 2011.
37 Harding 1995, 38.
38 Wanzek 1989, 308; König 2004, 38.
39 Vasić 1994, nos. 101, 183, 262, 282.
40 Vasić 2015, no. 250.
41 Jacanović 2000, 43; Gavranović et al. 2022, 13, tab. S1; 29, tab. S2.
42 FWF Stand-alone project, P 23095, PI M. Gavranović.

metallurgy in the Balkans and to elucidate copper supply networks by using the archaeological information and results of trace element and lead isotope analyses.

One of the important parts of the project was to examine the possible impact of the domestic copper raw materials from abundant sources in eastern Serbia or central Bosnia on the Bronze Age metallurgy in the Balkans. As our results demonstrated, the production of copper in Eastern Serbia, or more precisely in the sites around the city of Bor, took place mainly between the 19th and 16th centuries BC and then ceased for reasons that still need to be explored.[43] The copper from eastern Serbia is attested in several Middle Bronze Age objects from the central Balkans,[44] yet this source appears to be less significant for the Late Bronze Age. Instead, our investigations revealed that most of the copper used between the 15th and 9th centuries BC in different regions of western and central Balkans came from large smelting places in Trentino in northern Italy.[45] A similar dominance of Trentino copper is already attested for the neighboring Italian peninsula during that period.[46] Using the finds from Klenje and Kličevac-Rastovača hoards, this paper attempts to provide a deeper insight into the metallurgical background of finds from northeastern Serbia in terms of alloy compositions and copper raw material provenance. Considering the number of metals deposited in a relatively short period in this region, it was intriguing to see if the copper from any other sources could be detected and what the chemical composition of the deposited object would be.

Methods

The metal objects were sampled with a polished 1 mm stainless steel drill bit. Before use, each drill bit was cleaned with highly concentrated ethyl alcohol (97%) to remove possible remains from the production process (e.g., polishing emulsion). As a first step, the patina was removed with a drill, and afterwards, a new bit was used to drill a hole 1–2 mm deep. Finally, the resulting drill shavings were collected for analyses.

All samples were analysed at the Curt-Engelhorn-Centre of Archaeometry (CEZA) in Mannheim (Tab. 1). For the measurements of the trace element concentrations, an energy dispersive X-ray fluorescence (EDXRF) spectrometer (ARL Quant X, Thermo Scientific) was used to analyse the elements silver (Ag), arsenic (As), bismuth (Bi), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), tin (Sn), antimony (Sb), tellurium (Te) and zinc (Zn). The detection limits lie at approximately 0.005% for Ag, Sb, Sn, Pb, Bi, and 0.05% for Fe, and around 0.01% for Co, Ni, and As. Selenium and tellurium were measured but were below 0.005 % in all samples. All measurements are given in mass%.[47]

The lead isotope ratios ($^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{204}Pb$) were measured using a high-resolution multi-collector mass spectrometer (Thermo Scientific Neptune Plus) with inductively coupled plasma as ion source (HR-MC-ICP-MS) (Tab. 2). The drill shavings (samples) were rinsed with diluted HNO_3 to remove any surface contamination and then dissolved in half-concentrated HNO_3 in an ultrasonic bath (70˚C) for several hours.[48]

The elements Ni, Ag, As, and Sb were combined in double logarithmic diagrams, the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ lead isotope ratios were used to generate bivariate comparative lead isotope plots for the discussion of the data.

43 Kapuran et al. 2020; Mehofer et al. 2021; Gavranović et al. 2022.
44 Mitrović 2022.
45 Mehofer et al. 2021, 9; Gavranović et al. 2022.
46 See the contribution Mehofer et al. in this volume. Jung et al. 2011; Jung – Mehofer 2013, Mehofer et al. 2020; Jung et al. 2021.
47 Detailed description, see Lutz – Pernicka 1996.
48 For more details, see Niederschlag et al. 2003.

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	Cu	Fe	Co	Ni	Zn	As	Ag	Cd	Sn	Sb	Pb	Bi
PozM 32*	2131	MA-186760	92	0.20	0.05	0.42	0.1	0.69	0.034	0.005	5.6	0.40	0.14	0.006
PozM 33	2133	MA-196056	92	0.13	0.04	0.32	0.1	0.59	0.044	0.005	6.3	0.267	0.43	0.014
PozM 34	2132	MA-196057	91	0.05	0.03	0.37	0.1	0.46	0.041	0.005	7.5	0.30	0.42	0.008
PozM 35*	2222	MA-186761	96	0.16	0.03	0.28	0.1	0.133	0.048	0.005	3.6	0.076	0.04	0.021
PozM 36	2224	MA-196058	99	0.14	0.20	0.25	0.1	0.31	0.020	0.005	0.02	0.181	0.01	0.005
PozM 37	2134	MA-196059	76	12.6	0.12	0.07	0.1	0.251	0.013	0.01	11.1	0.015	0.03	0.005
PozM 38	2141	MA-196060	92	0.06	0.03	0.30	0.1	0.45	0.044	0.005	5.8	0.274	1.19	0.01
PozM 39	2144	MA-186762	100	0.05	0.01	0.01	0.1	0.005	0.007	0.002	0.03	0.003	0.006	0.005
PozM 40	2147	MA-196061	94	0.08	0.03	0.26	0.1	0.62	0.041	0.005	3.7	0.45	0.36	0.061
PozM 42	2153	MA-196062	93	0.05	0.03	0.30	0.1	0.73	0.069	0.005	4.7	0.41	0.56	0.02
PozM 44	2159	MA-196063	94	0.05	0.03	0.30	0.1	0.73	0.057	0.005	3.9	0.54	0.41	0.015
PozM 45	2136	MA-196064	86	0.16	0.02	0.33	0.1	0.226	0.041	0.01	13.2	0.167	0.24	0.014
PozM 46	2138	MA-196065	90	0.09	0.03	0.37	0.1	0.52	0.032	0.005	8.7	0.35	0.36	0.006
PozM 48	2193	MA-196066	94	0.24	0.05	0.29	0.1	0.250	0.027	0.005	5.0	0.091	0.28	0.005
PozM 49	2196	MA-186763	89	0.05	0.02	0.67	0.1	0.38	0.029	0.005	9.2	0.083	0.15	0.006
PozM 51	1003	MA-196068	91	0.05	0.03	0.45	0.1	0.40	0.051	0.005	7.2	0.276	0.12	0.007
PozM 52	1004	MA-196069	91	0.08	0.05	0.34	0.1	1.10	0.042	0.005	7.0	0.248	0.12	0.009
PozM 53	1005	MA-186764	96	0.13	0.03	0.20	0.1	0.27	0.048	0.005	3.46	0.202	0.15	0.008
PozM 54	1006	MA-186765	93	0.17	0.03	0.39	0.1	0.38	0.057	0.005	5.22	0.252	0.25	0.012
PozM 55	1007	MA-186766	95	0.45	0.06	0.26	0.1	0.76	0.025	0.005	3.06	0.173	0.06	0.005
PozM 56	1007	MA-196070	100	0.41	0.01	0.01	0.1	0.01	0.012	0.005	0.01	0.002	0.01	0.005
PozM 57	1008	MA-186767	92	0.11	0.04	0.35	0.1	0.37	0.134	0.005	6.4	0.173	0.36	0.028
PozM 58	1008	MA-186768	78	21.2	0.01	0.06	0.4	0.01	0.181	0.002	0.19	0.010	0.005	0.005
PozM 60	1010	MA-196071	91	0.79	0.03	0.43	0.1	0.45	0.045	0.005	6.3	0.41	0.14	0.009
PozM 64	1044	MA-186769	87	0.05	0.03	0.52	0.1	0.31	0.048	0.01	11.3	0.33	0.33	0.009
PozM 65	1046	MA-196072	79	0.21	0.01	0.11	2.8	0.02	0.046	0.005	3.5	0.106	13.7	0.200
PozM 69	1000a	MA-186770	95	2.93	0.11	0.09	0.1	1.13	0.019	0.002	0.01	0.54	0.037	0.005
PozM 70	1015	MA-196073	93	0.05	0.03	0.41	0.1	0.47	0.036	0.005	5.2	0.283	0.14	0.007
PozM 71	1016	MA-196074	93	0.08	0.03	0.42	0.1	0.41	0.048	0.005	5.7	0.248	0.13	0.011
PozM 72	1017	MA-196075	94	0.05	0.02	0.29	0.1	1.05	0.039	0.005	4.3	0.31	0.18	0.013
PozM 73	1018	MA-196076	94	0.05	0.03	0.41	0.1	0.48	0.046	0.005	5.0	0.226	0.23	0.017
PozM 74	1019	MA-196077	95	0.05	0.02	0.30	0.1	0.42	0.053	0.005	4.0	0.141	0.15	0.012
PozM 75	1020	MA-196078	93	0.30	0.05	0.38	0.1	0.46	0.042	0.005	4.9	0.208	0.20	0.008
PozM 77	1055	MA-196079	94	0.24	0.03	0.32	0.1	0.52	0.037	0.005	4.8	0.138	0.18	0.006
PozM 78	1068	MA-196080	93	0.08	0.03	0.39	0.1	0.32	0.044	0.005	6.0	0.257	0.32	0.011
PozM 79	1081	MA-196081	91	0.22	0.07	0.28	0.1	0.46	0.021	0.005	7.5	0.199	0.05	0.005
PozM 80	1117	MA-196082	89	0.24	0.08	0.21	0.1	0.195	0.046	0.005	9.5	0.246	0.29	0.031
PozM 81	1118	MA-186771	95	0.12	0.04	0.36	0.1	0.36	0.041	0.005	3.3	0.143	0.15	0.017
PozM 82	1120	MA-196083	91	0.10	0.05	0.57	0.1	0.36	0.039	0.005	6.4	0.43	1.19	0.02
PozM 83	1115	MA-186772	88	0.06	0.02	0.47	0.1	0.245	0.066	0.01	10.9	0.237	0.18	0.011
PozM 84	1083	MA-196084	94	0.12	0.03	0.40	0.1	0.31	0.049	0.005	4.5	0.254	0.18	0.010
PozM 85	1087	MA-196085	94	0.19	0.03	0.56	0.1	0.35	0.040	0.005	4.1	0.241	0.18	0.006
PozM 86	1090	MA-196086	97	0.12	0.02	0.13	0.1	0.118	0.031	0.005	2.82	0.067	0.06	0.005
PozM 87	1092	MA-196087	91	0.09	0.03	0.39	0.1	0.45	0.040	0.005	7.8	0.271	0.18	0.005
PozM 88	1101	MA-196088	93	0.26	0.04	0.41	0.1	0.38	0.045	0.005	5.2	0.31	0.10	0.028
PozM 89	1102	MA-196089	93	0.05	0.04	0.35	0.1	0.74	0.039	0.005	5.1	0.197	0.08	0.005
PozM 90	1040	MA-196090	94	0.05	0.02	0.42	0.1	0.37	0.042	0.005	4.6	0.251	0.10	0.006

* Data first published in Gavranović et al. 2022, 8 tab. 1.

Tab. 1 Chemical composition of the analysed objects as determined with energy-dispersive XRF. All values are given in mass percent. Se and Mn was below the detection limit of 0.01% only sample VIAS lab. no. PozM 54 contained 0,02% Mn. Te below 0.005% in all samples

VIAS lab. no.	Inv./ mus. no.	CEZA lab. no.	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$
PozM 32*	2131	MA-186760	2.0986	0.85316	18.362	38.534	15.666
PozM 35*	2222	MA-186761	2.1029	0.85591	18.303	38.489	15.666
PozM 39	2144	MA-186762	2.0786	0.84366	18.485	38.422	15.595
PozM 49	2196	MA-186763	2.1101	0.86185	18.157	38.313	15.649
PozM 54	1006	MA-186765	2.1017	0.85545	18.311	38.483	15.664
PozM 55	1007	MA-186766	2.1040	0.85662	18.285	38.471	15.663
PozM 56	1007	MA-196070	2.0384	0.82267	19.084	38.901	15.700
PozM 57	1008	MA-186767	2.0985	0.85283	18.368	38.547	15.665
PozM 58	1008	MA-186768	2.0852	0.84723	18.472	38.516	15.65
PozM 60	1010	MA-196071	2.1020	0.85518	18.319	38.506	15.666
PozM 64	1044	MA-186769	2.1033	0.85677	18.278	38.444	15.660
PozM 65	1046	MA-196072	2.0777	0.83969	18.640	38.729	15.652
PozM 69	1000a	MA-186770	2.0751	0.82973	18.907	39.233	15.687
PozM 81	1118	MA-186771	2.1005	0.85417	18.342	38.527	15.667
PozM 82	1120	MA-196083	2.1010	0.85591	18.295	38.437	15.658
PozM 83	1115	MA-186772	2.1002	0.85449	18.328	38.492	15.661

* Data first published in Gavranović et al. 2022, 8 tab. 1.

Tab. 2 Lead isotope ratios in the samples discussed within this article. The precision of measurement is less than ± 0.01% for ratios with ^{206}Pb in the denominator and up to ± 0.03% for $^{206}Pb/^{204}Pb$

Each of the analysed samples has three identification numbers. First is the sample number of the VIAS Lab within the ongoing project (VIAS lab. no.), followed by the museum's inventory number, and finally, the Laboratory number from CEZA Mannheim, starting with MA (Appendix). The three-step validation of each sample ensures clear assignment of the analytic results to the object.

Results and Discussion

Trace Element Concentration and Lead Isotope Analysis

The majority of the analysed objects from Klenje and Kličevac-Rastovača have mutually similar amounts of nickel, silver, arsenic and antimony, resulting in a well-recognisable cluster in Ag-Ni, As-Ni, and Sb-Ni diagrams (Fig. 2). Such an outcome suggests a similar basic raw material for most of the finds. Lead isotope analyses confirm this and a cluster of objects with geochemical signatures that very well fit with the copper ores from the Trentino region, more specifically with the ores from the mining district known as AATV (Alto Adige, Trentino, Veneto region) (Fig. 3). The group of finds made of Trentino copper includes four socketed axes from Klenje, a massive bracelet, a bronze sheet belt, torques and a pin with maze shaped head from the same hoard as well as a flange hilted sword from the Kličevac-Rastovača hoard. These results align with the already postulated prevalence of copper raw material from Trentino in the Late Bronze Age objects from the western and central Balkans.[49] Nevertheless, with finds from Klenje and Kličevac-Rastovača hoards, there is an opportunity to take a more nuanced approach and to point out possible alterations from a general trend.

In the Sb-Ni diagram, a small group of three objects from Kličevac-Rastovača within the main cluster attracts attention with a slightly lower antimony concentration (Fig. 2). All three objects

49 See Mehofer et al. in this volume. Mehofer et al. 2021, 9–10, fig. 14; Gavranović et al. 2022, 16.

are metal types of a wide distribution in the Carpathian Basin, including a pin of Velemszentvid type (Appendix, VIAS lab. no. PozM 49),[50] a pin with biconical head (Appendix, VIAS lab. no. PozM 48)[51] and an object described as a rod ingot (Appendix, VIAS lab. no. PozM 35).[52] Regarding the possible copper provenance, the lead isotope signature of the rod ingot falls in the same cluster as the above-mentioned finished objects, with a most probable assignment to the copper sources from AATV.[53] The pin of Velemszentvid type has a somewhat different lead isotope value that varies between the isotopic ratios of the copper ore deposit areas in AATV on one side and the Valsugana VMS (Volcanogenic Massive Sulphides) on the other side, both located in northern Italy. In between are also isotopic values of the slags from various smelting sites in the same area. Thus, although undoubtedly made of copper from northern Italy, the pin's copper signalises most probably the mixing of raw metals from different areas of the same Bronze Age copper mining district.

With regard to the rod ingot (Appendix, VIAS lab. no. PozM 35), it is important to point out that this object is made of already alloyed metal with 3.6% tin (Tab. 1). This is a strong indication of intentional mixing of tin or re-smelting of tin bronzes. Conversely, the second analysed rod ingot from the Kličevac-Rastovača hoard (Appendix, VIAS lab. no. PozM 36) consists of an unalloyed copper (99%) with trace element concentrations, which corresponds to the cluster of finished objects. Since the lead isotope analysis is not available, a statement regarding the copper provenance cannot be made, but according to the trace elements, there is certainly a possibility that the copper for this object also originates from Trentino.

The rod ingots with oval or rectangular-shaped sections are widely spread between central Europe and the Carpathian Basin, but only a few were the subject of archaeometallurgical analyses.[54] The ingots from the sites Wartau in Switzerland and Tiszabes in Hungary were made of tin bronze (5.3% and 4.8%) and thus described as semi-finished products, probably for the production of bracelets.[55] On the other hand, the rod ingot from the Hočko Pohorje hoard (Ha A1) in Slovenia shows no significant trace of tin but somewhat higher amounts of arsenic and antimony.[56]

Together with our results for two ingots from Kličevac-Rastovača, we can preliminarily conclude that rod ingots could be classified either as copper ingots without any added materials (Appendix, VIAS lab. no. PozM 36) or as an intermediate form already containing alloyed metal (Appendix, VIAS lab. no. PozM 35).

Clearly outside the main cluster in the diagrams of trace elements lies the *Petschaftkopfnadel* with a massive metal bead from Kličevac-Rastovača (Appendix, VIAS lab. no. PozM 37) with lower nickel, silver and antimony amounts than all of the other finished objects (Fig. 2). This jewellery type is widely distributed in the Carpathian Basin in BA D and Ha A1.[57] The differences in concentration of main elements (apart from arsenic, which is similar to the main group) could hint at a somewhat different origin of the used copper. Still, since the lead isotope data is not on hand, this must remain a hypothesis for now.

Another object with somewhat deviating values of trace elements as compared to the main cluster is a bracelet with a triangular section from Klenje with a lower concentration of nickel, silver and antimony (Appendix, VIAS lab. no. PozM 65). What makes this object exceptional is a very high percentage of lead (13.7%), which is clearly an outcome of an intentional admixture in the alloy that has only 3.5% tin (Tab. 1). Hence, the lead isotope values of this object display, in fact, the isotopic signature of the added lead that overprinted the lead isotope signature

50 Říhovský 1979, 102; Říhovský 1983, 20; Majnarić-Pandžić 1992, 62.
51 Vasić 2003, 61.
52 Primas – Pernicka 1998; Tarbay 2014, 219, fig. 40.
53 Artioli et al. 2016.
54 Primas – Pernicka 1998, 54–55; Tarbay 2014, 219, fig. 40.
55 Primas – Pernicka 1998, 55.
56 Trampuž Orel 1996, 179, pl. 86, 110.
57 Říhovský 1979, 110; Novotná 1980, 84; Mozsolics 1985, 66; Vasić 2003, 37–42, pl. 54.

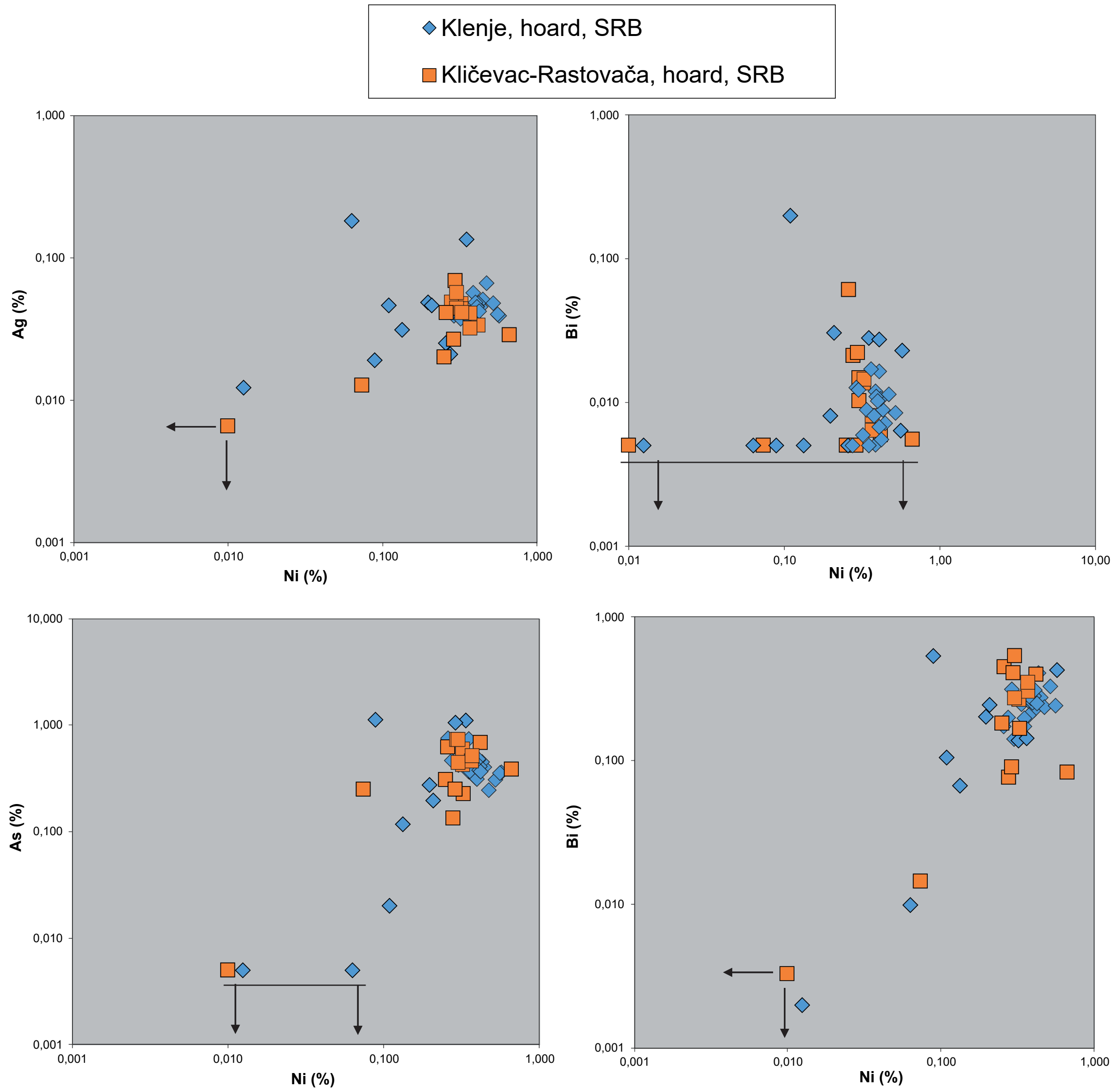


Fig. 2 Double logarithmic diagrams of the trace element composition of the analysed objects from the Klenje and Kličevac-Rastovača hoards (chart: M. Mehofer, VIAS, University of Vienna)

deriving from the copper ore (Fig. 3). Consequently, the provenance of copper cannot be assumed in this particular case. It is nevertheless interesting that the isotope signature of the added lead falls close to the signature of the ore mines in Rudnik between Majdanpek and Bor in eastern Serbia, where lead-zinc minerals e.g., containing galenit, spalerite, pyrite and chalcopyrite do occur.[58] The elevated Zn concentration of 2.8% found in this object underlines the assumption that the deliberately added lead in this alloy can come from some of the local sources.

All remaining outliers from the Klenje and Kličevac-Rastovača hoards both in terms of trace elements and in terms of lead isotopes are ingots. These include two smaller pieces stuffed in the socket of the two axes (Appendix, VIAS lab. no. PozM 56, PozM 58), a fragment of plano-convex ingot (Appendix, VIAS lab. no. PozM 69) from the Klenje hoard as well as an axe-shaped ingot from the Kličevac-Rastovača hoard (Appendix, VIAS lab. no. PozM 39). The three ingots from Klenje mutually differ in terms of arsenic, silver, antimony and iron amounts and do not correlate

58 Pernicka et al. 1993, 26, tab. 8.

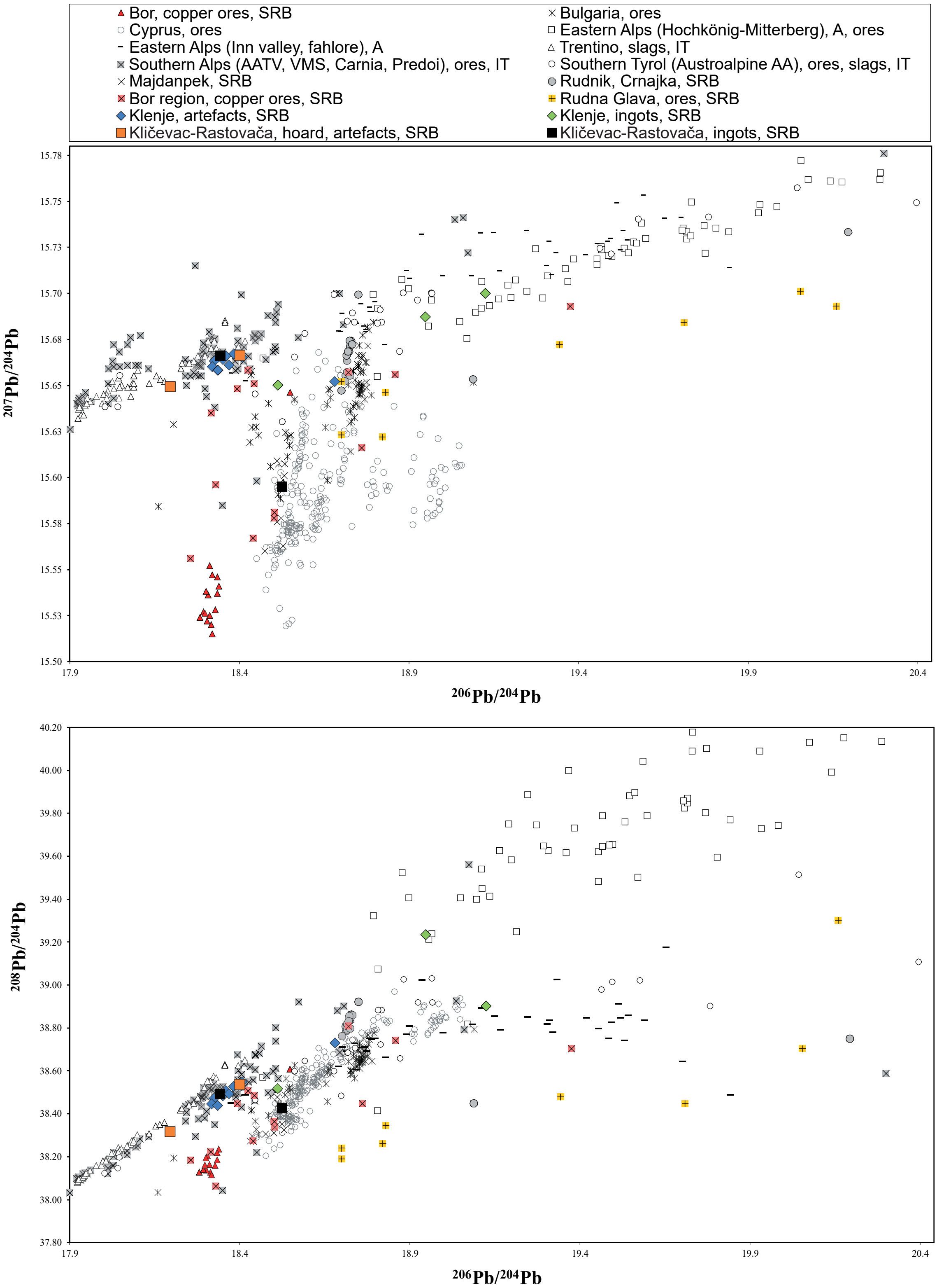


Fig. 3 Lead isotope diagram with lead isotope values of analysed object and major copper ore deposits between central Europe and Mediterranean (data: OXALID database; Pernicka et al. 1993; Pernicka et al. 1997; Artioli et al. 2016; Koch Waldner et al. 2020) (chart: M. Mehofer, VIAS, University of Vienna)

with any of the analysed finished objects. One of the smaller ingots from an axe (Appendix, VIAS lab. no. PozM 58) also has an unusually high concentration of iron (21.2%), possibly caused by corrosion. The same fragment stands out with relatively high silver and low arsenic and antimony concentrations (Fig. 2). The fragment of an ingot from the second axe (Appendix, VIAS lab. no. PozM 56) has very low nickel, arsenic, and silver and antimony values that to a certain extent relates only to the chemical composition an axe-shaped ingot from Kličevac-Rastovača (Appendix, VIAS lab. no. PozM 39), which also has a marginal concentration of trace elements (Tab. 1). Finally, the larger piece of the plano-convex ingot from Klenje (Appendix, VIAS lab. no. PozM 69) has a significantly different chemical composition with higher arsenic and lower silver amounts than most of the discussed objects. (Fig. 2).

Considering the provenance of copper in ingots, the lead isotope analysis provides an interesting picture that is in line with the differences visible in trace element concentrations. The larger fragment of the plano-convex ingot from Klenje (Appendix, VIAS lab. no. PozM 69) contains copper with a lead isotope signature that is congruent with the copper ore deposits in the Hochkönig-Mitterberg area near Salzburg, which was, beside Trentino, one of the largest copper production places in the Middle and Late Bronze Age Europe.[59]

The two ingots with low concentrations of trace elements, the small fragment from the socket of one of the axes from Klenje (Appendix, VIAS lab. no. PozM 56), and an axe-shaped ingot from Kličevac-Rastovača (Appendix, VIAS lab. no. PozM 39), contain copper with distinctly diverse lead isotope signatures, pointing at two different areas of provenance. The small ingot fragment has isotope ratios, which would correspond with those of the fahlore deposits of the Inn Valley, but has – as mentioned – very low trace element concentrations, which contradict an origin from these mining regions.[60] The copper from the axe-shaped ingot overlaps with copper ore deposits from Cyprus but also with some sources from Bulgaria and slags from eastern Serbia (Fig. 3). As the evidence of the Late Bronze Age copper production is thus far known only from Cyprus, it is more likely that ingot from Kličevac-Rastovača actually contains copper from Cyprus.[61] This result also emphasises the necessity of lead isotope analyses when it comes to the determination of copper sources since the trace element composition of two ingots (VIAS lab. no. PozM 56 and VIAS lab. no. PozM 39) could, at first glance indicate a similar copper source, which is definitely not the case (Figs. 2–3).

The second small ingot fragment from the socket of one of the axes in Klenje (Appendix, VIAS lab. no. PozM 58) has a copper with lead isotope signature that does not fully match with any of the known copper ore deposits (Fig. 3). It partially overlaps with some fahlore samples from Bosnia, but as its metal clearly is not fahlore based, this possibility can be excluded. The specific led isotope signature of this fragment could also result from mixing of copper from different regions.

In summary, despite the relatively small sample size, the analyses of objects from the Klenje and Kličevac-Rastovača hoards have demonstrated that, apart from the dominant Trentino raw material, the copper from other equally distant areas of Hochkönig-Mitterberg in Austria and most probably Cyprus,[62] was during the 13th and 12th centuries BC present in this part of the central Balkans. It is also clear that none of the analysed objects can be linked with domestic nearby copper ores in eastern Serbia and/or slags from production sites such as Trnjane, Ružana or Čoka Njica.[63]

We can assume that the local Late Bronze Age communities in northeastern Serbia were well integrated into a broad, trans-regional copper circulation and supply network. Furthermore, the question arises to what extent the deposited objects can be assigned to local founders and

59 Pernicka et al. 2016.
60 See Mehofer et al. in this volume.
61 Cypriot copper is seldomly found on the Balkans, mostly in the form of oxhide ingots or as finished products. See Mehofer et al. in this volume.
62 Athanassov et al. 2020.
63 Mehofer et al. 2021.

workshops. So far, there are only isolated indications of local metal production, such as the cast moulds for socketed axes from Boljetin,[64] but by no means to the extent that would correspond to the number of deposited objects and ingots.

Tin Concentration

The amount of the added tin in the analysed objects from the Klenje and Kličevac-Rastovača hoards varies greatly depending on the object group (Fig. 4). This result supports the assumption about the existence of specific copper alloys for specific object groups (sickles, spearheads, swords, pins. etc.), which is already postulated in studies with large sample sets from Slovenia[65] and the Carpathian Basin.[66] The results obtained from Serbia and Bosnia are mostly in line with this, especially when it comes to finds dated in Ha A1.[67] The fact that certain alloys were used for specific object groups is also an indication of widespread metallurgical knowledge and a common practice that corresponds with the emergence of Urnfield phenomena (BA D–Ha A1) and the diffusion of characteristic metal types ('Urnfield bronzes') between the Alps, the Carpathian Basin and southeastern Europe. Despite the position on the geographical fringe, the finds from northeastern Serbia can be described as a part of this large 'Urnfield' metallurgical network, evident not only from the typology but also from the tin values presented here.[68]

The amount of tin in the sickles from Klenje and Kličevac-Rastovača ranges between 3.7 and 5.7%, with most finds having between 4% and 5.2% (Fig. 4), which corresponds to the concentration in contemporary finds from Slovenia, Bosnia and the Carpathian Basin. In this respect, the anticipated existence of an alloy with between 4% and 5% tin, used primarily for the production of sickles, seems possible.[69] An alloy with a relatively small amount of tin, between 2.8% and 5%, was also used for the production of bracelets, neck rings and anklets from Klenje (Fig. 4). Currently, there is little comparative data for bracelets or neck rings of Ha A1 period. The two analysed bracelets from southern Poland have a similarly low amount of tin (3.8%), but the measurements are made only on the surface of the objects.[70]

The alloy for the socketed axes from Klenje and Kličevac-Rastovača contains, on average, more tin than in the case of sickles and bracelets, with most of the finds having between 5.2% and 7.2% of tin (Fig. 4). However, there are also two axes with markedly less tin (3.1% and 3.5%). Similar variations are attested in Slovenia[71], Bosnia[72] and the Carpathian Basin. However, most axes tend to have an alloy with between 4% and 7% tin, which fits well with our results from northeastern Serbia.

Our analyses also included three swords from Kličevac-Rastovača with 5.6%, 6.3% and 7.5% of tin in the alloy (Fig. 4). Despite the small sample size, it is noticeable that all three swords are below the average 8% of tin, which is calculated for the contemporary swords from Slovenia and Carpathian Basin.[73] The tendency that the flange hilted swords of local types with a distribution in the western and central Balkans have a lower amount of tin than the 'classical' swords of supra-regional distribution (e. g., Reutlingen type or Aranyos type)[74] is already observed in our

[64] Wanzek 1989, 196, pl. 38. 6; see also 197–199, cat. nos. 27 (Kladovo), 30 (Livade, Mala Vrbica), 40 (Velešnica).
[65] Trampuž Orel 1996; Trampuž Orel et al. 2016.
[66] Liversage 1994.
[67] Gavranović – Mehofer 2016; Molloy – Mödlinger 2020; Gavranović et al. 2022.
[68] At the same time, investigations in Switzerland (Rychner – Kläntschi 1995) showed the use of same alloy for all types of objects throughout almost the entire Late Bronze Age.
[69] Liversage 1994; Trampuž Orel 1996; Gavranović et al. 2022.
[70] Janiak et al. 2021, 173.
[71] Trampuž Orel 1996, 186.
[72] Gavranović – Mehofer 2016, 104.
[73] Liversage 1994; Trampuž Orel 1996.
[74] Harding 1995, 28, 35–49.

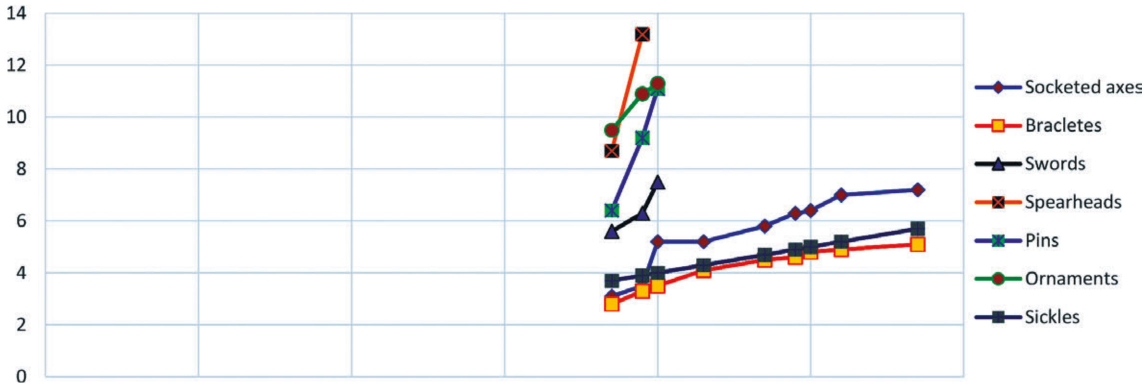


Fig. 4 Tin concentration of the objects from Klenje and Kličevac-Rastovača hoards (in %) (M. Gavranović)

previous studies.[75] Thus, the three swords of local types from Kličevac-Rastovača corroborate this trend.

The alloy used for the production of three analysed pins has a relatively higher concentration of tin (6.4%, 9.2% and 10.9%), with two of them belonging to the category of well-alloyed tin bronzes (8%– 14%). Comparable tin concentration was also attested in the contemporary pin of a different type from the Futog hoard in Vojvodina.[76] Being a decorative item, the higher tin amount may be connected with the desired golden yellow colour, which appears in the case of such alloys when the surface is polished.[77] The same explanation applies to the three objects with higher amounts of tin (9.5%, 10.9% and 11.3%) from Klenje (a bell-shaped pendant, a massive bracelet and a belt), which we have described as ornaments due to their exceptionality (Fig. 4).

The concentration of tin in two spearheads (8.7% and 13.2%) resembles the available results for spearheads of the Ha A1 period from Serbia and Bosnia[78], Slovenia[79] and the Carpathian Basin.[80] The somewhat higher proportion of tin in the alloy for the spearheads reflects once more a common metallurgical tradition over the vast areas of central and southeastern Europe during the early Urnfield period (Ha A1) and a well-balanced relationship between the material required for a specific object category and ability to make a specific alloy mixture. Given the large geographical scope and time depth over the several generations of people engaged in metal productions, it is not surprising that there will also be deviations and exceptions from the general trends,[81] but certain regularities are hard to overlook.

Conclusion

The chemical and lead isotope analyses of 45 copper-based objects from the Klenje and Kličevac-Rastovača hoards provided the first insight into the metallurgical background of the Late Bronze Age objects from the territory of northeastern Serbia. While the metal hoards in this specific region were linked in previous research with nearby copper ore deposits and their exploitation, the results of our research dismissed the possibility that domestic copper ore sources

75 Gavranović et al. 2022.
76 Gavranović et al. 2022, 10, fig. 2, 15.
77 Molloy – Mödlinger 2020, 35, tab. 2.
78 Gavranović – Mehofer 2016, 102; Molloy – Mödlinger 2020, 38, fig. 10; Gavranović et al. 2022, 27.
79 Trampuž Orel 1996, 186.
80 Liversage 1994, 87.
81 Molloy – Mödlinger 2020. Few of the disused spearheads from Bingula Divoš and Bradradac hoards are described as products of failed casting with tin amount below 1%. The values are however not displayed in the study.

played a significant role in the local Late Bronze Age metallurgy. Instead, we can attest to a dominant presence of raw copper from the Trentino region in northern Italy, revealing the existence of copper supply networks that, until recently, have hardly been considered.[82] The fact that copper with an isotopic signature corresponding to the Hochkönig-Mitterberg area in Austria is detected only in ingots but in none of the analysed finished objects is particularly interesting and requires further explanation. The influx of copper from the Eastern Alps (Mitterberg) to the Balkans is not surprising, given the extent of the production and long-established communication routes between the Balkans, the Carpathian Basin, and the Alps.[83] However, not only in the case of northeastern Serbia but also in all of the other hitherto conducted analyses of Late Bronze Age finds from western and central Balkans, there are no finished objects with isotopic values pointing at the Mitterberg area.[84] The fact that among 270 lead isotopically analysed objects from Bosnia, Serbia and North Macedonia, the copper from Hochkönig-Mitterberg appears only in ingots and never in finished objects may be a result of coincidence, but it is still quite remarkable.

One possible explanation is that the mixing of raw copper from Trentino and Hochkönig-Mitterberg in the course of the production of metal objects would result in the overprinting of Mitterberg lead isotope values with only Trentino copper being visible in the analytic result.[85] Consequently, this would mean that the possible use of Mitterberg copper in the founding workshops was always connected with mixing raw materials, with other components being predominantly copper from the Trentino area.[86] This is certainly a possibility in some cases, but we rather assume that Mitterberg copper had a subordinate role in the production of metal objects in the Balkans. The occurrence of ingots with Mitterberg copper may also be an outcome of long-distance exchange and collection of values and goods during the Urnfield period for the purpose of deposition and not directly linked with the production of metal objects. The presence of an object in the Kličevac-Rastovača hoard (Appendix, VIAS lab. no. PozM 39) with copper, most probably originating from Cyprus, can also be attributed to the interlinked networks of exchange and underlines once again the scope of mobility of goods across the Late Bronze Age Europe.[87] Apart from North Macedonia,[88] the copper from Cyprus did not have a significant role in the metal production of the western and central Balkans, with only a few ingot fragments having this exotic raw material.[89]

The question of the place of manufacture of the numerous deposited objects from northeastern Serbia cannot be answered at the present state of research. The finds of casting moulds from Pleniţa in southwestern Romania suggest the existence of founder workshops in the area around the Iron Gates that operated on a regional level.[90] Comparable sites are thus far not known from northeastern Serbia. However, as our analyses partly revealed, acquiring raw material, producing metal objects, and depositing finds are three different agency layers that do not compulsorily correlate. Given the number of objects from the Ha A1 hoards in northeastern Serbia, it is hardly possible to ascribe their production to a mobile craftsman or even a group of itinerary founders[91] due to logistical reasons and the amount of processed raw material.

The case study of northeastern Serbia underlines once again that some of the initial plausible interpretations (the assumed connection between the nearby copper deposits and developed local metallurgy) are not tenable in light of new analytic results. The background of actions that led

82 Radivojević et al. 2018; Gavranović et al. 2022.
83 Trampuž Orel – Trampuž 2009; Pernicka et al. 2016; Powell et al. 2018; Mehofer et al. 2021.
84 Gavranović et al. 2021; Mehofer et al. 2021; Gavranović et al. 2022.
85 Mehofer et al. 2021; Gavranović et al. 2022.
86 See Mehofer et al. in this volume.
87 Hänsel 1997; Harding 2000; Vandkilde 2016; Cwaliński 2020; Nørgaard et al. 2021.
88 Gavranović et al. 2021.
89 Beside the object from Kličevac-Rastovača the copper from Cyprus is thus far attested only in a small fragment of an oxide ingot from the Ha A1 hoard Paležnica in northern Bosnia, see Pavlin – Jašarević 2016, 35 and in one ingot fragment from the hoard Šimanovci in Serbia, see Molloy 2018. For a general overview see Athanassov et al. 2020.
90 Boroffka – Ridiche 2005; Dietrich 2012.
91 Dietrich 2012, 212–213.

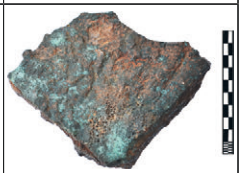
to the increased deposition in this specific region appears to be much more complex and can be understood only by considering the cultural development and results of material analyses.

Acknowledgements: This paper was realised in the frame of the FWF Stand-alone project 'Bronze Age metal producing societies in the western and central Balkans' (P32095-G25), 2019–2024.

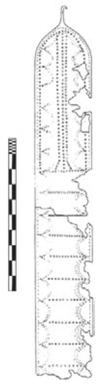
Appendix

List of analysed finds from Klenje and Kličevac-Rastovača hoards. PozM = National Museum in Požarevac (photos: M. Gavranović, National Museum in Požarevac)

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 51	1003 Jacanović 1986, pl. I.2	MA-196068	RFA	Slender socketed axe/chisel without loop	Klenje, SRB	
PozM 52	1004 Jacanović 1986, pl. I.3	MA-196069	RFA	Socketed axe	Klenje, SRB	
PozM 53	1005 Jacanović 1986, pl. I.4	MA-186764	RFA	Socketed axe	Klenje, SRB	
PozM 54	1006 Jacanović 1986, pl. I.5	MA-186765 (axe)	RFA, LIA	Socketed axe	Klenje, SRB	
PozM 55 PozM 56	1007 Jacanović 1986, pl. I.6	MA-186766 (axe) MA-196070 (ingot)	RFA, LIA	Socketed axe with the ingot fragments in the spout	Klenje, SRB	

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 57 PozM 58	1008 Jacanović 1986, pl. I.7	MA-186767 (axe) MA-186768 (ingot)	RFA, LIA	Socketed axe with the ingot fragments in the spout	Klenje, SRB	
PozM 60	1010 Jacanović 1986, pl. I.9	MA-196071 (axe)	RFA, LIA	Socketed axe with the saw and fragments of a bracelet in the spout	Klenje, SRB	
PozM 64	1044 Jacanović 1986, pl. III.4	MA-186769 (bracelet)	RFA, LIA	Massive, decorated bracelet	Klenje, SRB	
PozM 65	1046 Jacanović 1986, pl. IV.10	MA-196072	RFA, LIA	Fragment of a decorated bracelet, triangular section	Klenje, SRB	
PozM 69	1000a Jacanović 1986, pl. II.27	MA-186770	RFA, LIA	Fragment of a plano-convex ingot	Klenje, SRB	
PozM 70	1015 Jacanović 1986, pl. I.13	MA-196073	RFA	Knobbed sickle	Klenje, SRB	
PozM 71	1016 Jacanović 1986, pl. I.15	MA-196074	RFA	Knobbed sickle	Klenje, SRB	
PozM 72	1017 Jacanović 1986, pl. I.16	MA-196075	RFA	Tanged sickle	Klenje, SRB	
PozM 73	1018 Jacanović 1986, pl. II.1	MA-196076	RFA	Tanged sickle	Klenje, SRB	

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 74	1019 Jacanović 1986, pl. I.3	MA-196077	RFA	Tanged sickle	Klenje, SRB	
PozM 75	1020 Jacanović 1986, pl. II.3	MA-196078	RFA	Tanged sickle	Klenje, SRB	
PozM 77	1055 Jacanović 1986, pl. V.11	MA-196079	RFA	Decorated bracelet, round section	Klenje, SRB	
PozM 78	1068 Jacanović 1986, pl. I.13	MA-196080	RFA	Decorated bracelet, round section	Klenje, SRB	
PozM 79	1081 Jacanović 1986, pl. V.12	MA-196081	RFA	Decorated bracelet, triangular shaped section	Klenje, SRB	
PozM 80	1117 Jacanović 1986, pl. II.22	MA-196082	RFA	Bell shaped pendant	Klenje, SRB	
PozM 81	1118 Jacanović 1986, pl. II.21	MA-186771	RFA, LIA	Fragment of a twisted torc with bended ends	Klenje, SRB	
PozM 82	1120 Jacanović 1986, pl. II.23	MA-196083 (pin)	RFA, LIA	Pin (fragment) with a decorated, maze-shaped head	Klenje, SRB	

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 83	1115 Jacanović 1986, pl. VII.13	MA-186772	RFA, LIA	Decorated belt made of sheet	Klenje, SRB	
PozM 84	1083 Jacanović 1986, pl. VI.16	MA-196084	RFA	Bracelet, square section	Klenje, SRB	
PozM 85	1087 Jacanović 1986, pl. VI.5	MA-196085	RFA	Bracelet, D-shaped section	Klenje, SRB	
PozM 86	1090 Jacanović 1986, pl. VI.9	MA-196086	RFA	Ribbed bracelet, oval section	Klenje, SRB	
PozM 87	1092 Jacanović 1986, pl. VII.1	MA-196087	RFA	Ribbed bracelet, round section	Klenje, SRB	
PozM 88	1101 Jacanović 1986, pl. VI.20	MA-196088	RFA	Bracelet, square section	Klenje, SRB	
PozM 89	1102 Jacanović 1986, pl. VI.21	MA-196089	RFA	Anklet, triangular section	Klenje, SRB	
PozM 90	1040 Jacanović 1986, pl. IV.10	MA-196090	RFA	Knife blade	Klenje, SRB	

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 32	2131 Jacanović 2000, no. 2	MA-186760	RFA, LIA	Fragment of a flange hilted sword, ricasso on the blade	Kličevac-Rastovača, SRB	
PozM 33	2133 Jacanović 2000, no. 4	MA-196056	RFA	Blade of a sword	Kličevac-Rastovača, SRB	
PozM 34	2132 Jacanović 2000, no. 3	MA-196057	RFA	Fragment of a flange hilted sword	Kličevac-Rastovača, SRB	
PozM 35	2222 Jacanović 2000, no. 100	MA-186761	RFA, LIA	Rod ingot, round section	Kličevac-Rastovača, SRB	
PozM 36	2224 Jacanović 2000, no. 103	MA-196058	RFA	Rod ingot, trapezoidal section	Kličevac-Rastovača, SRB	
PozM 37	2134 Jacanović 2000, no. 68	MA-196059	RFA	Pin with a massive, ribbed attachment	Kličevac-Rastovača, SRB	
PozM 38	2141 Jacanović 2000, no. 19	MA-196060	RFA	Socketed axe, hammered and broken	Kličevac-Rastovača, SRB	
PozM 39	2144 Jacanović 2000, no. 22	MA-186762	RFA, LIA	Semi-finished object, ingot	Kličevac-Rastovača, SRB	

VIAS lab. no.	Inv./mus. no. reference	CEZA lab. no.	Analyses	Object	Site	
PozM 40	2147 Jacanović 2000, no. 12	MA-196061	RFA	Tanged sickle	Kličevac-Rastovača, SRB	
PozM 42	2153 Jacanović 2000, no. 29	MA-196062	RFA	Tanged sickle	Kličevac-Rastovača, SRB	
PozM 44	2159 Jacanović 2000, no. 30	MA-196063	RFA	Tanged sickle	Kličevac-Rastovača, SRB	
PozM 45	2136 Jacanović 2000, no. 7	MA-196064	RFA	Lower part of a spearhead, hammered	Kličevac-Rastovača, SRB	
PozM 46	2138 Jacanović 2000, no. 9	MA-196065	RFA	Spearhead, fragment of a leaf	Kličevac-Rastovača, SRB	
PozM 48	2193 Jacanović 2000, no. 67	MA-196066	RFA	Biconical head of a pin	Kličevac-Rastovača, SRB	
PozM 49	2196 Jacanović 2000, no. 70	MA-186763	RFA, LIA	Massive pin with ribbed neck and round head	Kličevac-Rastovača, SRB	

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Metal Exchange Networks and Metallurgical Practices in Central and Eastern Europe

Ingots or Commodities? Aspects of Raw Metal Distribution in Late Bronze Age Europe

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Abstract: Copper ingots appear in different shapes during certain periods of the European Bronze Age. Some types are widely distributed; others only circulate in regional networks. Some were distributed intact; others were portioned in various ways. More frequently than is realised, the portion shapes vary. This is especially the case of the so-called bun ingots or plano-convex cakes, which is the main subject of this article. Not only is this true in terms of appearance, but also for the raw material of which they are made. Considering this, it is striking that changes in the exploitation of ore sources are not necessarily affecting the shape of this raw metal form. Therefore, it seems reasonable to assume that plano-convex cakes might have been preferred in certain regions or by particular consumer groups. The generally accepted form of the raw metal 'cake' can be described as an early form of commodity, and the distinctive differences in their cross sections as well as their portion patterns suggest an attempt to transform these metal commodities into recognisable trade goods. This paper discusses the distribution patterns of plano-convex cakes and their relevance for a socio-economical interpretation of the Bronze Age copper exchange. We aim to identify the reasons behind the distribution and to get an understanding of the Bronze Age exchange networks and communication zones.

Keywords: Bronze Age, trade, commodities, plano-convex casting cakes, distribution patterns, connectivity

Trade and Commodities

Although explanatory models of exchange vary significantly, many researchers believe that there was trade in raw materials and goods during the European Bronze Age.[3] This means that some persons functioned as traders at least part of the time, which implies the existence and acceptance of commodities. This is particularly true for the trade and exchange of metal.

Commodities are described as products with a high level of standardisation, fungibility and conformity. As a result, although goods might not present themselves, the consumer and the supplier can still negotiate. The purchaser can expect a consistent product that is available in various, specified units. Within one product group, little or no quality differences and little differentiation are required. These aspects allow the application of common trading techniques and organisations.[4] Another important characteristic of commodities is that they are alienable. Therefore, there is little or no interest in exposing or highlighting them, which implicates a purely economical, non-sensitive treatment.[5] The commodities in Bronze Age Europe were not branded in the sense that they were marked by producer or distributor signatures. Still, their shapes were easily recognisable and could be sorted into certain groups, which in turn can be tied to particular activities and regional or supra-regional networks. The purpose of commodities is to build relationships and trust between producers and/or distributors and their consumers, trading partners, or recipient communities. An organisation such as this solves many problems for customers and suppliers

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3 E.g. Earle et al. 2015; Rahmstorf 2018, 35.
4 Bevan 2010, 37.
5 Brück 2019.

alike, such as the lack of secure information about the product and the risk of being deceived about its quality or quantity.[6] As expected, the pre-requisition is that a certain quality and quantity is desired in a particular defined and communicated way. Both parameters have defined values within the exchanging and receiving communities. The latter aspect is, of course, not visible and perhaps not entirely accessible to us without written sources.

Commodities and Ingots

Because the physical properties of objects are usually seen as a subject of a meaningful selection and a possible base for social and/or economic relationships, researchers try to identify these relationships through patterns in the material record. As Bevan pointed out,[7] some products make metrical claims about their efficacy, particularly if they are connected to a certain advertising strategy. In the case of raw metal in Bronze Age Europe, this could mean procuring a certain ingot form in order to produce good quality items because you have a raw material of known and good quality.

That being said, the difference between a commodity and an ingot must be clarified. The latter is a metallurgically standardised object consisting of melted metal. The concept of ingot trade is based on the assumption that the material quality of an object is visible through a particular shape and guaranteed by an (often not exemplified) entity. Since consumers most likely have less knowledge about the potential range of material qualities than producers or distributors, it is a good strategy to make raw material and production qualities visible through a particular shape which not only marks the material but also marks either the producers and/or distributors or the area of origin. Based on this assumption, one would expect separate ingot forms corresponding with different material compositions.

Several Bronze Age ingot forms have been well investigated. Therefore, we know that different types of raw copper were traded using the same ingot form.[8] Nevertheless, individual closed ingot hoards usually consist of the same material. However, the recently published Oberding hoard shows that this might not be as exclusive as previously believed.[9]

The major raw metal form of the European Late Bronze Age Europe was undoubtedly the so-called plano-convex or bun ingots, or plano-convex cakes, which were widely distributed from the late Middle Bronze Age until the end of the Urnfield period. The roundish cake form is almost exclusively associated with copper. Comparable silhouettes were only very rarely connected to gold, for instance, in the Eberswalde[10] and Bodrogzsadány hoards[11] or to tin as in the shipwrecks of Uluburun and Salcombe.[12] Tin bronze is a deliberately created alloy, usually considered to have been traded in other ingot forms such as rods and rings or different types of axes.[13]

Only one other largely distributed form of raw copper is known besides the bun-shaped cakes: the oxhide ingots. Although it has been repeatedly stated that portions of these are found in central and southeastern European hoards,[14] their distribution area is almost exclusively limited to the Mediterranean, with some found in Bulgaria.[15] In fact, the distribution areas of these two raw copper forms mutually exclude each other.

6 Bevan 2010, 37.
7 Bevan 2010, 38.
8 Krause 2003, 144–145.
9 Kutscher 2017, 142.
10 Schuchhardt 1914.
11 Mozsolics 1985a.
12 Pulak 2009; Needham et al. 2013.
13 Sommerfeld 1994, 7–9.
14 E.g. Soroceanu et al. 2017, 49–51.
15 E.g. Athanassov et al. 2020.

The difference between these metal forms is that oxhide ingots are specialised products, as they consist of smelted ore from a particular mining area,[16] with a predictable and deliberately created material homogeneity.[17] Exceptions are known where the origin of the metal is still under dispute, but it needs to be stressed that this mostly concerns very early ingots. Once the exchange system was established, the raw copper in oxhide ingots generally differed from other raw copper sources, which meant that a clear distinction based on ingot shape could be made by consumers, who saw the shape as a brand.[18] Over time, this probably led to some attempts to copy the shape using other raw copper.[19] Intriguing in this regard is that some oxhide ingots were cast in the vicinity of the mines, while others were cast in settlement areas.[20] This would mean that the ingots were either re-melted or cast again in similar moulds or that the used raw metal was also traded in other ingot forms. Maybe this is what Hauptmann and his colleagues saw when they found some evidence for the melting of bun ingots to produce oxhide ingots.[21] Nevertheless, all of these aspects, but especially the homogeneity of the copper, justify the use of the term 'ingot' for the metal in oxhide shape. Most items weigh between 29 and 30 kg, with a total range between 20 and 40 kg.[22] Despite not being metrically exact, they were part of a predictable system which only had a few easily noticeable differences. In contrast, none of these aspects are applicable to central European plano-convex casting cakes.

European Casting Cakes

Although they are usually considered uniform, cakes, as well as their segments, vary significantly in size, shape and weight. This variation is found in most closed finds, although for some reason, many researchers seem to expect only divided parts of the same cake type.

The items discussed here were found in hoards from the Carpathian Basin, central and northern Europe. Their silhouettes are round, oval, rectangular or amorphous, whereas their cross sections can be plano-convex, flat, uneven or disc-like. Previous studies of this raw metal form have focused on different aspects of the objects, their biographies, and, of course, the material's composition.[23] Furthermore, it has been discussed whether casting cakes found in hoards were meant for later use as raw materials.[24] Plano-convex and flat cakes usually have a similar surface structure and a high level of material homogeneity. In contrast, cake disks always show strong pitting and blistering, and they are brittle.

Since fragmentation patterns of these cakes in hoards are obvious, it has been proposed to interpret and describe this practice as 'metal partition' or 'metal portioning' instead of 'deliberate' fragmentation.[25] On the one hand, the shapes of the partitions are intrinsically linked to the shapes of complete cakes, but they also have other different geometric forms. The partition units do relate to each other and have complementary functions within the partition system. Smaller units were cut from bigger portions (Fig. 1). Most of the Late Bronze Age raw metal is deposited as cake segments of different shapes. However, all kinds of shapes and sizes are present in Late Bronze Age hoards.

16 Gale 2011, 219.
17 Gale 2011, 213–214.
18 Stos-Gale 2011, 222.
19 Sabatini 2016, 47.
20 Stos-Gale 2011, 226.
21 Hauptmann et al. 2002, 18.
22 Knapp 2008, 309–312.
23 Czajlik 1997; Bachmann et al. 2003; Nessel 2017.
24 Rusu 1981, 377; Mozsolics 1985b, 42.
25 Nessel 2014; Nessel 2017.

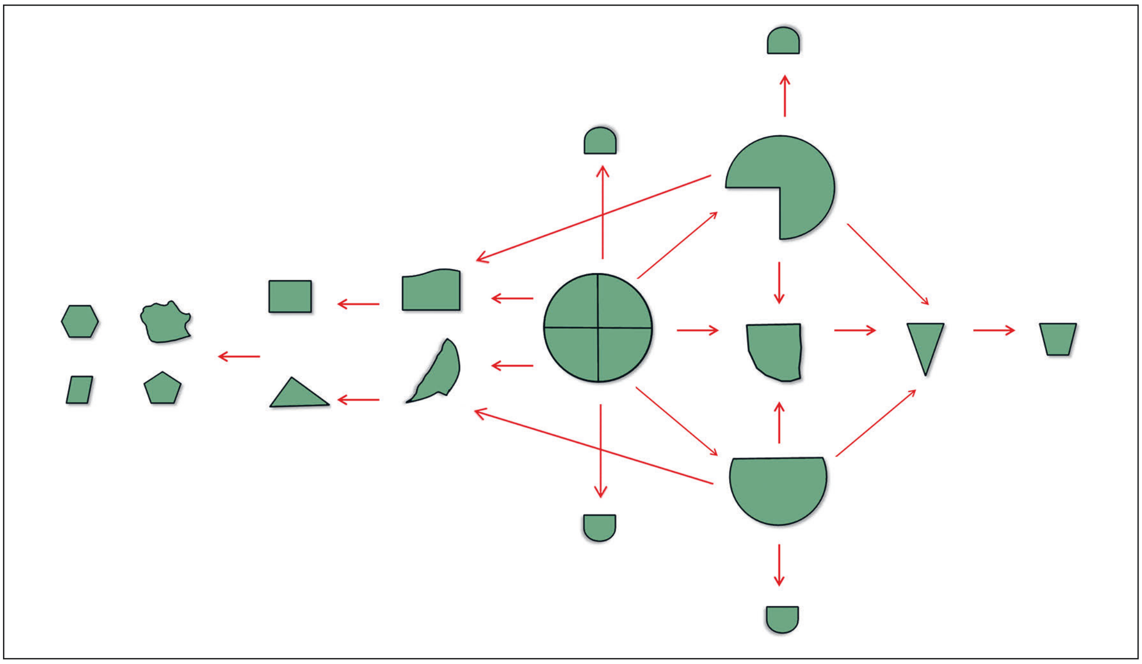

Fig. 1 Portioning scheme of plano-convex casting cakes (B. Nessel, JGU Mainz)

Since the cakes are usually referred to as an ingot form, there is an immanent desire to match particular ingot forms or portions to different material compositions. This implies that specific material compositions or qualities should be connected to particular cake shapes. However, this is not the case. The majority of the casting cakes consist of 96% to 98% copper and less than 1% tin. Specimens with very high amounts of trace elements exist but are very rare. The same can be said about cakes with extremely low amounts of trace elements, less than 1% total. In general, it can only be stated that small cakes have more homogeneous metal than large cakes because they often consist of pure copper or tin bronze and are considered to be the product of melting in a crucible.[26]

The chemical analyses[27] of the last seven decades made it clear that different copper types from different sources were used to produce Late Bronze Age casting cakes in central Europe.[28] Several types of fahlore copper with high and low natural impurities, as well as almost pure copper, were used to produce them.[29] The available lead isotope analyses also tie the cakes to different ore deposits.[30] The copper came from various occurrences in the Slovakian Ore Mountains, as well as the Alps,[31] northern Italy and possibly Romania. The material analyses also point to different stages of production[32] and refinement, which are sometimes obvious by surface structure and inner viscosity.[33] A (smaller) part of cake portions is probably the result of re-melting, but most of the casting cakes are produced with freshly smelted metal.

None of this is surprising if one considers the changes in raw material preferences and the material crisis in the late phase of the Early and Middle Urnfield period when fahlore once again

26 E.g. Jantzen 2008, 224 nos. 307–308; 368 no. E 407.
27 OES, XRF, NAA, ICP, ICP-MS.
28 E.g. Pernicka et al. 2016; Lutz 2016; Lutz et al. 2019a.
29 Junghans et al. 1968; Junghans et al. 1974; SAM groups A1 and A2.
30 Lutz et al. 2019a, 368–370; Lutz et al. 2019b, 326.
31 Töchterle et al. 2012, 42.
32 Bachmann et al. 2003; Krutter 2015; Jansen – Löffler 2016, 129–130.
33 E.g. Töchterle et al. 2012, 42.

became the dominant raw material.[34] But as a result, no indication could lead to the assumption that the quality of the metal was obvious to consumers judging by the visual appearance of the cakes and portions. The metal colour might have given indications to experienced craftsmen, who were capable of accurately estimating the refining extent and the presence of mineral and metal components in an alloy just by its colour. They would certainly be able to differentiate between cakes made of copper and tin bronze. It can be assumed that suppliers facilitated this by making large triangular cut-outs, especially from massive plano-convex casting cakes, which are more than 3 cm thick. Cakes this thick are technically not the most suitable form to separate into smaller pieces. This is much easier done with thinner cakes that have a flat cross-section. However, the practice reveals the material structure and homogeneity of the cake centre, which makes it possible to see and evaluate the quality of the material.

Casting cakes have variable sizes and weights. Although similar cakes and portion segments fall in certain weight ranges, there are also substantial weight differences and large overlaps.[35] The portioning of cakes cannot be connected to an accurate or somewhat exact weight system, despite the fact that the cakes and fragments in hoards are occasionally organised into 'weight classes'.[36] A metric relation between weights and certain portion shapes cannot currently be established, even within portion groups.

Distribution Patterns

Against this background, it might be interesting to see if the distribution of specific casting cake portion patterns in a way that can be connected to possible involvements in specific distribution networks. The large number of hoards in which cakes have been found are scattered over the entire area of central Europe. The clusters given in the distribution of the finds are in part connected to the state of research but also reflect metal hoarding traditions across Europe. Both aspects are considered in the following.

The distribution maps of casting cake forms show the distribution in hoards, graves and items without context information (single finds). Settlement and unpublished finds, as well as cakes from the Western Alps (Switzerland), are not included. To study their distributions, they were divided into different typological groups according to their cross-section. In particular, cakes with plano-convex cross sections were further divided. Besides plano-convex sections of average height, cakes with strong plano-convex cross-sections, as well as with only slightly plano-convex cross-sections, can be observed.[37] Cakes and fragments of the latter type are concentrated around the eastern and southeastern Alps. Still, they also appear in southwestern Germany and the Carpathian Basin (Fig. 2). Strongly plano-convex cakes and fragments are less common and are found mainly at the fringes of the Eastern Alps, and Moravia, with some finds in Transylvania (Fig. 3).

Cake disks and fragments are much less frequent than flat cakes and have a different distribution. They are loosely scattered through southern Germany, the fringes of the Eastern Alps, and Pannonia. In comparison to all other forms of cakes, they are much less common in Bohemia and Moravia and virtually unknown in Italy, the Balkans, and the regions east of the Danube (Fig. 4).

Flat cakes and fragments are much more common and have the largest distribution range. They were found in greater numbers in the Eastern and southeastern Alps but are even more concentrated in Moravia. They have also been found in southern Germany, northern Italy, Pannonia, and the western Balkans (Fig. 5).

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34 Rychner – Kläntschi 1995; Sperber 2004; Lutz – Pernicka 2013; Pernicka – Lutz 2015; Lutz 2016.
35 Nessel 2014; Nessel 2017.
36 E.g. Jansen – Löffler 2016.
37 Nessel 2014; Nessel 2017; see for similar schematic visualisation also Bachmann et al. 2003; Modl 2019.

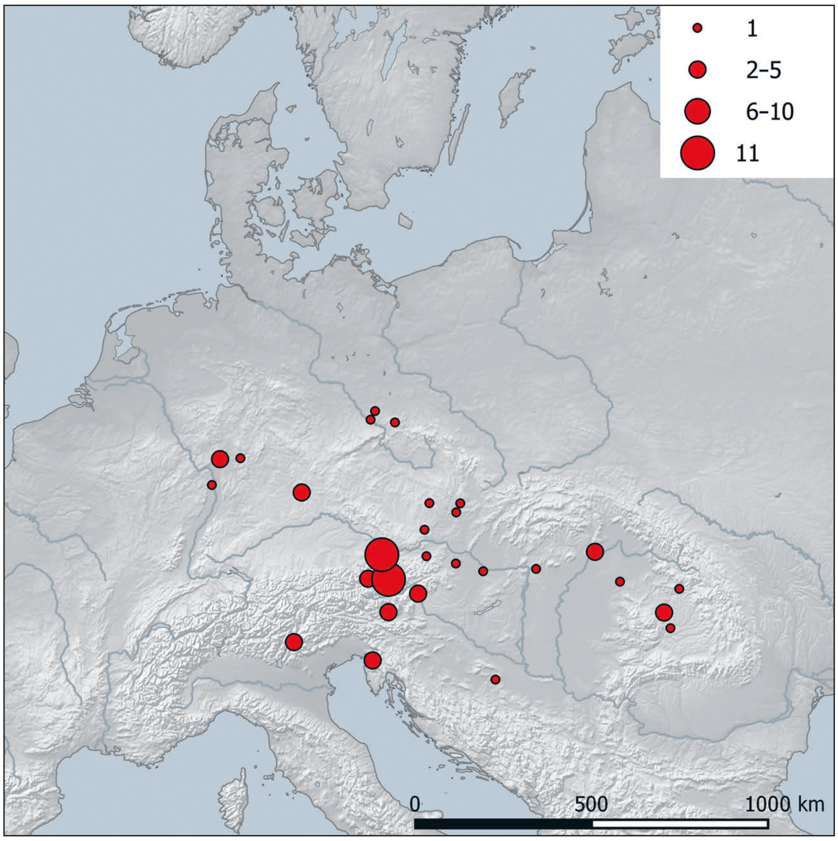

Fig. 2 Slightly plano-convex cakes and fragments (T. Lang, JGU Mainz)

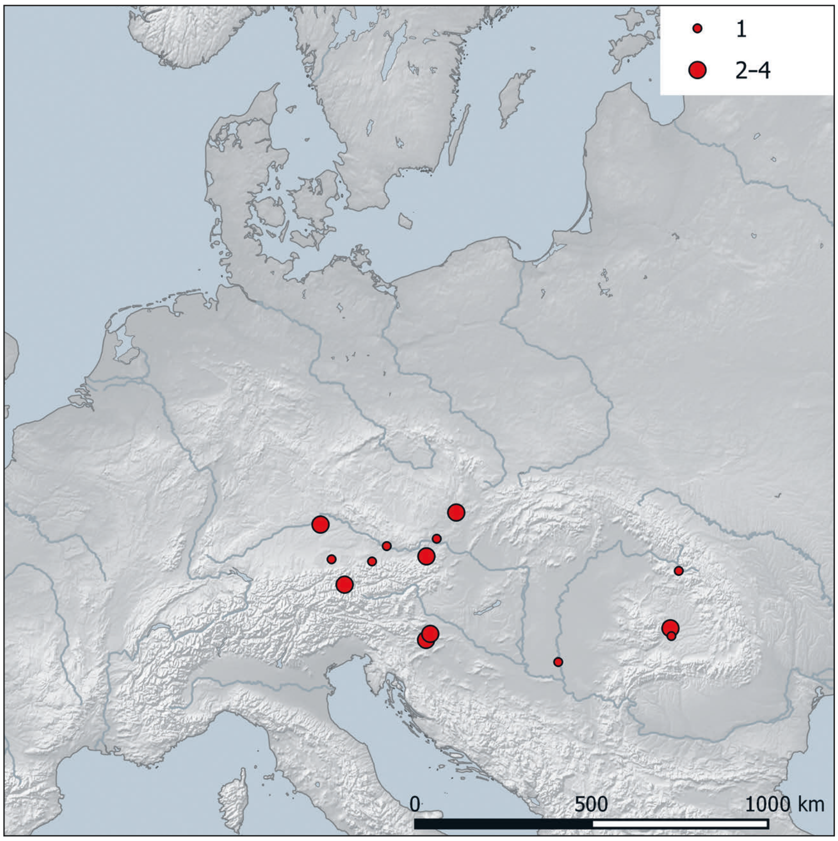

Fig. 3 Strongly plano-convex cakes and fragments (T. Lang, JGU Mainz)

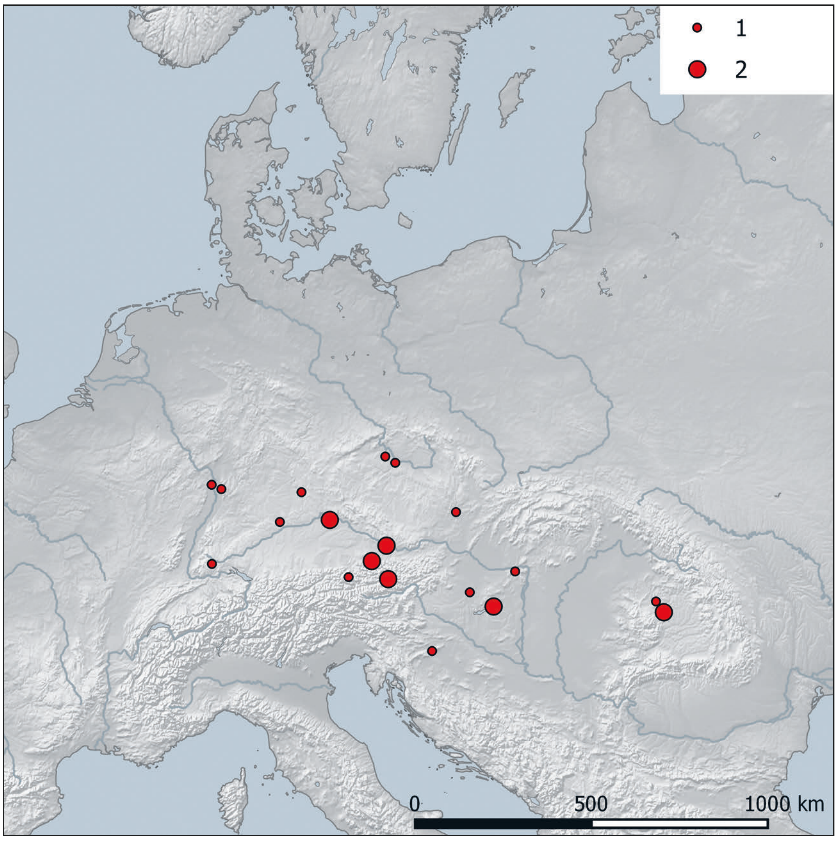

Fig. 4 Disk-like cakes and fragments (T. Lang, JGU Mainz)

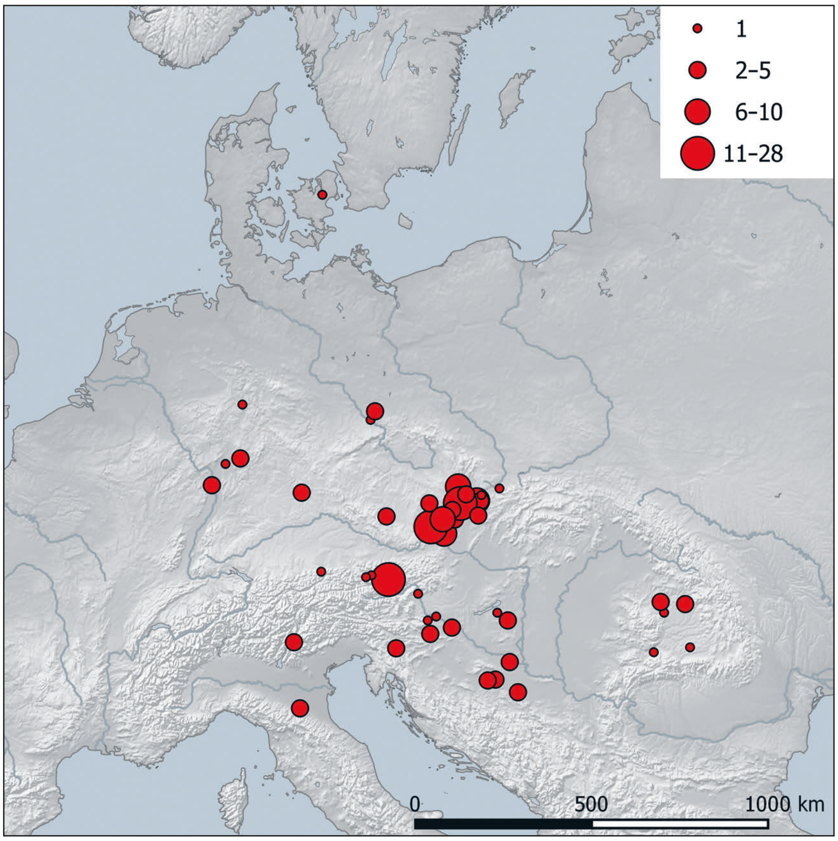

Fig. 5 Flat cakes and fragments (T. Lang, JGU Mainz)

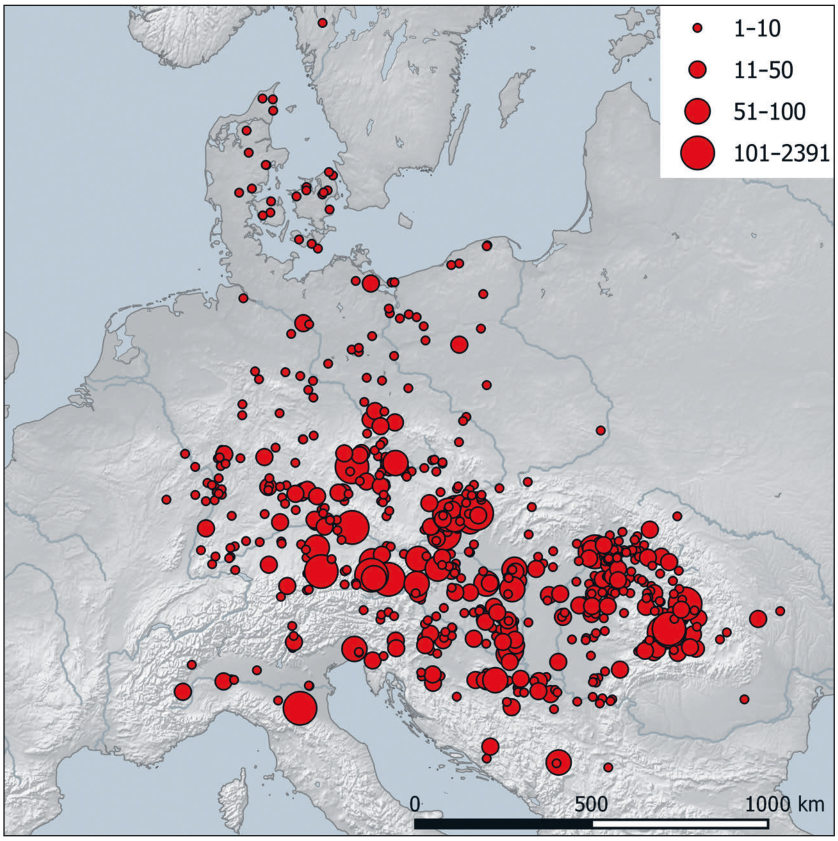

Fig. 6 Distribution of all cakes in hoards (T. Lang, JGU Mainz)

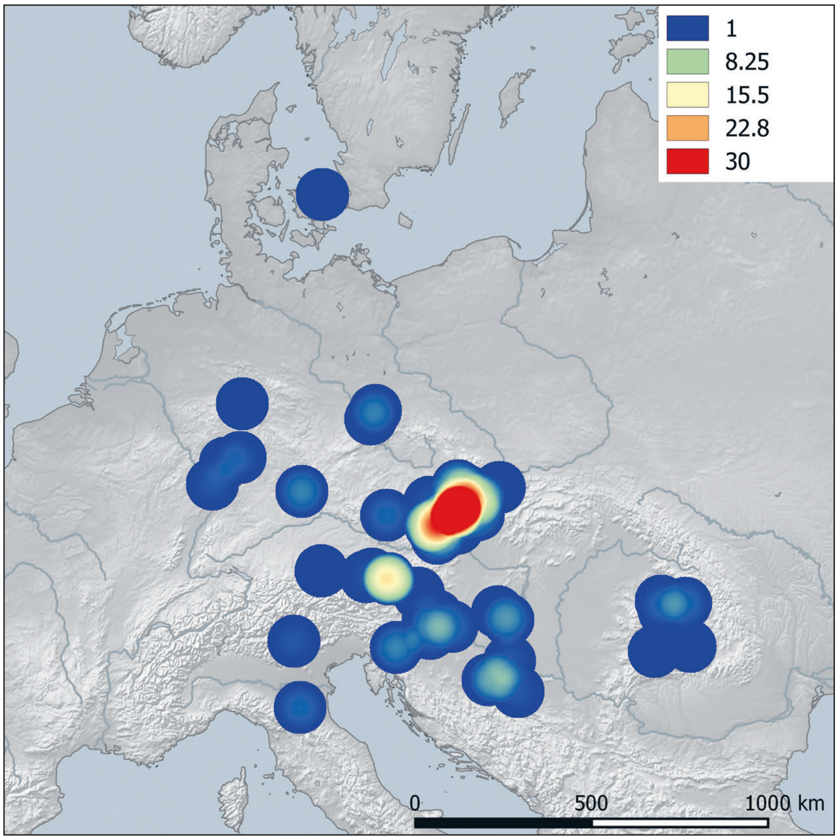

Fig. 7 Kernel-density-heatmap of flat cakes and fragments (T. Lang, JGU Mainz)

Most of the cakes and fragments have plano-convex cross-sections and average heights. Figure 6 shows that casting cakes are generally distributed all over the studied area, and their numbers are high enough in different regions to expect an equal distribution of shapes and cross-sections if there were no distribution preferences and/or meaningful established exchange strategies. This is, however, not the case.

Discussion

The main portion patterns of casting cakes developed in the Middle Bronze Age and stayed unmodified until the late Urnfield period. This points to a wide-reaching, long-term acceptance of an established portioning system and the stability of the exchange networks. Although it is not possible to connect the quality of the copper to specific types or portion unit sizes, it is evident that different cake shapes and surface structures can be tied to different production stages. Most cakes are made of 'black' copper, while pure copper cakes or slag cakes with very high degrees of natural impurities (matte[38]) are rare. The latter material needed further processing to become 'black' copper, which is most likely the reason why this type of cake was rarely deposited. The material was obviously not suitable for this purpose.

However, whereas exchange networks are difficult to discern based on the distribution of all plano-convex casting cakes, the distribution of the different cross-section types gives indications for different circulation networks. The Kernel-density-map of cakes and fragments with a flat cross-section (Fig. 7) shows that although they have a wide distribution, there is a clear cluster located in Moravia, especially in the Jihomoravský kraj region in its south and in the northeastern Alps. Although it must be acknowledged that hoards from both regions are comprehensively published,[39] it is evident that no other regions in Europe have clusters of cakes comparable to this cross-section.

It is also obvious that disc-like cakes and slightly plano-convex cakes are not found in southern Moravia. This again supports the conclusion that we are not looking at a coincidental distribution pattern. A connection between the Eastern Alps and southern Moravia is visible not only for flat cakes but also in the distribution of strongly plano-convex cakes. It is only in these two regions that equally big clusters appear, which indicates a stronger connection concerning raw metal forms compared to other regions. Flat cakes have a much smaller distribution area than slightly plano-convex cakes. The latter mainly occurs in the southeastern Alpine area and nearby regions south of the Danube. Several very strongly plano-convex cakes from western Pannonia are not mapped[40] but fit very well in this picture. In contrast, the randomly scattered distribution of tin bronze cakes (Fig. 8) is coincidental and best explained by the occasional re-melting of bronze artefacts.

Interpretation

But what does all of this tell us about the economic structures of the metal trade? Because Bronze Age ore extraction in the Eastern Alps was on an industrial scale,[41] it is safe to say that the distribution of metal was not based on gift-giving. However, although the majority of the investigated plano-convex cakes are made of Alpine ore, there is no real indication that they were distributed within a large centralised economy.[42] Even for the well-investigated Mitterberg region, it is not

38 E.g. Mehofer et al. 2021.
39 Salaš 2005.
40 Czajlik 1997.
41 Shennan 1998, 200–201; Stöllner et al. 2010; Goldenberg et al. 2012.
42 Cf. Polanyi 1960; Earle 1977; Killen 1998; Nakassis et al. 2011; Schon 2011.

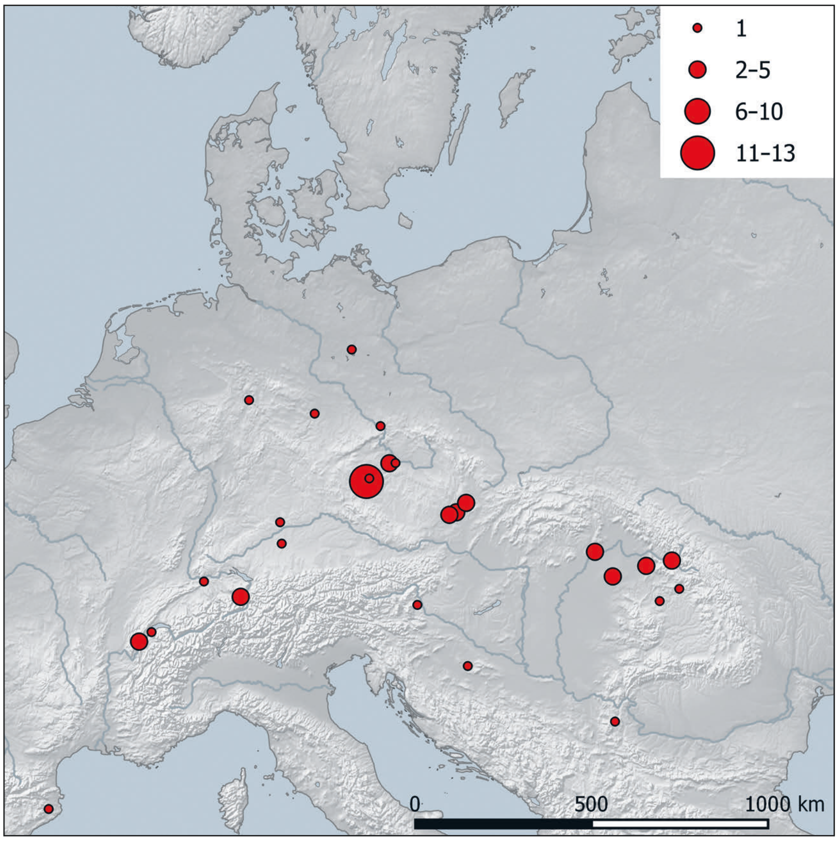

Fig. 8 Plano-convex cakes made of tin bronze (T. Lang, JGU Mainz)

possible to determine if the copper extraction was one large interconnected operation. That ore from the whole mountain area was traded through one large network, or different valleys and/or communities exploited local copper veins individually and traded the metal in separate trade networks.[43] That being said, the latter fits much better with the archaeological record as there is no obvious dominant centre in the region, and the copper producers seem to have lived in largely autonomous settlements that were rather poor compared to communities immediately outside the mining region.[44] Another indication that there was no centralised control of the mining operations and that metal was distributed through several networks is that casting cakes come in several shapes with various cross sections. These different forms may be intentional visual distinctions made by producers to promote their products. Similar strategies to promote products may also explain various ingot forms.[45]

Most consumers probably did not have the same skills and knowledge to assess metal quality as the producers or distributors. Furthermore, it is difficult to evaluate metal properties such as homogeneity, viscosity, mineral inclusions or alloying content, which, combined with the lack of means to replace a metal of poor quality, meant that consumers tried to avoid risks when acquiring raw material. It, therefore, made economic sense to stick to particular distributors, especially if the quality of their goods had been verified through previous purchases.[46] Minor visible differences between raw metal cakes might have been useful distinctions that the consumer recognised, and these differences marked the quality and origin of the metal. This behaviour can be

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43 Stöllner 2015, 183.
44 Shennan 1999, 359–361.
45 Hensler 2014, 46.
46 Bevan 2010, 39.

understood as a reaction to a deliberately formulated demand in a market for copper and copper alloys. Employing these visual distinctions was beneficial both for suppliers and consumers in the sense that the suppliers could market their products, and the consumers could make informed purchase decisions. The varying distribution patterns of specific cake shapes and portions indicate overlapping distribution circles within a supra-regional network. The first includes the Alps, central Germany, Bohemia and Moravia. A second circle, which overlaps the first one in Bohemia, Moravia, and Pannonia, also includes Transylvania, northern Italy, and the eastern Adriatic coast, as well as its hinterland.

Nonetheless, since different cake shapes and segments were deposited together, it seems that, to a large extent, plano-convex cakes were interchangeable. This means they had full or substantial fungibility, which is one of the base criteria of commodities. The term ‘commodity’ is oftentimes associated with industrial, primarily capitalistic economies, but actors in pre-capitalist societies also act as ‘rational economisers’.[47] Furthermore, the large scale of exploitation and production of metal during the Bronze Age, and because the traded raw copper was remarkably standardised despite that a number of maybe autonomous communities exploited the ore in different valleys, it is warranted to describe copper and copper-tin alloys as an early form of commodity. But it is also likely that, to some extent, plano-convex cakes can be understood as trade goods. A large unit of unspecified material, in this case, plano-convex cakes, might have been traded in a standardised shape as a commodity. In contrast, certain visually distinguishable casting cake sub-types, as well as cake segments, could have functioned as trade goods. The efforts of suppliers to customise and, therefore, mark their products within the frame of the generally accepted raw metal ‘cake’ form suggests that attempts were made to transform metal commodities into recognisable trade goods. These efforts were probably not entirely successful, even during the Late Bronze Age. Still, the pattern in the material record can be interpreted as an early stage of commodity and trade goods exchange.

Distribution areas for various plano-convex cake types overlapped, and some find locations contain various cake forms, whereas other finds from the same region only contain cakes of one type. This is consistent with the exchange of a widely used raw material. Various consumers wanted specific copper which they were familiar with and trusted, which in turn was linked to specific distributors and ores. However, if this trade good was not obtainable, it could be substituted by other copper to fulfil the immediate needs. A necessary promotion and protection of an established market share could have happened through interpersonal connections. Consumers probably associated the appearance of people with types and/or visual appearances of raw copper. Therefore, raw metal needs to be further processed and transformed into a recognisable product that fits the expectations of consumers regarding its shape and cross-section. That these attributes are also connected to different (regionally preferred) production processes[48] supports our idea of product promotion through the recognition of raw metal shapes.

Acknowledgements: We are very grateful to Timo Lang, M. A., Johannes Gutenberg University Mainz, for supporting this paper by creating all the maps that illustrate our arguments.

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[48] Hanning et al. 2015; Reitmaier-Naef 2022, 181–192.

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Interpretation of the Lead Isotope and Chemical Analyses of the Copper-based Artefacts from Lower Silesia

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Abstract: In this paper, we present some of the results of interdisciplinary research based on copper-based objects from Lower Silesia dated to the Bronze Age. The preliminary results discussed here focus on the study of the provenance of metal used by the people belonging to the Urnfield Culture (Lusatian Culture) in the southwestern part of Poland. The objects that were analysed are bracelets from two hoards – Bogaczów and Wądroże Wielkie, as well as stray finds, including an axe from Wilków and a bracelet from Prusice. These items are dated to Ha A1–Ha A2, i.e. ca. 1200–1000 BC. An additional incentive to analyse the composition of these particular finds was the fact that these artefacts were discovered near the outcrops of copper deposits in the Kaczawskie Foothills. Bracelets made of D-shaped bars appeared in several deposits in Lower Silesia, mainly in the vicinity of Legnica, so it was considered that they could have been made in local workshops. The chemical and lead isotope analyses provided scientific information that allowed us to suggest the possible provenance of copper used in the production of these bracelets and the axe. Additionally, in this paper, we also report analyses of traces of manufacture found on bracelets from Bogaczów that were made locally.

Keywords: Lusatian Urnfield Culture, Bronze Age, hoard, ornaments, lead isotope analyses, chemical composition, traces of manufacture.

Introduction

In recent years, the number of lead isotope and chemical analyses of copper-based artefacts from Poland dated to the Late Neolithic and the Bronze and Early Iron Ages has been increasing steadily. They include 32 Chalcolithic copper objects,[5] five Early Bronze Age *Ösenringe* from western Poland published by Elke Niederschlag et al.[6] and a group of 46 2nd millennium BC bronzes.[7] There are also analyses of 30 tin-bronzes from the Late Bronze – Early Iron Age,[8] bringing the total to 113 prehistoric metal artefacts.

The analyses of copper from the selected hoards and stray finds from Lower Silesia (Fig. 1) are significant in view of an investigation of the possibility that the ores from the copper deposit in this region in the Kaczawskie Foothills (Pol. Pogórze Kaczawskie), have been exploited in prehistory.[9] This mining region is one of the copper deposits in Poland known to have been exploited for copper in the Middle Ages. The minerals found currently in the Kaczawskie Mountains (Pol. Góry Kaczawskie) include bornite, chalcocite and chalcopyrite, as well as some galena and native silver.[10] There are no reports of the occurrence of tetrahedrites containing high quantities of Sb and Ag. Unfortunately, at present, we do not have a comprehensive

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[4] Polish Geological Institute – National Research Institute, Poland; pder@pgi.gov.pl.
[5] Kowalski et al. 2019; Kowalski et al. 2024; Wilk et al. 2024.
[6] Niederschlag et al. 2003.
[7] Rassmann – Stos-Gale 2015; Stos-Gale 2019.
[8] Nowak et al. 2023.
[9] Gedl 1988; Gediga 1988; Nowak et al. 2023.
[10] Stolarczyk 2013, 342.

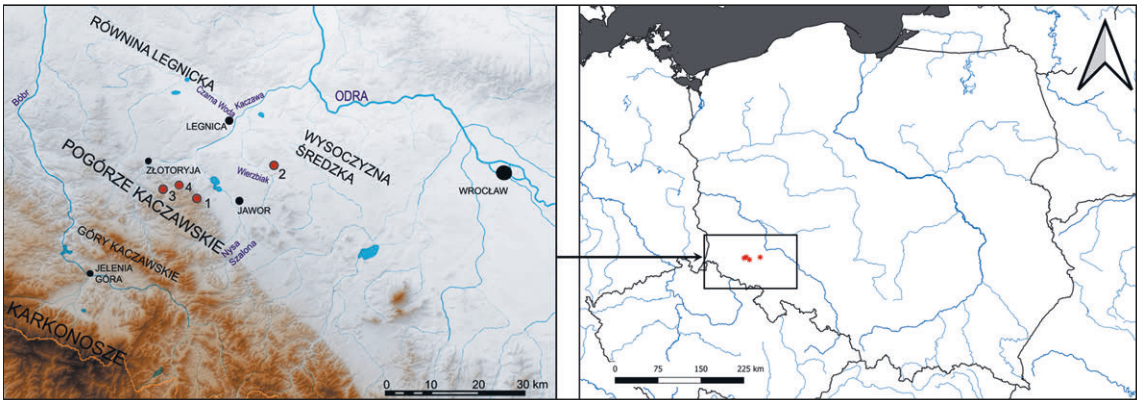

Fig. 1 Location of the analysed finds on the map of Poland and Lower Silesia. No. 1 – Bogaczów; no. 2 – Wądroże Wielkie; no. 3 – Wilków; no. 4 – Prusice (source: Copper Museum in Legnica. Development: T. Stolarczyk, K. Nowak)

database of mineralogical and isotope results for copper ores or prehistoric slags from this mining area. In the literature, there is a report of an analysis of one sample of *Kupferschiefer* from the mine of Lubin in this deposit. However, the lead isotope ratios of this rock are highly radiogenic and do not resemble any of the prehistoric metals from Poland. Copper was also mined in the Mediaeval period in the Holy Cross Mountains (Pol. Góry Świętokrzyskie). Still, there is no indication that there was any prehistoric exploitation of copper in these mountains. Additionally, a few lead isotope data published in the geological literature for minerals from mines in this area are not consistent with any data obtained for the prehistoric metals found in Poland.

The Analysed Artefacts

Four copper-based artefacts selected for this research come from two hoards discovered in Bogaczów and Wądroże Wielkie, distr. Jawor (Fig. 1, nos. 1–2). Additionally, we have sampled two stray finds: an axe found in Wilków, distr. Złotoryja, and a bracelet fragment found in the area of Prusice, i.e., from the immediate vicinity of the copper outcrops in the Kaczawskie Foothills located in Leszczyna (Fig. 1, nos. 3–4).

Hoard from Bogaczów, distr. Jawor

The first hoard was discovered accidentally in 2009 in the area of Bogaczów, distr. Jawor. According to the report, the bracelets were put together by placing one inside the other. Photographs of the excavated objects were taken at their find spot shortly after the excavation (Fig. 2.1) and delivered to the Copper Museum in Legnica together with three other metal objects (no. ML/A 3785 in the inventory book in the Copper Museum in Legnica). Artefacts of this type are commonly interpreted as bracelets, but some of them, especially larger-size items, could have been used as arm or leg ornaments. Most of them come from hoards or stray finds and have never appeared in graves, so the manner in which these ornaments are worn is not clear. There are several groups of bracelets made of bars with a flat-convex, concave-convex or lenticular cross-section with non-tapered ends, differing in form and surface decoration. According to Wojciech Blajer, the bracelets found in Bogaczów belong to type 10: bracelets

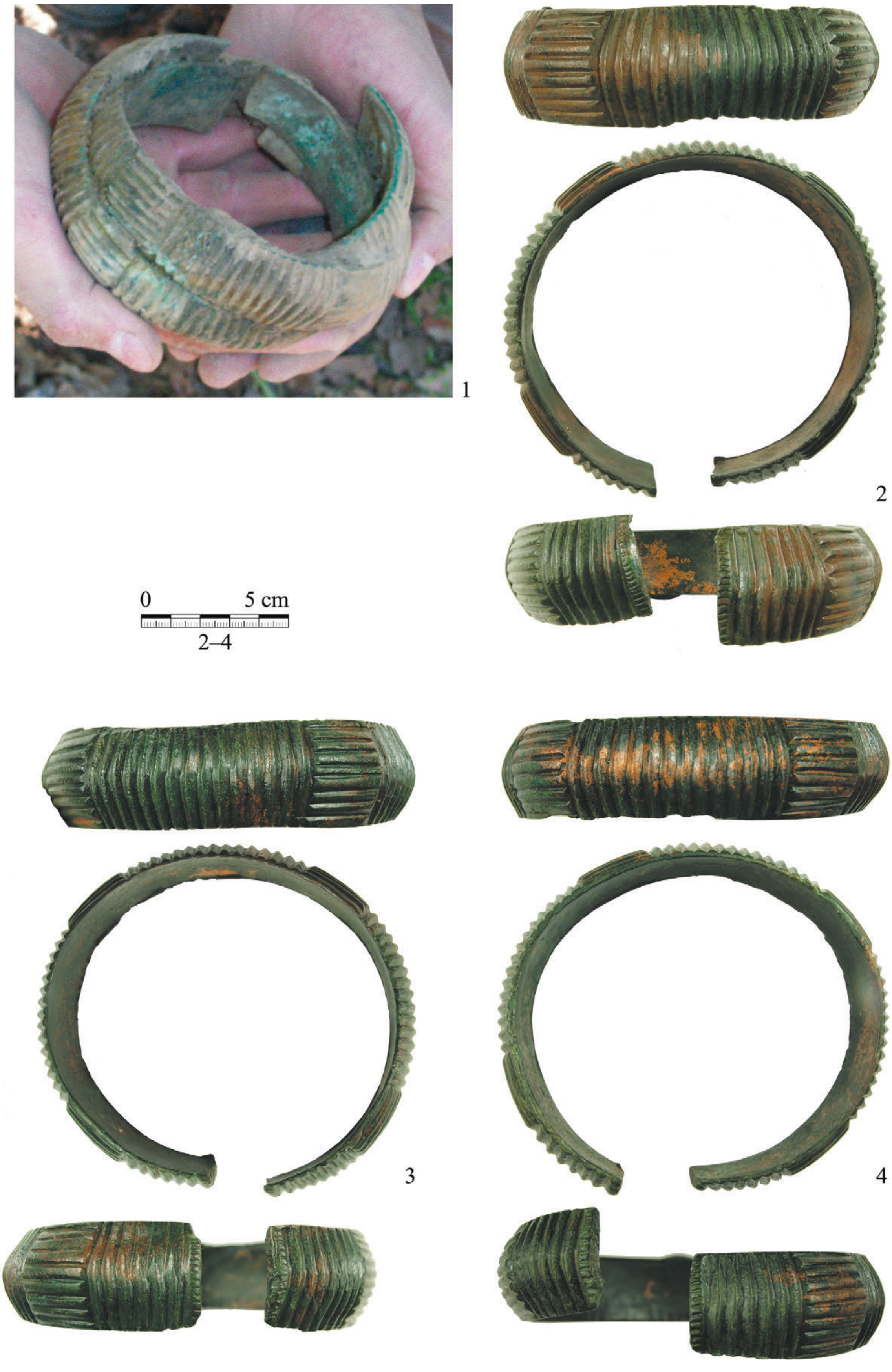

Fig. 2 Hoard from Bogaczów, distr. Jawor. No. 1–2 were sampled and analysed (sample no. 5–6) (photo: T. Stolarczyk)

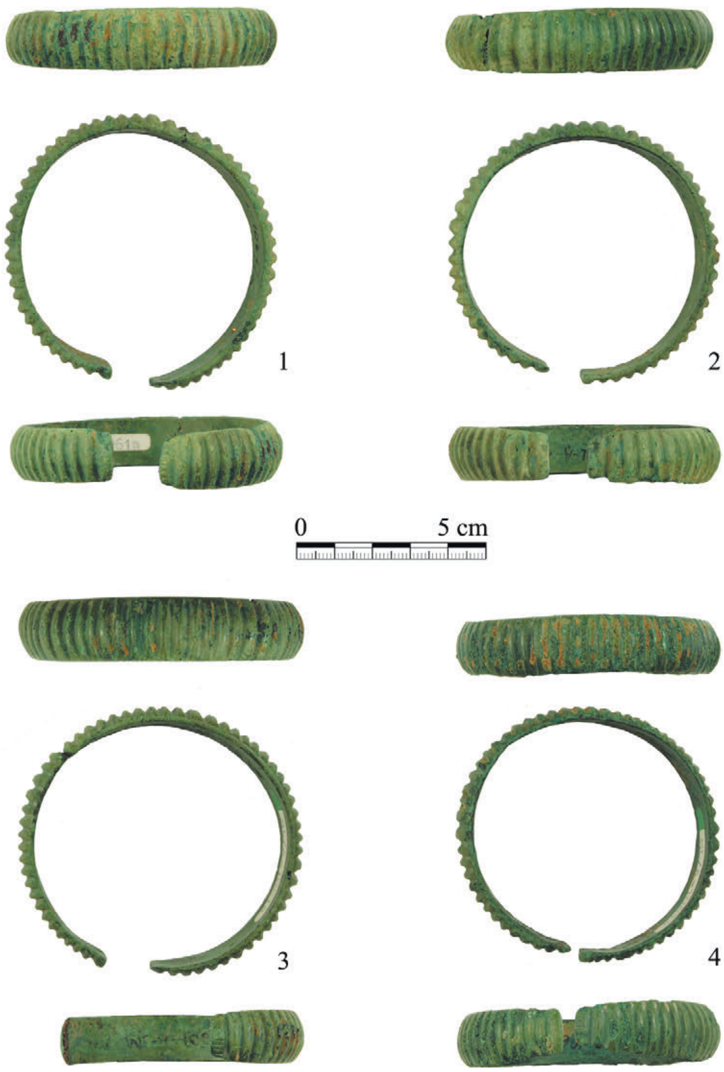

Fig. 3 Hoard from Wądroże Wielkie, distr. Jawor. No. 1 and 3 were sampled and analysed (sample no. 7–8) (photo: T. Stolarczyk)

made of bars decorated with groups of deep transverse and longitudinal (or oblique) grooves/ notches.[11]

The hoard with three similar bracelets was found in 1938 near the Brachów village, distr. Jawor is located very close to Bogaczów. Similar artefacts are also known amongst the 19th century finds from Ustronie, distr. Lubin[12] and Rokitki, distr. Legnica.[13] These types of ornaments have been found only in the regions of the Silesia, western Greater Poland, Lubusz Land and Upper Lusatia. According to the analysis of hoards, it was assumed that the described variants of the banded bracelets, decorated with groups of 'grooves' in various arrangements, can be dated to the Ha A1–Ha A2.[14]

11 Blajer 1999, 66.
12 Kleemann 1977 [1939], pl. 20.a
13 Kleemann 1977 [1939], pl. 21.c
14 Blajer 1999, 72.

Hoard from Wądroże Wielkie, distr. Jawor

Five bronze bracelets were accidentally discovered in 1973 in Wądroże Wielkie, dist. Jawor and delivered to the Copper Museum in Legnica (no. ML/A 1061 in the inventory book from the Copper Museum in Legnica). Unfortunately, there is no information regarding the more accurate location of the place where this deposit was discovered or about the arrangement of the artefacts at the place of discovery. A brief mention in the inventory book states that they were discovered in the vicinity of the sand pit in Wądroże Wielkie. One of the bracelets is missing,[15] leaving four bracelets in the collection.

Three of the four bracelets are undamaged; the fourth is slightly cracked (no. 2; Fig. 3.3). They are open bracelets with a flat-convex cross-section decorated with deep vertical grooves (so-called fluting). The slightly rounded ends are decorated with a row of horizontal lines and have a straight cut. The diameter of three of the bracelets (nos. 1–3) is 7 cm, and the fourth bracelet has a smaller diameter of 6.5 cm. The bracelets all have a consistent width of 1.4 cm. They are covered with a dark green patina and dirt (soil). Unfortunately, because the objects have not been subjected to conservation, the analysis of manufacture traces preserved on the objects is difficult. Similarly shaped bracelets are found, among others, in the hoard from Krzydlina Mała, distr. Wołów dated to Ha A1–Ha A2 (ca. 1200–1000 BC) and are known as stray finds, like a bracelet from Parszowice, distr. Lubin.[16]

Artefacts from Wilków and Prusice, distr. Jawor

Another bracelet sampled for analyses in our project was found in the course of a metal detector survey in 2011 in Prusice, in the settlement (?) of the Lusatian culture identified before the Second World War. Only a small fragment of this bracelet was preserved, and it is difficult to determine

Fig. 4 An axe stray find from Wilków, distr. Złotoryja (sample no. 9) (photo: T. Stolarczyk)

[15] Jacyk 1989, 193
[16] Blajer 1999, 71.

accurately the chronology of this artefact. However, it is most likely to be of a later date than the previously discussed artefacts (1000–650 BC). However, we decided to include this object in the study due to the proximity of this find to the copper outcrop in Leszczyna.

One different type of artefact included in this research project is an axe discovered in 2008 during archaeological surveys in the vicinity of Wilków, distr. Złotoryja (Fig. 4)[17]. This axe is of a so-called Czech type (or Bohemian palstave), dated for the territory of Poland mainly to Ha A1–Ha A2.[18]

Analytical Methods

Scanning Electron Microprobe Analyses (EPMA)

Six copper-based artefacts from Lower Silesia were sampled and analysed for their elemental compositions using EPMA (sample no. 5–6 – Bogaczów; no. 7–8 – Wądroże Wielkie; no. 9 – Wilków; no. 12 – Prusice).

Samples for analyses were taken from these artefacts using a drill with a 1–1.5 mm diameter drill bit. The samples were embedded in resin, polished, and covered with the conductive layer.

The EPMA was carried out at The Polish Geological Institute – National Research Institute (PIG-PIB) in Warsaw using Cameca SX100 microprobe. Electron beam parameters were set to 15 kV of accelerating voltage and 20 nA beam current. The electron beam diameter (spot size) was set to 50 µm. In order to obtain a statistically relevant value, approximately 20 areas (15 to 22) were analysed per sample.

The results of EPMA analyses are presented in Table 1.

The obtained results indicate that the artefacts were made of tin bronze with varying amounts of tin and all the other metal impurities below 0.5%. Bracelets from Bogaczów and Wądroże Wielkie are characterised by considerable homogeneity. They have similar tin contents (3.81–4.14 wt%), and the main impurities (As, Ni, Pb, Co) show very similar contents, approximately between 0.1–0.2%, with Pb content slightly higher (0.45%) in one of them. All samples have the silver, zinc, and gold content below 0.05%. The axe from Wilków has a significant addition of tin in the alloy (over 5%). Additionally, relatively high levels of sulphur have been identified, indicating poor ore refining. A fragment of the bracelet from Prusice has a somewhat different metal composition. It has a high tin (around 11%), and the lead and antimony levels are also higher at around 1%.

Lab no.	Site	Cu	Sn	As	Ni	Pb	Co	Sb	S	Ag	Zn	Fe	Au	Total
5	Bogaczów, bracelet no. 1	93.43	4.14	0.20	0.20	0.22	0.09	0.16	0.39	0.02	0.02	0.04	0.04	99.04
6	Bogaczów, bracelet no. 2	93.94	4.13	0.20	0.19	0.49	0.08	0.14	0.71	0.02	0.04	0.04	0.02	100.10
7	Wądroże Wielkie, bracelet no. 3	94.59	3.91	0.18	0.26	0.18	0.08	0.24	0.53	0.02	0.05	0.08	0.02	100.28
8	Wądroże Wielkie, bracelet no. 1	94.51	3.81	0.14	0.19	0.17	0.06	0.19	0.27	0.02	0.03	0.02	0.01	99.56
9	Wilków, axe	91.31	5.49	0.01	0.32	0.07	0.03	0.07	2.21	0.01	0.03	0.04	0.01	99.72
12	Prusice, bracelet fragm.	86.13	10.80	0.04	0.06	1.23	0.03	0.82	0.57	0.03	0.04	0.11	0.04	100.07

Tab. 1 Chemical compositions (EPMA, averaged). Results are in weight%; 'total' values include light elements not listed in this table (e.g., Si). Limits of detection for the listed elements are as follows: Cu, As, Au, Pb: 0.2%; Co, Fe, Sb, Sn, Ag: 0.1%; S 0.02%.

[17] Stolarczyk et al. 2015, 21–22.
[18] Blajer 1999, 24.

Lead Isotope Analyses

The aliquots of these six samples, from the hoards in Bogaczów and Wądroże Wielkie (nos. 5–8), from the axe (of Czech type) found in Wilków near Złotoryja (no. 9) and from the bracelet found in Prusice (no. 12) were analysed for their lead isotope compositions. The analyses were conducted by Jon Woodhead and Roland Maas at the Isotope Laboratory, School of Earth Sciences of the University of Melbourne, using a multi-collector inductively coupled plasma mass spectrometry (MC ICP MS). The drillings, as submitted, were weighed into 12 ml Savillex beakers and reacted with 2 ml of hot 7M HNO3 overnight. The blue solutions (with occasional undissolved specks) were dried in HEPA-filtered air. Pb was extracted using a single pass on a 0.2 ml bed of AG1-X8 (100–200 mesh) anion resin with the HBr-HCl technique. After strong dilution, Pb isotope ratios were measured on a Nu Plasma MC-ICP-MS for two separate sessions, using thallium doping to correct for instrumental mass bias.[19] The thallium doping technique is expected to yield iPb/204Pb results that have an external precision of 0.04–0.08% (2std dev). This is confirmed by the results for the SRM981 Pb standard done in the same sessions. Seven analyses of Pb extracted from the BCR-2 reference basalt show greater variability, but the average is in excellent agreement with the GeoREM-preferred compositions[20] and are consistent with the long-term laboratory average and with TIMS (Thermal Ionisation Mass Spectrometry) reference data. Estimated Pb concentrations (ppm Pb*) are based on sample weights, dilutions and signals in the mass spectrometer. They are minimum values (some Pb lost during processing) and of low precision.[21] Results are presented in Table 2. The four heavy bracelets have nearly identical lead isotope and chemical compositions, having been made of copper with low impurities of As, Pb, Ag, Sb and Ni (all below 0.5%) and a small addition of tin (3–5%). The axe (no. 9) has a slightly higher tin content, but all other metallic impurities are below 0.1%. The elemental compositions indicate that these bracelets and the axe were made of copper smelted from sulphide copper ores, not tetrahedrites (*fahlerz*).

The lead isotope ratios of these four bracelets and the axe are not consistent with the ores located in the Lower Silesia, the Erzgebirge, or Harz Mountains,[22] but they have somewhat similar compositions to the multi-metallic ores from Slovakia in Brezno and Vyšná Boca in the Low Tatras[23] (Fig. 5). However, the ores in this region of the Slovak Ore Mountains are mostly

Lab no.	Site	Description	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb	ppm Pb* ppm
5	Bogaczewo	Bracelet no. 1	2.09818	0.85322	18.362	15.667	38.526	0.13	1366.1
6	Bogaczewo	Bracelet no. 2	2.09897	0.85338	18.370	15.676	38.557	0.2	2041.5
7	Wadroże Wielkie	Bracelet no. 3	2.09776	0.85208	18.389	15.669	38.575	0.2	1641.1
8	Wadroże Wielkie	Bracelet no. 1	2.09713	0.85118	18.418	15.677	38.625	0.2	1919.1
9	Wilków	Axe	2.10585	0.85763	18.257	15.658	38.447	0.6	566.7
12	Prusice	Bracelet (fragment)	2.09317	0.84979	18.427	15.659	38.570	0.15	1522.4

Tab. 2 Results of the lead isotope analyses

19 Woodhead 2002.
20 Jochum et al. 2007; <http://georem.mpch-mainz.gwdg.de> (last accessed 12 March 2024).
21 R. Maas and J. Woodhead, University of Melbourne, personal communication.
22 Bielicki – Tischendorf 1991; Niederschlag et al. 2003.
23 Schreiner 2007.

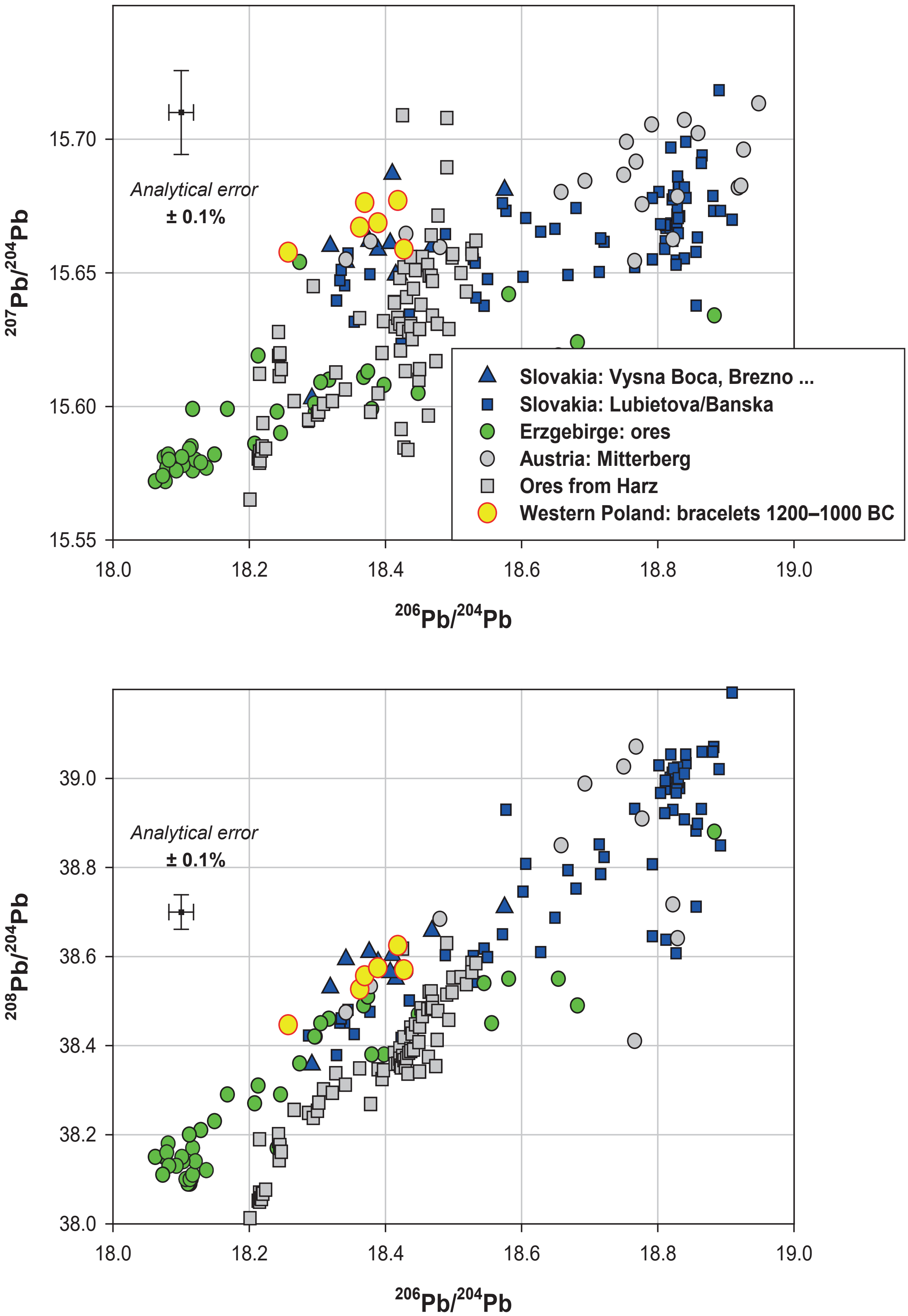

Fig. 5 Lead isotope compositions of the bracelets from Lower Silesia dated to 1200–1000 BC compared with the data for ores from Erzgebirge, Harz, Slovak Ore Mountains and Mitterberg. It is quite clear that none of these deposits could have provided the copper from which the bracelets were made. Lead isotope data after: Bielicki – Tischendorf 1991; Niederschlag et al. 2003; Schreiner 2007; Modarressi-Tehrani et al. 2016; Pernicka et al. 2016 (development by Z. A. Stos-Gale)

Fe-Pb-Zn-Cu-Sb ores.[24] The samples analysed by Schreiner that have the lead isotope compositions matching the bracelets are silicates from various outcrops with varying amounts of Fe, Cu, Pb and Sb. These samples of minerals from Low Tatras have very low copper contents (c. 1–2%) compared to the copper ores from the Hron Valley in Ľubietová and Kremnica, which contain, on average, copper above 20% and, in some cases, over 80%, as well as varied quantities of Pb and Sb.[25] The Test Euclid calculations also show that these ores from Low Tatras do not match the compositions of the bracelets within 1 analytical error.

Therefore, it seems that the similarity of the lead isotope compositions of the bracelets with the ores from the region of the Low Tatras, as presented in Figure 6, is superficial. Additionally, the bracelets (nos. 5–8) and the axe (no. 9) have very similar chemical compositions with approximately 0.2% lead and arsenic, 0.4% nickel, 3–4% tin, and less than 0.1% silver and antimony. In contrast, the ores in the Slovak Ore Mountains have a high concentration of antimony. Schreiner[26], who published most of the chemical and lead isotope data for the copper deposits in the Slovak Ore Mountains, distinguished different ore types, including pure copper ores and tetrahedrites containing high antimony contents. In his analyses of Chalcolithic and Early Bronze Age copper-based artefacts from this region, he also determined that there is a large variation of chemical compositions: from nearly pure copper (particularly for the earliest Neolithic copper objects) to high antimony metal. It seems possible that the high-quality pure copper was not as readily available in the later periods because Diana Modarressi-Tehrani analysed 26 copper ingots found in various parts of Slovakia, and these ingots, on average, contain nearly 4% of Sb, so antimony is the most common impurity in copper from this region.

On the other hand, the lead isotope ratios and the purity of copper of the bracelets are fully consistent with the chalcopyrite copper ores from the Italian Alps, which were exploited in this period and were widely traded in the later part of the 2nd millennium BC[27] (Fig. 6). Also, the axe from Wilków (no. 9), albeit of a Czech type, is isotopically and chemically consistent with the ores from the Italian Alps near Trentino-Bolzano. The plots of the ratios to ^{204}Pb in Figures 5 and 6 demonstrate clearly that there is a linear shift between the lead isotope ratios of the copper ores from the Hron Valley and the bracelets. The axe (no. 9) is fully consistent with the lead isotope ratios of the ores from Trentino-Bolzano, and at present, there are no data for any copper ores used in Bronze Age Europe that could have produced copper of such lead isotope ratios. As shown in Figure 7, when the radiogenic lead isotope ratios (to ^{206}Pb) of the 4 bracelets and the axe from Wilków are compared with the data for copper ingots from Slovakia published by Modaressi-Tehrani,[28] it is clearly visible that the lead isotope ratios of these ingots plot along the line falling below the distribution line formed the ores from Trentino Bolzano, the Lusatian Culture bracelets and the axe from Lower Silesia. Therefore, it can be concluded that the lead isotope ratios of these 4 bracelets and the axe are not consistent with the copper produced in the Slovak ore Mountains but are consistent with the copper from the Italian Alps.

The fragment of a bracelet from Prusice of uncertain date (no. 12) has a slightly higher content of lead and antimony and a slightly different lead isotope composition; it is also marginally consistent with the lead isotope compositions of the ores from the Italian Alps in the region of Trentino-Bolzano, but its antimony and lead contents are higher than it would be expected in the copper from the Italian Alps. Its lead isotope composition is also similar to the ingot from Špania Dolina in the Hron Valley in Slovakia[29] but not to the copper ores from this region analysed so far.

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24 Pouba – Ilavsky 1986, 155, 158–165.
25 Schreiner 2007, 227.
26 Schreiner 2007.
27 Artioli et al. 2016; Ling et al. 2019.
28 Modarressi-Tehrani et al. 2016.
29 No. 947 in Modarressi-Tehrani et al. 2016.

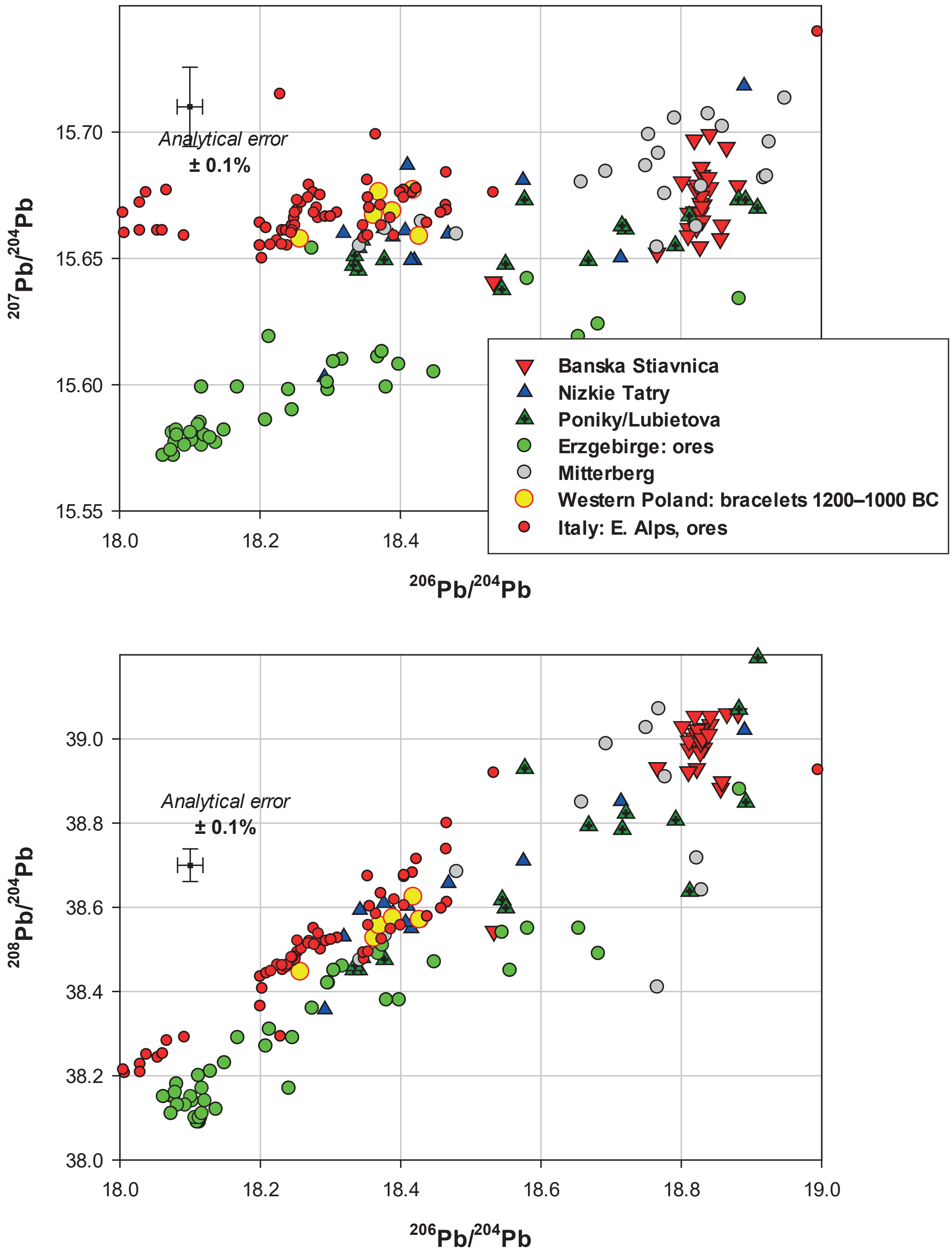

Fig. 6 The lead isotope and chemical compositions of ores from the Italian Alps, from the region of Trentino Bolzano that were exploited in the 2nd millennium BC are fully consistent with data for these bracelets. The data points for ores from the Low Tatras are only superficially consistent with the bracelets. Lead isotope data after: Niederschlag et al. 2003; Artioli et al. 2016; Modarressi-Tehrani et al. 2016; Pernicka et al. 2016 (development by Z. A. Stos-Gale)

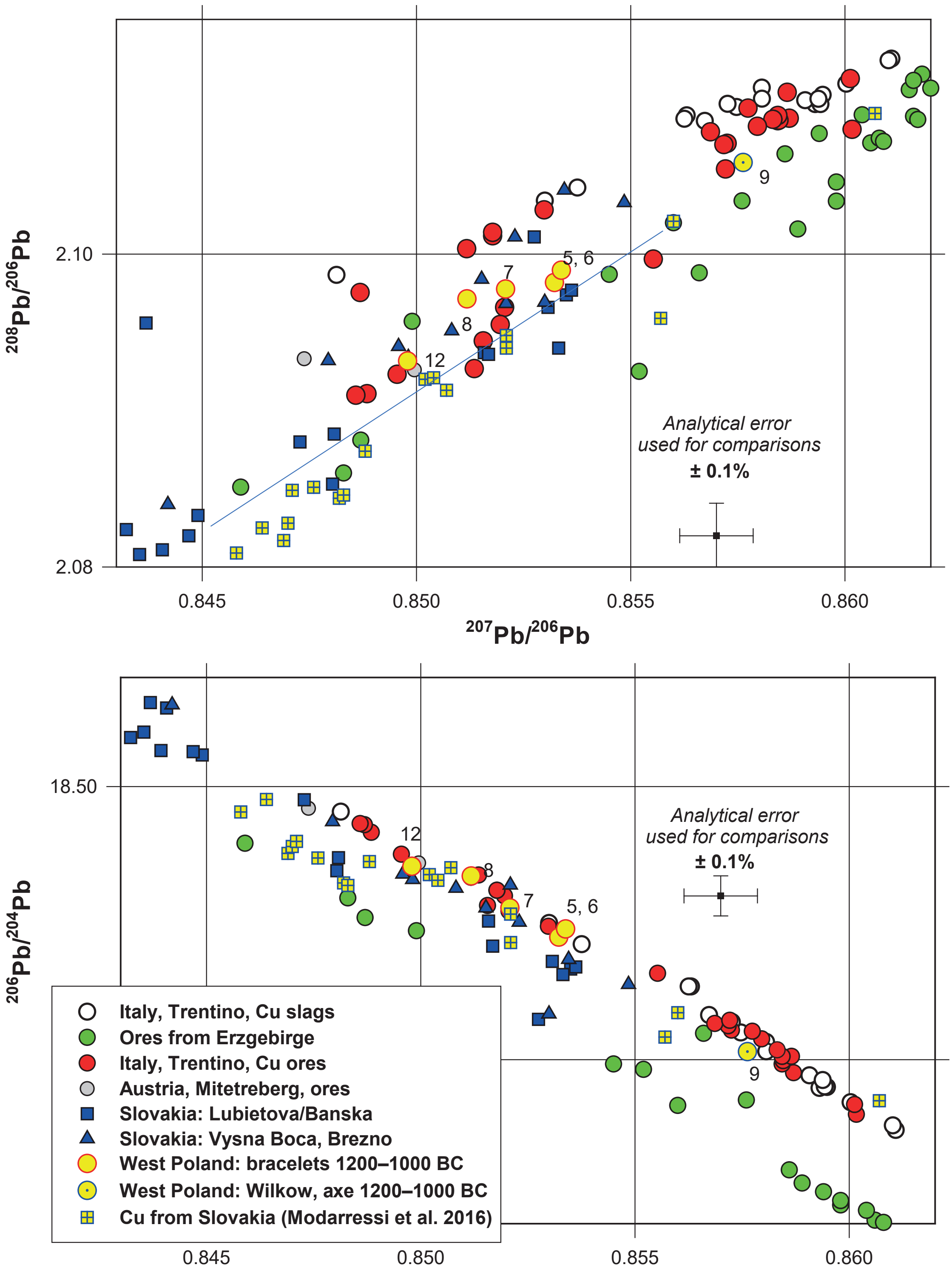

Fig. 7 The plot of the radiogenic lead isotope ratios for the bracelets and the ores from Trentino-Bolzano and the Slovak Ore Mountains, with added data for the copper ingots from Slovakia, demonstrates that there is a shift in the ratios 208Pb/206Pb for the bracelets and copper from Slovakia. Lead isotope data after: Niederschlag et al. 2003; Schreiner 2007; Artioli et al. 2015; Artioli et al. 2016; Modarressi-Tehrani et al. 2016; Pernicka et al. 2016 (development by Z. A. Stos-Gale)

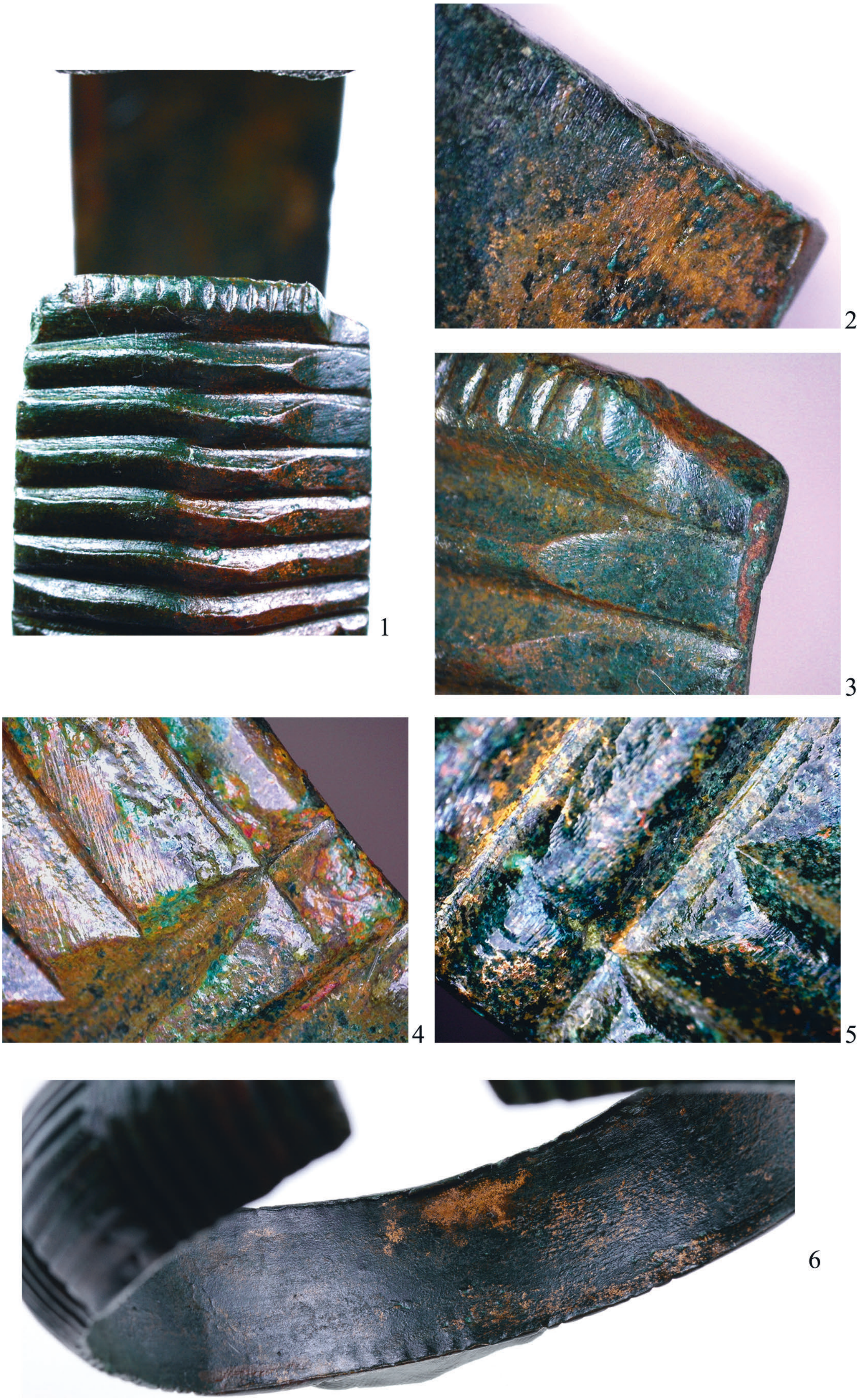

Fig. 8 Production and use-wear traces observation (photos no. 2–5 were taken with a digital microscope Dino-Lite with a 1.3 megapixels camera with zoom of 20× to 30×) (photo: K. Nowak)

Manufacturing of the Local Flat Banded Bracelets from Bogaczów Hoard

As a part of research on the products of probably local metal workshops of the Lusatian culture community in Lower Silesia, we also decided to attempt a reconstruction of the process of making flat bracelets. For this purpose, we analysed three bracelets from the Bogaczów hoard (Fig. 2).

Bracelets from this collection are massive objects made of a D-shaped bar. The manufacturing process can be reconstructed by looking at the traces preserved on the surface of each of the bracelets. In the first place, the bar was cast. Casting moulds for bars or rods are not very common amongst archaeological finds. The known casting moulds are characterised by small sizes of the mould cavity,[30] which may indicate that only small bars were produced in these types of moulds and, after casting, lengthened by forging. This type of operation had to take place in several stages and was associated with many forging and annealing sessions. All tested items have very similar chemical compositions (Tab. 1), which may indicate that they were made from the same batch of bronze during one casting session. It is difficult to state unequivocally whether the three bars were poured at once using a mould with three cavities or that only one bar was cast.

In the second scenario, such a bar should be lengthened and formed by forging to a length of over 1 m and then divided into three pieces. The dimensions of individual bracelets from Bogaczów are very similar in terms of both dimensions and weight. Bracelet no. 1 is 36.5 cm long, bracelets no. 2 and no. 3 are slightly shorter (about 35.5 cm). The fact that no. 1 is only slightly longer suggests that the bracelets were not made from separate bars but that they were made from the division of one long bar that was not accurately divided. Research shows that the Bronze Age metallurgists or 'smiths' were able to change the shape of metal by forging it in an accomplished manner, producing metal vessels, or sometimes even wires several meters long for making ornaments.[31] The chemical composition of the bracelets and the low proportion of tin (about 3%) meant that this type of metal had very good forging properties. The fact that the bars are broken off from a larger piece can also be proven by the presence of unevenness at the edges of all the pieces, which is the edge of the fracture (Fig. 8.2).

In the next step, a metal bar of suitable length was decorated with groups of longitudinal and transverse grooves that were cut and ground (Fig. 8.4). These grooves were made on a semi-finished product (not bent yet) and were not made at the casting stage (in the mould cavity), as evidenced by the unevenness and cuts visible on the item's surface. Grooves were made from two side edges, as evidenced by errors in the incision, which often do not meet in the right place (Fig. 8.1). In some cases, the order in which the grooves were made can be determined because by making one groove, another previously made groove is damaged (Fig. 8.4–5). An interesting issue is the process of making such cuts/grooves. It is recognised that saws made of a thin bronze sheet, often found in hoards inventories (for example, Transylvania),[32] were not suitable for cutting bronze. Rather, they were used for softer materials, such as bone, wood or soft types of stone.[33] Perhaps the grooves in the case of bracelets from Bogaczów hoard were made with a suitable stone or a sharp chisel (or both).

On most of the longitudinal grooves, there are additional diagonal cuts made with sharp chisels or punches. The bracelets are very similar, almost identical in ornament. However, upon closer observation, some differences are noted. In each bracelet, the arrangement of grooves

[30] Compare e.g. to the casting mould for small bars from the Heilbronn-Neckargartach hoard (Overbeck 2018, pl. 57.134) or from the grave no. 24 in Gogolin-Strzebniów (Jockenhövel 2018, fig. 17; Tomczak et al. 2021, figs. 28, 32).

[31] Compare: Pietzsch 1967; 1968.

[32] E.g., Soroceanu et al. 2017.

[33] Nessel 2009.

Bracelet no.	Size (cm)				Ornament (grooves) counted from the edge having characteristic bend								
	length	width	diameter	weight (g)	short	long	short	long	short	long	short	long	short
1	36.5	2.9	12.1	319	7	8	16	9	16	8	16	9	8
2	35.8	2.9	12.2	317	7	8	15	8	16	8	15	9	7
3	35.5	2.8	12.3	327	7	8	16	8	15	8	15	9	7

Tab. 3 Dimensions of the bracelets from Bogaczów hoard (short – transverse grooves, long – longitudinal grooves)

is arranged alternately—transversely and longitudinally. However, the number of grooves in individual arrangements varies (Tab. 3).

The last stage of production was bending. Traces associated with this process are visible on the inner side in the form of characteristic protuberances (Fig. 8.6), which confirms that the bracelets were bent after decorating. All items also bear a trace of the crush at one end, possibly associated with holding the bracelet while bending (Fig. 8.3).

Conclusions

The results of our preliminary research on the provenance of the metal that was used to produce objects dated to Ha A1–Ha A2 discovered in Lower Silesia are very promising.

These Bronze Age artefacts selected for lead isotope analyses have been found near the outcrops of copper deposits located in the Kaczawskie Foothills. While the axe from Wilków can hardly be considered a local item, bracelets from Bogaczów could have been produced locally, as evidenced by the discoveries of such forms in Lower Silesia. Observations related to the manufacture traces showed that the bracelets from the Bogaczów hoard were most likely made of one ingot or a large bronze artefact, which was melted, cast into a bar and divided into three fairly equal parts. Then, before bending each of them into an open circle, the bracelets were decorated with the specific technique of cutting and grinding the grooves.

The research was mainly aimed at determining where the metal, that was used for the production of locally cast objects, originated. The bracelets found in the two hoards and the axe from Wilków have lead isotope and chemical compositions fully consistent with the copper produced in the Italian Alps in the region of Trentino-Bolzano, where copper was produced in large quantities during this period. Due to the excellent quality of copper produced in this region, it was the main material for 2nd millennium BC swords made across Europe from the British Isles and Scandinavia to the Balkans, Greece and Egypt.[34] The peak of copper smelting in the Italian Eastern Alps was in the second half of the 2nd millennium BC, but a certain amount of copper was also smelted there at the beginning of the 1st millennium BC. The bracelet fragment from Prusice is only marginally consistent with the ores from the region of Trentino-Bolzano, and the natural impurities are also not typical of copper from the Italian Alps. Its lead isotope composition is similar to that of one ingot from the Slovak Ore Mountains but not the copper ores from the Hron Valley, which are the main copper deposits in this region.

The chemical and lead isotope analyses of thousands of artefacts from western, northern and southern Europe have fundamentally changed old archaeological concepts in this field. However, as of now, very little is known about the origin and development of copper metallurgy in Poland and other countries of eastern Europe in the 2nd and 1st millennium BC. It is with great optimism that, in the near future, this situation will change.

Acknowledgements: The research presented in the article was financed by the National Science Centre, Poland (NCN UMO-2017/27/N/HS3/01097 and 2021/40/C/HS3/00097).

[34] Ling et al. 2019; Gavranović et al. 2022.

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Analysis of Lead Segregation in a Late Bronze Age Socketed Axe from the Biatorbágy-Herceghalom Hoard

János Gábor Tarbay[1] – *Boglárka Maróti*[2] – *Zoltán Kis*[3] – *Péter Barkóczy*[4]

Abstract: Nowadays, several analytical techniques are available for the characterisation of a bronze artefact's elemental composition. All have different advantages, which should be considered if we wish to have a proper answer to our historical or technological questions. Our work is a case study that compares the results of various non-invasive and non-destructive analytical techniques (X-ray fluorescence spectroscopy, Prompt Gamma Activation Analysis, Neutron Imaging) and invasive techniques (Metallography, EDS Analysis). The examined object is a Late Bronze Age socketed axe with high lead content from the Transdanubian Biatorbágy-Herceghalom hoard (Pest County, Hungary), which has been previously analysed in the framework of the SAM Project (SAM 27373, SAM 27374).[5] In addition to comparing the results of the analytical technique and discussing the object's archaeological context, we shall investigate the phenomenon of lead segregation and provide a brief overview of high-leaded objects from the Late Bronze Age Transdanubia.

Keywords: Late Bronze Age, socketed axes, lead, metallography, Transdanubia

Archaeological Background

The hoard from Biatorbágy-Herceghalom (Pest County, Hungary)[6] was found in the estate of Pauline Clémentine Marie Walburga, Princess of Metternich Winneburg zu Bleistein (Countess Pauline Sándor de Szlavnicza) in 1890 (Fig. 1). It was kept by the administrator of the Princess, Emil Májer. On July 30, 1893, the Hungarian National Museum (HNM) contacted Imre Remenyik, an estate inspector, to mediate the acquisition of the finds. On January 1, 1894, the hoard was presented to the collection of the HNM.[7] The assemblage contains 197 objects,[8] mainly partitioned plano-convex ingots and metallurgical by-products, as well as several rings and socketed axes. In addition, smaller ornaments, flanged sickles, a knife, a spearhead, and some swords can also be found in this hoard. From a technological point of view, the hoard consists of two main components: 1. partitioned raw materials (ingots, jets, droplets, as-casts, defective products, and semi-finished objects), 2. finished products with or without different intensities of use. Fragmentation is present in all groups, especially in the first, where most ingots were partitioned by

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5 Mozsolics 1985b, pl. 237.3; Liversage – Pernicka 2002, 423–425.

6 Key studies on this hoard, see Hampel 1894, 85; Hampel 1895, 7, pl. 1; Hampel 1896, pl. 209; Mozsolics 1985a, 56, pls. 10–15; Mozsolics 1985b, 127–128, pls. 237–238; Kemenczei 1991, 83, pl. 68.392; Váczi 2013, 260–264, pls. 41–44; Tarbay 2018, 482–488, pls. 13–30.

7 No. 246/1893 archive document of the HNM; Inventory Book of the HNM 1894.1.1–197; Hampel 1896, pl. 209; Mozsolics 1985b, 127–128.

8 József Hampel refers to the possibility that the acquired finds were only a part of the original assemblage. Amália Mozsolics also noted that several finds have been lost. Currently, only 173 bronze objects are preserved. Hampel 1896, pl. 209; Mozsolics 1985b, 127–128; Tarbay 2022, fig. 8.2.

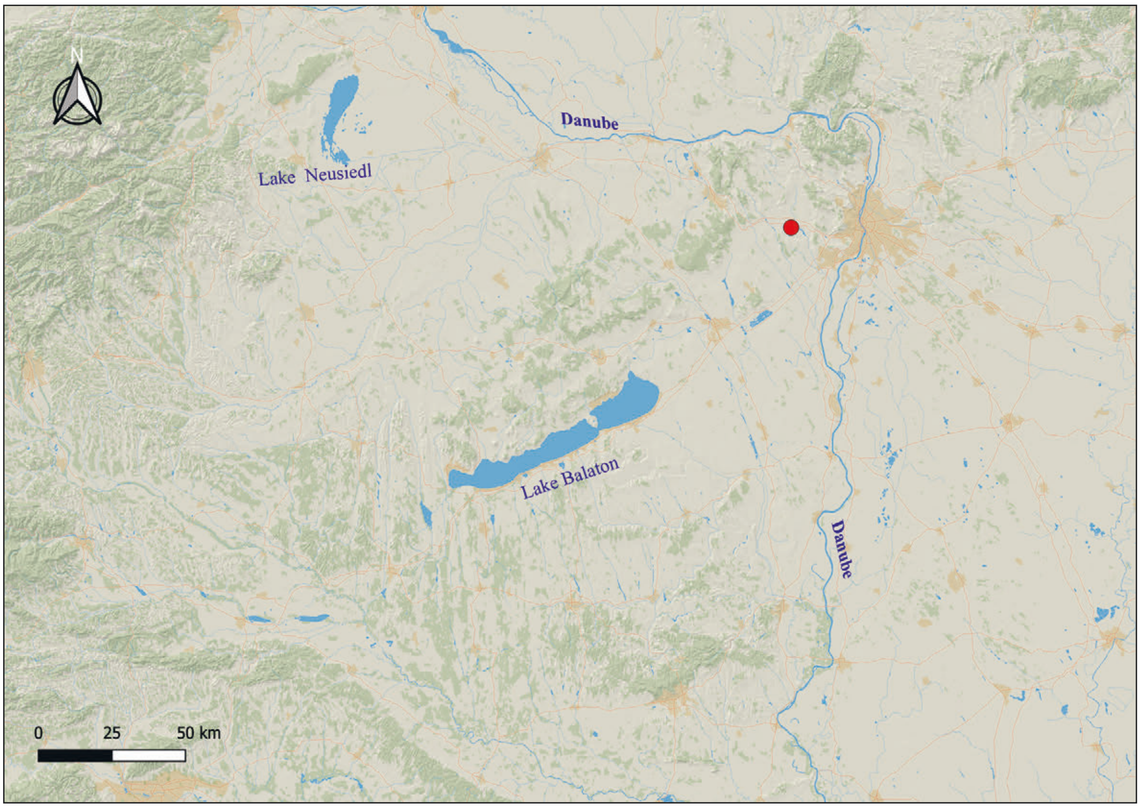

Fig. 1 Map with the position of the site Biatorbágy-Herceghalom (J. G. Tarbay)

different techniques. The intact deposition is more characteristic of the second group, especially for the rings of Lovasberény-type with tapered terminals (Fig. 3.a). Amália Mozsolics and Tibor Kemenczei assigned this hoard to phases associated with the Ha A2 period.[9]

In terms of deposition time, we essentially agree with Gábor Váczi's[10] proposed relative chronological position (Ha A2–Ha B1) based on the fine analyses of the socketed axes of the Debrecen type and the arch-profiled socketed axe.[11] Although we have to emphasise that the complete relative chronological pattern of the finds started at BA D–Ha A1, Ha A1 is based on a fibula of Čaka type, a pin of Diviaky type and a phalera of Nadap-Poljanci type (Fig. 3.b).[12] Technological phenomena like an overused spearhead, an axe modified as a hammer, and a socketed axe with worn breakage surfaces also support the possibility that the assemblage was accumulated for a long period of time (Fig. 3.a).

The socketed axe that was studied has a thin body, a slightly curved rim, and one thick rib right below its collar (Fig. 2). Along its wider sides, one will observe an emphasised arch. The object shows characteristic signs of horizontal and vertical mismatch defects. The axe's blade is fragmented, and part of the blade is missing due to breakage.[13] It falls into the group of arch-profiled socketed axes,[14] which were discussed first by József Hampel as axes of the Transylvanian type.[15] After the seminal work of Ion Nestor, Márton Roska reviewed the parallels and chronological

[9] Mozsolics 1985b, 128; Kemenczei 1996a, 77.

[10] Váczi 2013, 168.

[11] Tarbay 2018, 482.

[12] Tarbay 2018, 482.

[13] Dimensions of the object: length 11.1 cm, width of the rim 3.7 × 2.9 cm, width of the blade-socket interface: 3.5 × 1.9 cm, width of the blade: 4.9 cm, weight: 223 g. Inv. no. 1.1894.78.

[14] Mozsolics 1985b, 36–37.

[15] Hampel 1886, pls. 4.7, 9–10; Hampel 1892, 45–46.

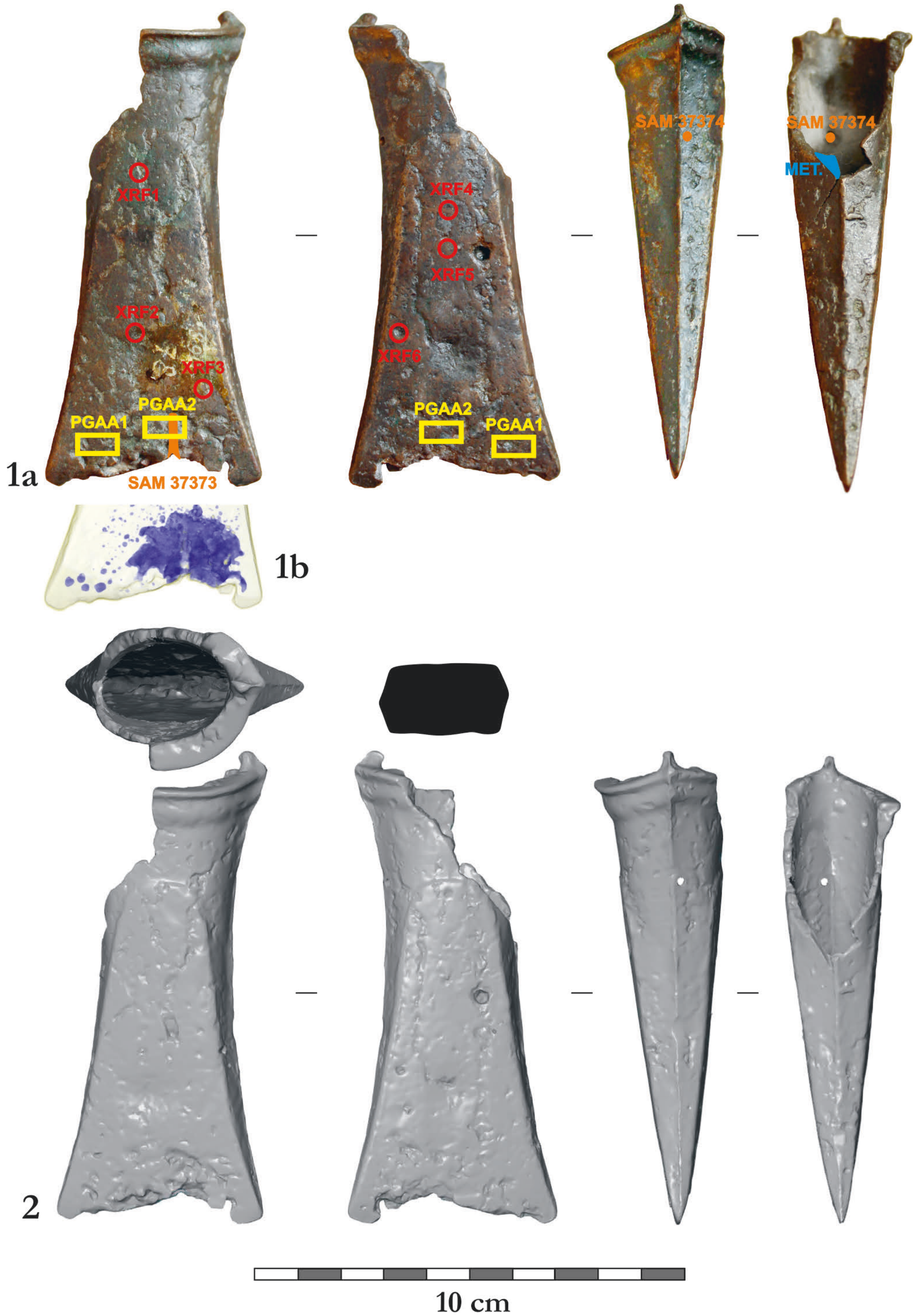

Fig. 2 The socketed axe from Biatorbágy-Herceghalom: 1a. Photography and drawings of the object; 1b. Traces of SAM analysis on Neutron Imaging; 2. Images from a 3D model of the axe (made by GOM Industrial 3D Measurements Techniques)

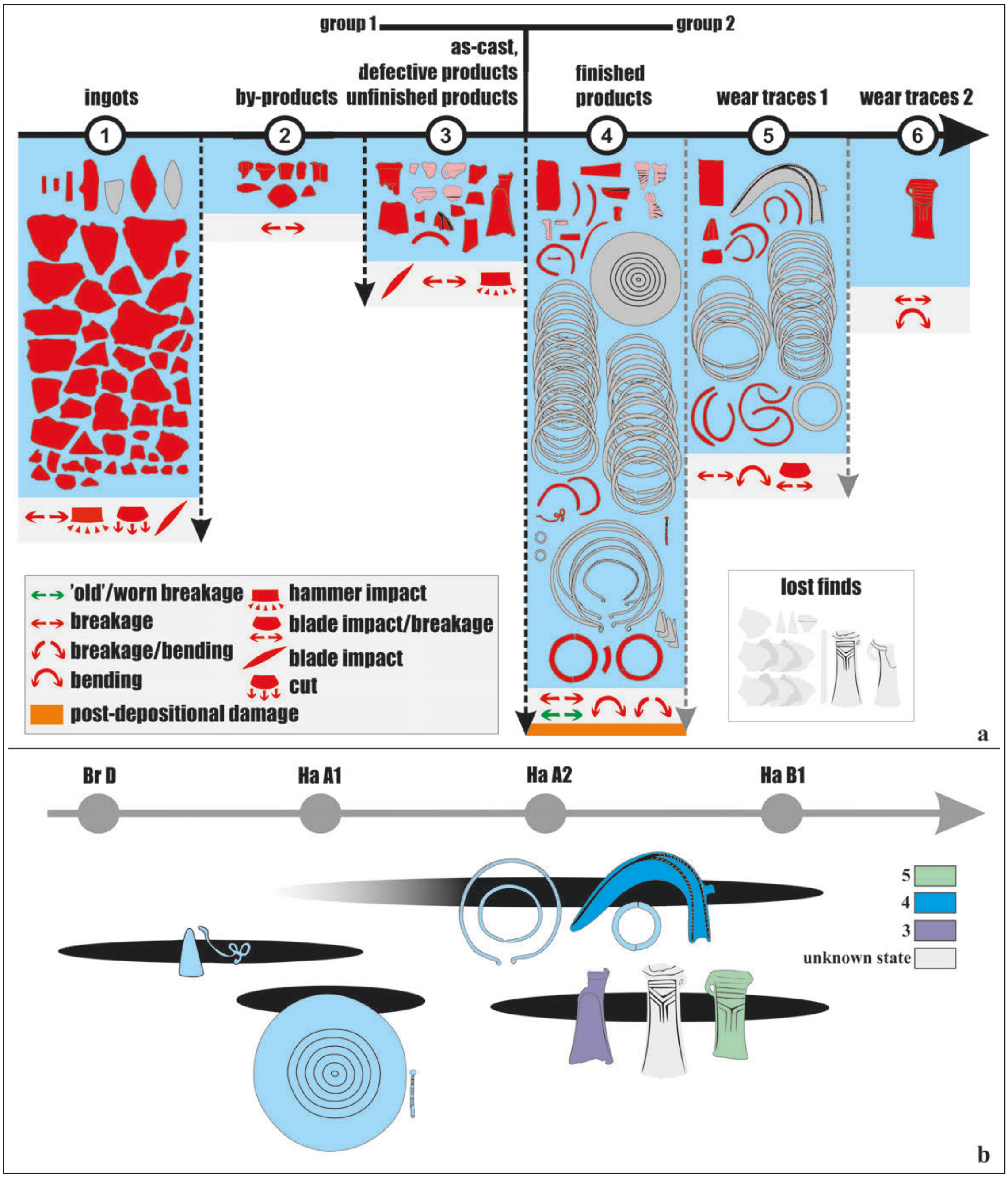

Fig. 3 The selection of the Biatorbágy-Herceghalom hoard: a. Technological selection and treatment based on metalwork wear analysis (data obtained from Tarbay 2018, 482–488); b. Chrono-technological selection (data obtained from Tarbay 2018)

position of these tools.[16] In-depth typological characterisation of axes of the Transylvanian type was provided by Mircea Rusu. The arch-profiled socketed axes can be sorted into his subvariants C6–10, which were dated between the Ha A1 and Ha B2.[17] Tibor Kemenczei pointed out that these axes appeared sporadically at the Ha A in the Tisza Region, and they have been produced

16 Nestor 1933, 131, fn. 530; Roska 1937; Roska 1938, fig. 1.

17 Rusu 1966, 27, fig. 4.

until the Ha B2 and Ha B3 (Type F) in smaller sizes.[18] As the research progressed, not only were several new specimens found, but the terminology of these axes became quite diverse.[19]

Important results were provided by Valentin Dergačev, who classified them as Negrești-type and pointed out their distribution on the territories of Transylvania as well as the area north of the Black Sea. According to his model, the first representatives of this axe group appeared around the BA D in southeastern and central Transylvania, while specimens north of the Black Sea were present in the Ha A1. After Mircea Rusu, he dated the axes outside of these core areas to later periods (Ha A1, Ha A2–Ha B3).[20] Nikolaus Boroffka and Florin Ridiche combined Burger Wanzek's fine typology with V. Dergačev's scheme and came to a similar conclusion. Axes decorated with cast ribs (1 to 4) were defined as a form with sporadic distribution in the territories of Serbia, Transdanubia, Transylvania, and northeastern Hungary. According to their concept, these axes appeared in the BA D and became frequent in the Ha A1, while their number decreased in the Ha A2 and showed an increase again in the Ha B1.[21] The latest results were published by Mario Gavranović and Aleksandar Kapuran on these axes, who studied different types from the Balkans. According to their scheme, Type C and Type E fall close to the Biatorbágy-Herceghalom axe. Both types were dated to Ha A2–Ha B1.[22]

It is also worth noting that arch-profiled socketed axes were also present in northern Europe between Period III and Period VI and in even larger numbers in Period IV and Period V. The typological similarities between the northern and eastern European axes have already been observed by Henrik Thrane, who related Mircea Rusu's Variant C6–10 with some of the Scandinavian Late Bronze Age axes. He noted that a connection between the two regions could have existed, although the Scandinavian specimens were much smaller and had a rectangular cross-section. Despite the differences in fine typology, some Nordic specimens (e.g., Løvskal, Witkowo) seem very similar to the eastern European finds. The hoard from the Sebeș area (Romania), which shows the combination of plate fibulae and socketed axes, as well as the fibula mould from Geoagiu (Romania), is also puzzling.[23] It is important to emphasise that arch-profiled socketed axes are known in large numbers in the territory of the Lower Danube and the Carpathian Basin, where casting moulds were also found. Axes dated to Ha A have clear eastern European relations, whereas the possibility of northern connections is more likely in Ha B2–Ha B3 (Period V) on typological grounds.

In summary, different variants of arch-profiled socketed axes can be dated between the Ha A1 and the Ha B1 in the Carpathian Basin and its adjacent areas. Towards Ha B2 and Ha B3, their shapes have changed, becoming smaller.[24] Those axes with one loop and decoration made of

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[18] Kemenczei 1981, 34; Kemenczei 2005, 76–77. See Iron Age variants also: Metzner-Nebelsick 2005.

[19] Novotná 1970, 97–98; Chernykh 1976, 77, fig. 33; Mayer 1977, 186–187; Chernykh 1978, 200–201, pl. 4.9; Mozsolics 1985b, 37; Wanzek 1989, 101–105, 2.b.5; Hansen 1994, 180; Dergačev 1997, 144; Kobal' 2000, 41; Dergačev 2002, 138–139; Kemenczei 2005, 76–77; Dergačev 2011; Dergaciov 2013, fig. 2; Gavranović – Kapuran 2014, 32.

[20] Rusu 1966, 27; Dergačev 1997, 144, fig. 5.II, map 8; Dergačev 2002, 138–139, Pl. 109. Typo-chronology of variants without loop, See Dergačev 2011, 92–97, 138–139, 151, figs. 51, 55, 92.

[21] Boroffka – Ridiche 2005, 153–155, fig. 9.3, lists 9A–B, map 6A–B. It should be noted that the Ha A2 dating of these socketed axes was strongly influenced by Amália Mozsolics, who cross-dated the Hungarian find with axes from Romanian hoards that she dated to the Horizon Gyermely, too. Among these 'contemporaneous' hoards (Jupalnic 1, Arad 2, Bancu, Cetea, Nou Săsesc), only Jupalnic was dated to the Ha A2. All these hoards contain axes and flange sickles that support M. Petrescu-Dîmbovița's Ha B1 dating. See Petrescu-Dîmbovița 1978, 132, 138–141, pl. 220b.9; pls. 223.1–5, 8–16, 23; pls. 225c.1–2, 6–8; pls. 227b.2; pl. 228.7–10; pls. 236b.6, 8; Mozsolics 1985b, 34–35, 37, fn. 58.

[22] Gavranović – Kapuran 2014, 36–39.

[23] Sprockhoff 1956, 88, fig. 17.6; Baudou 1960, maps 12–15, pls. 5–6 (VII C2a, VIIC3); Thrane 1967, DK 6.3; Thrane 1975, 113–114, 224–225, fig. 126; Petrescu-Dîmbovița 1978, pl. 274g.3–4; Bader 1983, 39–40, pls. 5.23–24; Kibbert 1984, 138, pl. 49.648; Kuśnierz 1998, 77, pl. 29.631; Boroffka – Ridiche 2005, 185, fn. 228; Laux 2005, pl. 41–42; Jantzen 2008, pl. 27; pl. 30.153.

[24] Kemenczei 1981, 34.

horizontal ribs can be sorted into four combination groups similar to Nikolaus Boroffka's and Florin Ridiche's model.[25] Axes with one horizontal rib right under their collar or slightly below it have appeared in several territories of the Carpathian Basin.[26] In addition to the Biatorbágy-Herceghalom socketed axe, similar finds in hoards or as stray finds are known from Hungary, Transdanubia,[27] and east of the Danube.[28] Several specimens were discovered in Serbian hoards of Stufe III, IV and V.[29] Roughly at the same time, and these axes were also present in Transylvania.[30] A casting mould was found here in Plenița (Ha A2–Ha B1).[31] Similar specimens have appeared sporadically in Slovakia,[32] Ukraine,[33] Austria[34] and Poland.[35] It seems that socketed axes that were typologically similar to those found in the Biatorbágy-Herceghalom find were in circulation for an extended period of time. The dating of the parallels varies according to regional relative chronological schemes. The axes from Hungary were most likely deposited in the Ha A2–Ha B1, or Ha B1. This relative chronological position suggests that the axe belongs to the youngest time group of the Biatorbágy-Herceghalom hoard (Fig. 3.b).

ED-XRF Results

As a first step, on-site ED-XRF measurements were carried out in the HNM using an Innov-X Delta Premium type handheld analyser. Despite the possible surface contamination or patina, this method has proven to be useful in determining the type of alloy prior to neutron-based measurements.[36] The spot size of the X-ray beam is 3 mm. The socketed axe was analysed at six different points, where the surface of the artefact was macroscopically smooth. On the uncleaned surface of the object, the lead to copper ratio varies to a large extent (0.55–3.1), which makes it impossible to determine the exact composition of the alloy. However, it does predict the heterogeneity of the object. Later, the polished surface of the metallography subsample was also measured with ED-XRF. The cleaned and polished sample showed a macroscopically homogeneous alloy composition with approximately 58 wt% copper and 34 wt% lead contents. Besides these elements, the socketed axe contained minor amounts of antimony, tin, nickel, silver, and iron. On the polished surface, a lead droplet was visible to the naked eye. This was also measured with ED-XRF, but since the droplet was smaller than the X-ray spot, the determined lead concentration here was only 50 wt% (Tab. 1).

25 Boroffka – Ridiche 2005, 152–153, 183–185.

26 Rusu 1966, 35–38, C6–7; Wanzek 1989, Variante 2.b.5.b.-1; Boroffka – Ridiche 2005, 185, list. 9B.1–9; Gavranović – Kapuran 2014, 33, 36–37; Tarbay 2018, 47–48, appx. lists 20.1–4, maps 49–50.

27 Csabdi, Lovasberény, Tata-Dunamellék. All three hoards contain archaic objects that are characteristic to the BA D–Ha A1 or Ha A1 periods, although the time of deposition of these finds could have happened later in the Ha A2–Ha B1 (Csabdi), Ha B1–Ha B2 (Lovasberény, Tata-Dunamellék). See Tarbay 2018, 494, 566–567, 667.

28 Ha B1: Tarhos, Szentes 4; Ha B3: Prügy. Mozsolics 1985b, pl. 244.10; pl. 247.8; Kemenczei 1996b, pl. 11.1; Jankovich et al. 1998, pl. 23.24; Mozsolics 2000, pl. 96.9; Kemenczei 2005, pl. 29.35.

29 Stufe III: Gornja Bela Reka, Mali Izvor, Požarevac region, Sečanj 3, Vojilovo; Stufe IV: Alun; Stufe V: Adaševci, Boljetin; Stray finds: Ćuprija, Donje Štiplje, Dvorište, Kopaonik, Sekurić, Vinča. Garašanin 1954, pl. 36.2; Vinski 1955, pl. 2.12; Srejović 1961, figs. 1, 2a; Todorović 1975, pl. 70.2–3; Vasić 1982, fig. 3.2, 7; Vasić 1990, fig. 3.1; Marinković 1991, fig. 1.5; Radojčić 1994, pl. 5.2–3; Vukmanović – Radojčić 1995, 87–88, nos. 153, 155; Gavranović – Kapuran 2014, pl. 2.1–2, 4.

30 Ha A1: Cozla, Șpălnaca 2; Ha B1: Bancu, Jijia, Mileni. Roska 1937, fig. 85.3; Petrescu-Dîmbovița 1977, pl. 193.10; Șadurschi 1989, fig. 4.3; Gumă 1993, pl. 27.20; Crăciunescu 2005, fig. 3.1–2; Kemenczei 2005, pl. 29.35.

31 Boroffka – Ridiche 2005, fig. 6.2.

32 Ha A1: Levice. Novotná 1970, pl. 42.784.

33 BA D: Puzhaikove, Revovka. Černjakov 1964, fig. 2; Kločko – Kozimjenko 2017, 172, fig. 14.

34 Mayer 1977, pl. 72.992.

35 Period V: Witkowo. Kuśnierz 1998, pl. 29.631.

36 Maróti et al. 2018.

		Cu	rel. unc (%)	Pb	rel. unc (%)	Sn	rel. unc (%)	Sb	rel. unc (%)	Ni	rel. unc (%)	Ag	rel. unc (%)	Fe	rel. unc (%)
Intact surface	XRF 1	57.7	0.2%	33.4	0.4%	1.55	2.2%	3.56	1.4%	0.51	2.9%	<0.41		0.52	3.8%
	XRF 4	45.7	0.2%	41.1	0.4%	1.52	2.2%	3.63	1.4%	0.35	3.7%	0.48	0.01	3.58	1.2%
	XRF 5	22.6	0.4%	69.9	0.3%	1.04	3.1%	2.31	2.0%	0.18	6.1%	<0.45		1.71	2.1%
	XRF 2	58.0	0.2%	32.0	0.4%	1.60	2.2%	4.03	1.5%	0.49	3.0%	0.49	0.01	0.58	3.6%
	XRF 6	29.9	0.3%	60.5	0.3%	1.48	2.7%	3.07	2.0%	0.17	7.1%	<0.88		0.81	3.5%
	XRF 3	22.5	0.4%	69.9	0.3%	1.02	3.1%	2.62	1.9%	0.22	5.3%	<0.54		1.22	2.6%
Cleaned subsample	polished surface	59.5	0.3%	33.9	0.5%	1.40	3.0%	4.07	1.7%	0.59	3.3%	<0.07		0.04	0.01
		58.6	0.3%	33.9	0.5%	1.34	3.1%	3.96	1.8%	0.59	3.3%	0.44	0.02	<0.5	
		58.8	0.3%	33.9	0.5%	1.40	3.1%	4.26	1.6%	0.60	3.4%	<1.2		<0.5	
		58.7	0.3%	33.4	0.5%	1.42	3.0%	4.12	1.7%	0.59	3.3%	0.43	0.02	<0.5	
		58.5	0.3%	34.2	0.6%	1.40	3.2%	4.07	1.7%	0.57	3.7%	<1.4		0.05	0.02
		57.7	0.3%	34.5	0.7%	1.44	4.2%	4.35	2.3%	0.51	4.9%	<2.0		<0.7	
		58.5	0.3%	34.2	0.6%	1.48	3.1%	4.10	1.7%	0.60	3.5%	<1.4		0.07	0.02
		58.7	0.3%	34.4	0.5%	1.35	3.0%	3.98	1.8%	0.55	3.4%	<1.2		<0.5	
		58.4	0.3%	34.6	0.5%	1.42	3.1%	4.09	1.7%	0.56	3.6%	<1.3		<0.5	
	lead droplet	41.3	0.9%	50.2	1.2%	1.3	13%	3.1	8%	0.53	11%	<1.3		0.35	22%
	outer side	54.5	0.3%	34.4	0.6%	2.0	3.0%	4.54	2.0%	0.512	4.3%	0.58	4.4%	0.8151	4.2%
		56.0	0.3%	32.5	0.6%	2.1	2.9%	5.24	1.7%	0.5546	4.1%	0.63	4.1%	0.7255	4.5%
		54.6	0.3%	34.4	0.6%	2.0	3.1%	4.79	1.9%	0.4704	4.5%	0.60	4.2%	0.7579	4.3%

Tab. 1 Results of the handheld-ED-XRF analyses. Concentrations are in weight percentage unit (wt%), the uncertainties are relative (%)

PGAA Results

Prompt Gamma Activation Analysis (PGAA) was used to determine the bulk composition of various materials in a completely non-destructive way.[37] Two different parts of the socketed axe were selected for PGAA measurements. The first was to determine the bulk alloy composition, while the second was at the sampling hole of a previous analysis.[38] Since earlier results drew attention to the heterogeneity of the axe from Biatorbágy-Herceghalom, we were interested in comparing the results from the destructive and non-destructive measurements. Metallography provided valuable information on the dendritic structure of the alloy and the inclusions. These specific results will be discussed later in this paper. Here, some concentration data are shown for comparison.

The matrix's lead concentration, determined with ED-XRF, PGAA, and SEM-EDS methods, is in good agreement, while the handheld-ED-XRF Pb result is 15% lower. Metallography identified almost pure lead droplets, sometimes containing copper dendrites. The second ED-XRF and PGAA results revealed higher lead concentrations, which also suggests the presence of lead droplets inside the object (Tab. 2–3).

Biatorbágy-Herceghalom socketed axe, alloy composition						
	Liversage – Pernicka 2002 (sampling, ED-XRF) SAM 27374	PGAA (bulk)	PGAA rel. unc (%)	Metallo-graphy (sampling, SEM-EDS)	handheld ED-XRF (average, cutting surface)	handheld ED-XRF rel. unc (%)
Cu	52	56	2.7%	54.42	58.47	0.6%
Pb	40	39	4.1%	38.76	34.13	1.1%
Sb	4.8	3.6	9%	5.85	4.12	3.2%
As	1.03	0.38	4.2%	no data	no data*	
Ni	0.54	0.63	5.0%	no data	0.57	5.5%
Ag	0.54	0.36	3.7%	0.97	0.43	1.6%
Sn	1.47	*<d.l. (2.0)*		no data	1.41	3.4%
Au	0.01	*<d.l. (0.27)*		no data	*<d.l. (0.1)*	
Zn	0.1	*<d.l. (2.0)*		no data	*<d.l. (0.06)*	
Co	0.011	*<d.l. (1.0)*		no data	*<d.l. (0.02)*	
Fe	0.07	*<d.l. (0.2)*		no data	0.06	20%
Bi	0.007	*<d.l.*		no data	*<d.l. (0.3)*	

*small As Kβ peak is visible

Tab. 2 Comparison of previously published alloy composition results with PGAA, ED-XRF and metallography. The concentrations are in wt%, together with their relative uncertainty. Please note that in the case of the ED-XRF results, the uncertainties are considered in the decimals.

37 Révay – Belgya 2004; Szentmiklósi et al. 2016.
38 Liversage – Pernicka 2002, 423–425.

Biatorbágy-Herceghalom socketed axe, alloy + Pb droplet			
	Liversage – Pernicka 2002 (sampling, ED-XRF) SAM 27373	PGAA (bulk)	PGAA rel. unc (%)
Cu	13	26	3.6%
Pb	86	73	1.3%
Sb	0.78	0.5	10%
As	0.009	0.17	8.0%
Ni	0.154	0.27	6.0%
Ag	0.54	0.136	4.0%
Sn	*0.121*	*<d.l. (2.0)*	
Au	*0.02*	*<d.l. (0.27)*	
Zn	*0.02*	*<d.l. (2.0)*	
Co	*0.014*	*<d.l. (0.3)*	
Fe	*0.09*	*<d.l. (0.2)*	
Bi	*0.126*	*<d.l.*	

Tab. 3 Comparison of previously published alloy composition results with PGAA. The concentrations are in wt%, together with their relative uncertainty. Please note that in the case of the ED-XRF results, the uncertainties are considered in the decimals.

Metallography Results

A sample was taken from the socket (Fig. 2). The sample was encased in a resin, and its machined surfaces were prepared for metallographic examination. The sample was first grinded by SiC particles and then polished by diamond particles (3 and 1 µm). It was etched by K_2CrO_4 reagent, and its prepared surface was studied by an optical (Zeiss AxioImager M1m) and a scanning electron microscope (Hitachi 3400CFE). EDS was also used for local chemical analysis. Figure 3 shows the optical micrographs of the prepared sample.

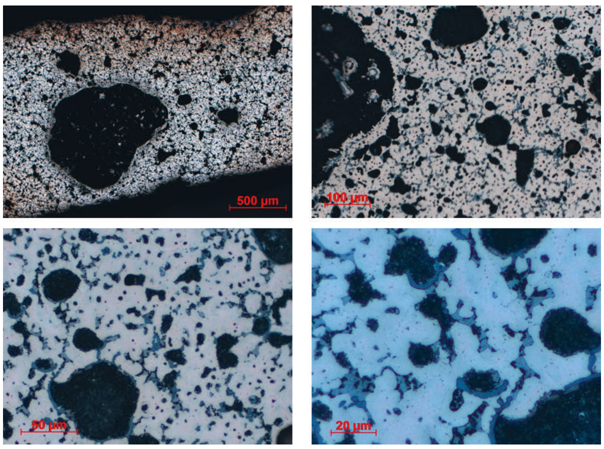

Fig 4 The optical micrographs taken from the metallographic sample of the socketed axe. Large and small black globular areas are corrosion products. In addition, the metallic matrix contains a large number of dark-grey inclusions (J. G. Tarbay, B. Maróti, Z. Kis, P. Barkóczy)

The microstructure contains large and small black globular materials inside the metallic matrix, which can be identified as the corrosion product. Most of the large spherical objects are likely casting defects filled with corrosion products, but this cannot be determined with certainty. The sample was taken from the socketed axe's surface, which was affected by long-term corrosion processes. However, it was possible to observe the metallic matrix, which is a single-phase metallic material with a large amount of dark-grey inclusions. A typical cast microstructure was observed. The dendrites are small due to the rapid cooling of the molten metal. The large cooling rate could come from the thin wall of the axe's socket, which demonstrates a good heat-conductive mould. The

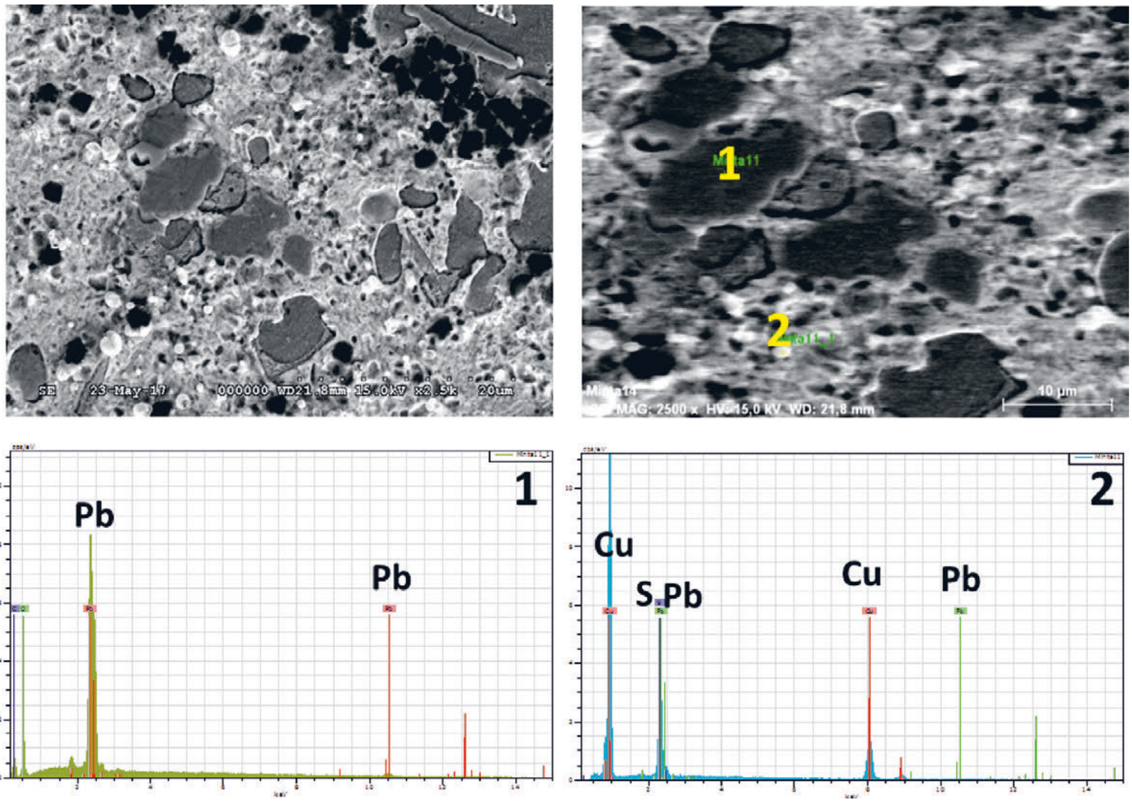

Fig. 5 SEM micrographs and the results of EDS analysis of the inclusions in the socketed axe's microstructure. The dark-grey inclusions can be identified as copper sulphide, while the bright inclusions are lead droplets. The EDS spectra show the identified elements in the measured points (J. G. Tarbay, B. Maróti, Z. Kis, P. Barkóczy)

inclusions showed the dendrites' boundaries and arms. Therefore, the inclusions were solidified at the final crystallisation stage, suggesting that these have a low melting point. SEM-EDS analysis was used to determine the inclusions and to analyse the local chemical composition.

The local EDS analysis (Fig. 5) revealed two inclusion types. The darker ones are copper-sulfide inclusions that come from the smelting process. The brighter ones with small spherical shapes are droplets, which consist of pure lead without any Ag or Sb content. Both inclusion types have a low melting point. In this amount (Tab. 2), the lead is not an impurity but an additive or alloying element. The copper does not dissolve the lead in the solid or liquid phases. The two metals form a monotectic system, which implies that the liquid phase is present in the solidification of the metals at low temperatures. This phenomenon helps the mould filling during the casting process, which allows small or thin-walled fine casts to be produced. Naturally, the lead addition decreases the strength of the metal, but the rapid solidification process turns the lead droplets into small particles, which compensate for this effect to a small extent. It must be noted that copper sulphate inclusions in this amount have a similar effect on the strength of the socketed axe. The general chemical composition was also measured by EDS for comparison with the other methods used; these results are summarised in Table 2.

Neutron Imaging Results

In its simplest form, classical attenuation imaging can be used for the 2D visual representation of the internal structure of non-homogeneous objects. It is a non-destructive method that detects the modification of the incident beam as it passes through the specimen. Computed tomography is an extension of this technique, where the 3D visualisation is achieved as a map of the relevant atten-

Type (in the order of elevating attenuation coefficient)	Number	Cumulative volume (mm^3)	Volume proportion (%)	Average sphericity
Air voids	45	31	0.12	0.60
Lead droplets	1953	1750 (= 1185 + 565)	7.02 (= 4.76 + 2.26)	0.61
Inclusions	543	302	1.21	0.52

Tab. 4 The cumulative volumes, the volume fractions relative to the object total volume, and the average sphericity factors of the air voids, lead droplets, and inclusions of the Biatorbágy-Herceghalom socketed axe (considering only volumes larger than 0.05 mm^3). The largest lead droplet has a huge volume of 1185 mm^3, which represents 4.76% of the total volume.

uation coefficients. X-ray imaging is more widespread compared to neutrons. However, it does have difficulties, such as when the metallic matter is thick and/or has a higher atomic number. In the case of the Biatorbágy-Herceghalom socketed axe, the high lead content proven by other methods is a proper example of this situation.

We used the RAD facility of the Budapest Neutron Centre to carry out thermal neutron-based tomography of the object with a spatial resolution of approximately 0.35 mm. The set of the attenuation coefficients obtained could then be divided into four separate ranges (we used the pore and inclusion finding algorithms of the VGStudio MAX 3.2 software) describing three different specimens (apart from the base metal). As a result, taking into consideration the spatial resolution of the setup, air voids, lead droplets, and inclusions with volumes larger than >0.05 mm^3 were found, as shown in Figure 6 and Table 4. The huge volume (1185 mm^3) of the largest lead droplet alone accounts for 4.76% of the total volume of 24916 mm^3 (Fig. 6.b and c). From the visualisation, we can get information on the direction of casting. As the spatial density of the lead droplets increases around the huge accumulation, we can conclude that it was cast from the socket, supporting the application of a mould design similar to that of Plenița.[39] Moreover, the material of the inclusions has higher attenuation coefficients than its neighbourhood. For example, these areas could be made of bronze, which contains less lead because the lead decreases the attenuation coefficient of the bronze.

Beyond simple volumetric data, there is a possibility of characterising the shapes of the specimens. Sphericity is a widespread parameter applied to describe how spherical the shape of an object is. It compares the surface area of a sphere to that of a specimen with the same volume. Values, by definition, fall in the range of 0–1, describing even more spherical bodies with an increasing number (a perfect sphere's sphericity is 1). The average sphericity values for the three specimens are shown in Table 4, while their distribution is shown in Figure 7. One can clearly see a difference between the general shapes. The lead droplets and the air voids have a more spherical shape compared to inclusions. Additionally, the larger the volume of both the lead droplets and the inclusions, the more elongated the shape.

[39] Boroffka – Ridiche 2005, fig. 6.2.

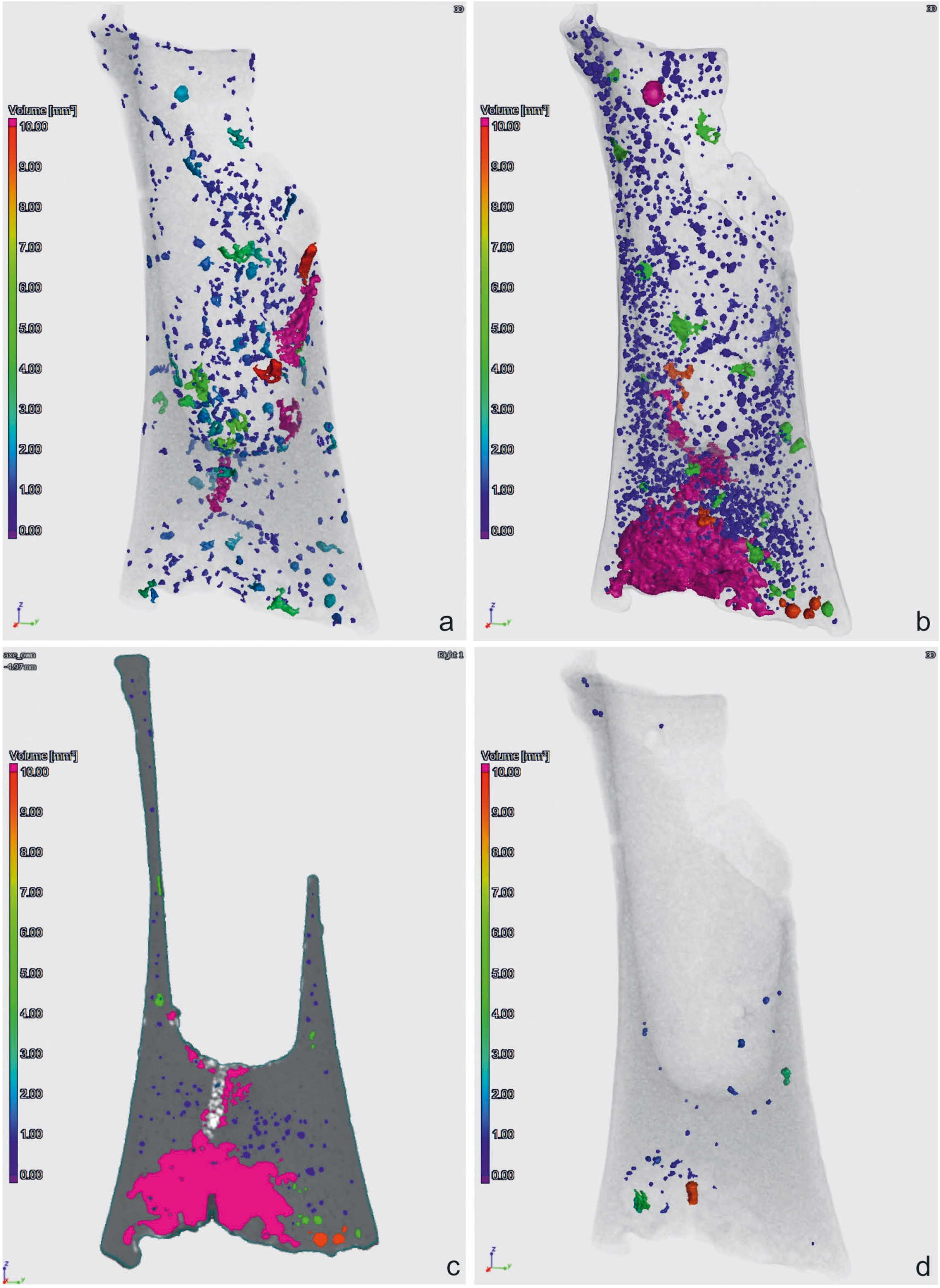

Fig. 6 The 3D visualisation of the three types of constituents (see text): a. Air voids; b. Lead droplets (among the smaller ones, there is a huge accumulation); c. A cut of the 3D dataset showing the lead droplets; d. Inclusions (J. G. Tarbay, B. Maróti, Z. Kis, P. Barkóczy)

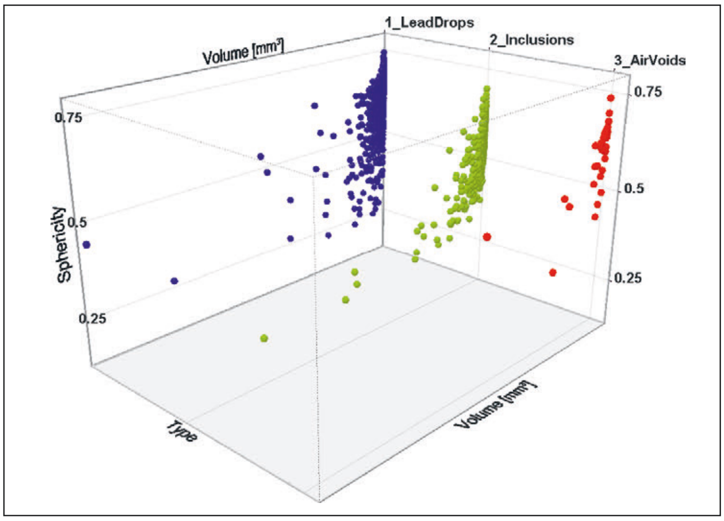

Fig. 7 The 3D visualisation of the sphericity factors of the three types of constituents (see text): lead droplets (1-blue), inclusions (2-yellow) and air voids (3-red). The lead accumulation with the largest volume is not shown (J. G. Tarbay, B. Maróti, Z. Kis, P. Barkóczy)

Discussion

In conclusion, we can approach the results of the Biatorbágy-Herceghalom socketed axe from three perspectives:

1. The phenomenon of lead segregation.
2. How can high-lead-content objects be interpreted in the territory of the Transdanubian Urnfield culture?
3. How do different analytical methods help to characterise a high-leaded artefact?

1. The high lead content of the object was highlighted earlier by both ED-XRF[40] and recent elemental-composition analyses (ED-XRF, PGAA, SEM-EDS). It was necessary to investigate this phenomenon and its cause. Neutron Imaging and its visualisation techniques played a key role in macroscopically presenting the types, quantities, sizes and spatial distribution of phenomena within the cast object. In Figure 4.b–c, it is clearly visible that lead accumulated in the lower part of the socketed axe. This spatial distribution in the elemental composition pattern suggests that we are dealing with the phenomenon of lead segregation, which has been observed in Bronze Age swords from Ireland by metallography and EPMA.[41] Since copper does not dissolve the lead, it forms small droplets in the bronze metal, either in the solid or liquid phase. Adding lead was a usual practice to produce thin-walled or small fine casting because the lead addition caused the existence of the liquid phase in a wide temperature range during the cooling of the melt. This phenomenon helps fill the mould cavity.[42] In the case of the Biatorbágy-Herceghalom socketed axe, there is a significant difference in the density of the lead (10.66 g/cm³ liquid at the melting point) and the copper (8.02 g/cm³ liquid at the melting point). Due to this difference, the lead droplets sank to the bottom of the melt, which caused the lead segregation in the socketed axe. This segregation phenomenon also proves that the socketed axe was cast from the direction of the rim, as we presumed from the archaeological material (stone casting mould from Plenița).[43] It should be

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40 Liversage – Pernicka 2002, tab. 2.SAM 27373, SAM 27374.

41 Tylecote 1962, 119; Harrison et al. 1981, 159–160; Hughes et al. 1982.

42 It is presumed that during the Bronze Age, lead was also used to alter the colour of bronze ornaments (e.g. pendants, beads). In some Bronze Age regions, it was also used for repair, or it was cast-on swords to shift their point of balance from the blade toward the hilt. Harrison et al. 1981, 168; Liversage – Pernicka 2002, 424; Johannsen 2016, 156.

43 Boroffka – Ridiche 2005, fig. 6.2.

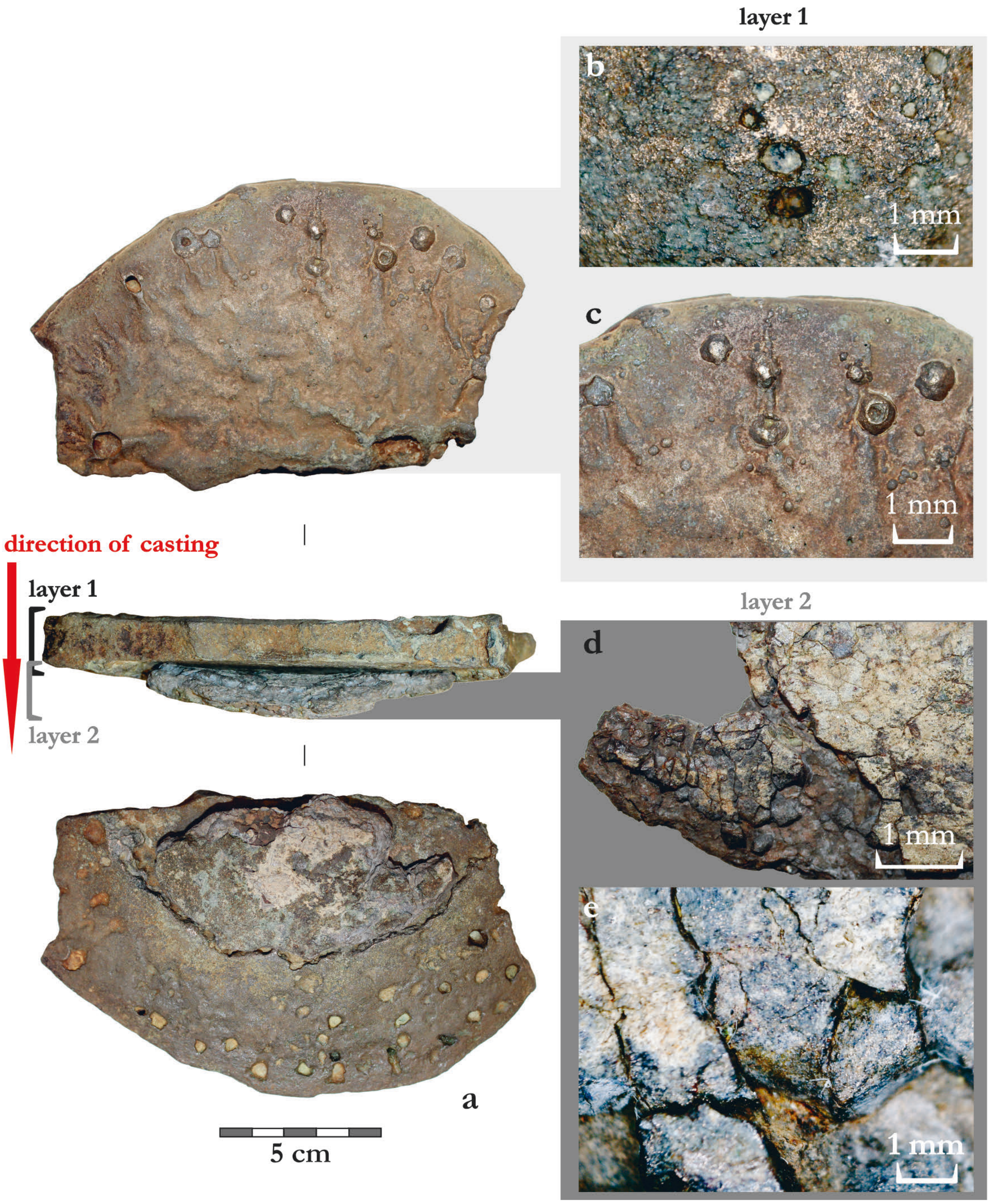

Fig. 8 a. Layered plano-convex ingot from the Kesztölc-Bodzás dűlő (Komárom-Esztergom County, Hungary) hoard with its detached convex side and plausible high lead content; b–c. The smooth, slightly reddish-brown surface of the plano side; d–e. The greyish, cracky surface of the detached convex side (J. G. Tarbay)

emphasised that a high percentage of lead content can affect the workability of the metal object and/or weaken its wear resistance, as it makes the material brittle.[44]

Objects with lead segregation in Transdanubia are not unique. We believe that this phenomenon is behind the formation of inhomogeneous plano-convex ingots, which caught the attention of Zoltán Czajlik and his colleagues. In the case of such ingots, a layered structure can usually

[44] Harrison et al. 1981, 168; Northover – Evely 1995, 96; Montero et al. 2003, 39.

be observed (Fig. 8), with lead segregation being one of the very plausible causes. The phenomenon is perfectly observable on the cross-section of a plano-convex ingot from Velem, which has been analysed by Zoltán Czajlik and Kamilla G. Sólymos. Based on four measurements taken from the object's cross-section, they have concluded that 'The Pb-content is extremely non-homogeneous and tends to decrease toward the plano side.'[45] Since the plano-convex ingots are cast from the plano side,[46] the phenomenon is identical to that of the Biatorbágy-Herceghalom socketed axe, which demonstrates that lead droplets sank to the bottom (convex side) of the ingot.

2. From a European context, the appearance of objects with a high lead content in the Late Bronze Age seems to be more of a pattern than an exception. Leaded artefact analyses are known from the Iberian Peninsula, the British Isles, Scandinavia, France and Slovenia. The type of heavily leaded objects varies by region. These are usually axes (socketed axes, palstaves, and shaft-hole axes), but ingots, weapons, and ornaments can also be found among them. Generally, the dating of these artefacts can be correlated with the periods of Ha A2–Ha B1 or Ha B1.[47] Regarding their context, they were primarily selected for hoards. The presence of high-leaded objects in the territory of the Transdanubia Urnfield culture is most likely part of this pan-European trend rather than a sign of a local event or 'crisis.[48] In addition to the many advantages of lead alloying mentioned above (it lowers viscosity and melting point), such artefacts could have been made for different purposes. Interpretations favour their economic or pre-monetary aspects or identify them as high-leaded copper ingots or solely as votive objects.[49] Among these possibilities, we propose a multicausal interpretation for the Transdanubian material. It is obvious that lead was used in part because of its technological advantages in casting. On the other hand, one should also consider the archaeological contexts of these finds. For example, the Biatorbágy-Herceghalom socketed axe comes from a hoard accumulated over a long time and deposited at the Ha B1 (Fig. 3.b). Based on the analysis of metalwork wear, the selection of objects is not uniform. It consists of two main groups: 1. predominantly partitioned or fragmented raw materials (ingots, by-products, as-casts, defective products, untreated/unfinished casts), 2. finished products (finished products with or without different intensities of use) (Fig. 3.a). The use-wear and archaeometallurgical analyses confirmed that our studied object belongs to the first group. It is an unfinished miscast, which has not been manufactured further as its cutting edge became brittle due to the high lead content.[50] A similar set of 'raw materials' to the Biatorbágy-Herceghalom hoard can also be found in other hoards in northeastern Transdanubia (e.g., Csabdi, Kesztölc, Lovasberény).[51] The various objects that make up a set are fragmented plano-convex ingots, a few special ingots, droplets, jets, as-cast, miscast, and unfinished products. Their selection into hoards shows a recurring pattern, reflecting a deliberate act of choosing particular objects following the pars pro toto concept for deposition.[52] This set was most likely selected from an active metallurgical workshop for the act of deposition. Therefore, objects composed of raw materials or miscasts were transformed into votive objects. The high-leaded objects of the Biatorbágy-Herceghalom hoard are ingots, by-products, or miscasts like the studied axe, whose technological pattern is analogous to the ones observed in western Europe.[53]

45 Czajlik et al. 1995; Czajlik – Sólymos 2002, 317–318, figs. 1–2.
46 Modl 2010, 138–140.
47 Bourhis – Briard 1977; Harrison et al. 1981; Trampuž Orel 1996, 192–197; Trampuž Orel et al. 1998; Trampuž Orel 1999, 417–418; Trampuž Orel – Heath 2001; Montero et al. 2003; Johannsen 2016; Tarbay et al. 2021, 18–19.
48 Liversage – Pernicka 2002, 425; Czajlik 2012, 53, 74, 95.
49 Huth 2000, 25–26; Montero et al. 2003, 40.
50 Czajlik 2012, 95.
51 Tarbay 2014; Tarbay 2018, 494–498, 566–580.
52 Tarbay 2022, 131–148.
53 Huth 2000, 26–31; Liversage – Pernicka 2002, 424, tab. 2.

3. Whether we follow the above hypothesis or interpret the appearance of leaded objects in Transdanubia in other ways, the analysis of these artefacts, whether archaeological or natural scientific, cannot be examined solely by one method. This is particularly important if one intends to characterise the elemental composition of Ha A2–Ha B1 or Ha B1 metalworks from the Transdanubian territory, as we can assume that the presence of high-leaded objects, along with them, the phenomena of lead segregation are of higher probability. In this case, it is essential to choose the proper sampling strategy or method to set up elemental composition series that are representative of the alloying ratio and composition of the objects.[54] From this point of view, the socketed axe from Biatorbágy-Herceghalom is a perfect case study, as we were able to compare previous SAM measurements and recent analyses made by different methods. The fastest, easiest, and most cost-effective technique is handheld ED-XRF analysis. The spectrometer provides results immediately after the measurements. The examined area is 7 mm² (the X-ray spot is 3 mm in diameter), while the penetration depth is 10-100 µm, depending on the alloy composition.[55] Unfortunately, a few tens of µm thick patina might distort the alloy composition results. The on-site, preliminary ED-XRF measurements on the uncleaned surface already reflected the heterogeneity of the object, as well as its high lead content. The quantity of the determined elements varied to a large extent; thus, these results did not provide accurate alloy composition data. In a later step of this study, the cleaned and polished side of the metallography subsample was also analysed with ED-XRF. The lead content of the matrix was lower than previously determined using other methods, and due to the relatively large spot size, the lead droplets could not be analysed separately. In contrast to ED-XRF, PGAA is a bulk method that provides the average composition of the irradiated volume. In this study, approximately 1 g and 2.3 g alloys were used in the selected parts, representing the matrix and a lead inclusion inside the axe, respectively. The socketed axe was analysed as received; no sample preparation was done before the analysis. The two analysed volumes, one for the matrix composition and one for the analysis of the lead-enriched part, were pre-selected with the help of neutron radiography.[56] The Pb, Sb, and Ni content determined with PGAA agreed well with the previous ED-XRF results. The PGAA Cu content was 8% higher, while the As and Ag contents were 63% and 33% lower than the ED-XRF, respectively. PGAA did not provide concentration data on the trace elements (e.g., Au, Co, Fe, and Bi). The Pb content determined by PGAA at the lead-enriched part was 15% lower than that determined by ED-XRF because PGAA examined not only the lead droplet but also the surrounding alloy matrix, which contained more copper. Both ED-XRF and PGAA determined significantly lower amounts of As and Sb in the vicinity of the large Pb droplet than in the metallic matrix, which suggests that these elements are not present in the pure Pb inclusions. This assumption was verified with the SEM-EDS, where the chemical composition of the Pb inclusions could be analysed separately. The two different bulk concentrations obtained with PGAA could be interpreted with the support of the other neutron-based method, neutron tomography. Not only could the 3D neutron imaging reveal the casting's direction, but it could also reveal the exact spatial and size distribution of pores, lead droplets, and inclusions. Direct information on the microstructure and the production technique could be identified only with the invasive metallographic examination. Metallography suggested that the cast cooled rapidly, and the matrix Pb and Cu concentrations determined with SEM-EDS agreed well with the earlier ED-XRF and the PGAA bulk results. SEM-EDS provided higher Sb and Ag results than the other methods.

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[54] Harrison et al. 1981, 160.

[55] Šatović et al. 2013.

[56] Kis et al. 2015.

Conclusion

In the study, an arch-profiled socketed axe from the Late Bronze Age Biatorbágy-Herceghalom hoard was analysed using non-invasive, non-destructive (on-site ED-XRF, ED-XRF of polished samples, PGAA, Neutron Imaging) as well as invasive analytical techniques (metallography, SEM-EDS analysis). The results of the new analyses were compared to each other and previous data of the SAM project (Tabs. 2–3). The Biatorbágy-Herceghalom axe is not only a high-leaded object but also affected by the phenomena of lead segregation. This prehistoric object can be interpreted as a miscast from a metallurgical point of view, as the high percentage of lead did not allow it to be a functional object with a resilient cutting edge. Our results suggest that such objects can only be thoroughly analysed by the combination of different methods, with the results supplementing each other. From a historical point of view, high-leaded casts belong to a European hoarding pattern that can be observed during the Ha A2–Ha B1 and Ha B1. This miscast axe was taken out of a metallurgical workshop and selected intentionally for a large hoard; thus, it was transformed into a votive object through the deposition practice.

Acknowledgements: The study has been supported by Project No. 134910 of the PD-OTKA Research Fund and Project No. 124068 of the K-OTKA Research Fund. Project No. 134910 has been implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the PD_20 funding scheme. Project No. 124068 has been implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the K_7 funding scheme. J. Gábor Tarbay is also grateful to the János Bolyai Research Scholarship (2020-2022) of the Hungarian Academy of Sciences.

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This volume presents contributions from the international workshop 'Bronze Age Metallurgy: Production – Consumption – Exchange' held in Vienna in May 2019. The conference was organised by the former Institute for Oriental and European Archaeology (now Department of Prehistory & West Asian/Northeast African Archaeology, Austrian Archaeological Institute) of the Austrian Academy of Sciences and VIAS (Vienna Institute for Archaeological Science, University of Vienna) on the occasion of the 20th anniversary of the Archaeometallurgical Laboratory at VIAS. The main goal was to gather renowned experts in Bronze Age mining archaeology and archaeometallurgy and to discuss recent developments and results concerning the production and use of copper, trade and exchange of raw materials and alloying practices in areas of central and southeastern Europe.

Altogether, 19 conference papers were presented, reporting on research achievements and new results on Bronze Age metallurgy in the territories of present-day Austria, Bosnia-Herzegovina, Croatia, Hungary, Germany, Italy, North Macedonia, Poland, Serbia, Slovenia and Switzerland. Nine of these are presented in this volume; they provide an excellent overview of the new results on Bronze Age metallurgy in the Balkans and most of the neighbouring regions. The results of new analyses, excavations and systematic studies presented here extend our understanding of metallurgical processes at regional and supra-regional levels during the Bronze Age.

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ISBN 978-3-7001-9483-5

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